PROTON CAPTURE TO EXCITED STATES IN $^8$BE

by

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Department of Physics
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Date: 9/18/81

Approved:

N. Russell Roberson, Supervisor

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics in the Graduate School of Duke University

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ABSTRACT

(Physics)

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The 90° yield curve has been measured for proton capture to the region of the $2^+$ isospin-mixed pair of levels in $^8$Be (7Li(p,γ$_{16}$)$^8$Be*) for incident proton energies from 4 to 30 MeV. The γ-rays from the capture reaction were observed for proton energies from 11.5 to 30 MeV. For $E_p = 4$–13 MeV, the yield curve was measured by observing the decay products (two α-particles) of the isospin-mixed pair. Cross section angular distributions for 7Li(p,γ$_{16}$) have been measured at nine energies from 12 to 30 MeV for various angles from 30° to 154°. Angular distributions of analyzing power have been measured at 13, 14, and 16 MeV proton energy for various angles from 30° to 154°. The data are compared to the predictions of a direct capture model including E1 and E2 radiation, and the model provides a good description of the data. No conclusive evidence for a giant dipole resonance built on the 16 MeV states is seen. The predictions of a direct-semidirect (DSD) model are investigated.

The 90° yield curves for 7Li(p,γ$_0$)$^8$Be and 7Li(p,γ$_1$)$^8$Be* have been measured for incident proton energies from 11.5 to 30 MeV. Cross section angular distributions for these reactions have been measured at 8 energies from 12 to 30 MeV for various angles from 30° to 154°. Angular distributions of analyzing power have been measured at 13, 14, and 16 MeV proton energy for various angles from 30° to 154°. The data are compared to the predictions of a direct capture model including E1 and E2 radiation. The model fails
significantly to predict the cross sections in the region of the observed giant dipole resonances for the two reactions. A DSD model calculation has been performed for the $^7$Li$(p,\gamma_0)$ reaction. The model provides a good description of the data.
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PROTON CAPTURE TO EXCITED STATES IN $^8$Be
Chapter 1  Introduction

The photonuclear reaction has been and continues to be a useful tool for investigating nuclear structure. Such a reaction is denoted here by \((\gamma,x)\), where \(\gamma\) denotes a \(\gamma\)-ray incident upon a nucleus and \(x\) denotes an emitted nuclear particle. The fact that one of the channels contains a \(\gamma\)-ray, whose interaction with charged particles is well known theoretically, makes photonuclear reaction theories in principle more simple than other reaction theories. This simplicity can allow the extraction of more information about the particle-nucleus channel, as well as information about intermediate states (nuclear structure).

The most important nuclear structure information which has been obtained through photonuclear reactions is the systematic occurrence of a large resonance in the photonuclear cross section as a function of \(E_x\). The peak of this resonance occurs at an excitation energy of about \(80/A^{1/3}\) MeV for medium and heavy nuclei and at about 20 MeV for light nuclei, and the resonance has a width from 5 to 10 MeV (Hanna, 1976). This resonance has been shown to be excited primarily by the absorption of E1 photons and is called the giant dipole resonance (GDR). The integrated photonuclear cross section in the region of the GDR is often parametrized in terms of the percentage of the classical E1 sum rule which has been exhausted by the particular reaction studied. A sum rule is an approximate theoretical limit of the
photoabsorption cross section, integrated over energy, for a given multipolarity. The classical E1 sum rule is given by \( \int \sigma \cdot dE = 60 \cdot NZ/A \text{ MeV-mb} \) (Hayward, 1970).

In recent years, giant resonances of multipolarities other than E1 have been observed. The general requirements for a giant multipole resonance are that a localized resonance be observed in the partial photoabsorption cross section for the appropriate multipolarity, that the resonance should exhaust a significant fraction of the corresponding sum rule, and that it be located systematically with energy in many nuclei.

The capture reaction, denoted \((x, \gamma)\), which is the time inverse of the photonuclear reaction, has also proved to be a very useful tool for studying giant resonances. The capture reaction has the advantage of using particle beams, which are easy to produce and manipulate, and it often allows the investigation of giant resonances which, due to target problems, can not be investigated by the photonuclear reaction. Furthermore, the measurements of angular distributions of cross section and analyzing power have provided stringent tests of various capture and giant resonance models. In some cases, the angular distributions have allowed the extraction of the T-matrix elements for the capture reaction, which can be used to further test the models and to look for strength due to multipolarities other than E1.

The GDR's that can be investigated with the photonuclear reaction are those built on the ground state of the target nucleus. Alternatively, the capture reaction, which can leave the residual nucleus in an excited state, should be a powerful tool for studying giant resonances built on excited states and for testing the Brink hypothesis (Brink, 1955), which states that a giant dipole resonance should be built on every state with some single-particle strength, regardless of its detailed nature.
In the past few years, Blatt and co-workers (Kovash et al., 1979, and Blatt et al., 1981) at Ohio State and Indiana University have studied proton capture on $^{11}\text{B}$ to a final state which is a highly excited unbound state, or rather, set of states, at about 19 MeV excitation energy in $^{12}\text{C}$. The yield curve for this reaction, denoted $^{11}\text{B}(p,\gamma_{19})$, was measured from 23 to 60 MeV and shows pronounced peaking at about 29 MeV proton energy, which corresponds to 42 MeV excitation in $^{12}\text{C}$, or about 23 MeV above the 19 MeV region. The excitation energy of 23 MeV is typical for a giant dipole resonance in light nuclei. For example, the GDR built on the ground state of $^{12}\text{C}$ peaks at about 23 MeV excitation energy, and the GDR built on the first excited state in $^{12}\text{C}$ peaks at about 22 MeV above the 4.44 MeV state. Blatt has in fact suggested that the observed peaking in the yield curve for $^{11}\text{B}(p,\gamma_{19})$ is due to a GDR built on the states formed from the stretched configuration $(d_{5/2}p_{3/2}^{-1})^4\text{^{-}}$.

It was suggested, however, by Arnold (1979) that the capture strength might in this case be the result of direct capture only. Tsai and Londergan (1979) then performed a direct capture calculation which included effects of residual two-nucleon interactions but treated the final state as a bound state. Following this, Halderson and Philpott (1981) performed a direct capture calculation which treated the final state properly as a continuum state. They concluded that direct capture could account for the major features of the data. Therefore, a particular ambiguity exists for proton capture to the 19 MeV region in $^{12}\text{C}$, since the direct calculation peaks at about 20 MeV above the 19 MeV region, which is the same energy region as might be expected for the peak of a GDR built on the stretched configuration states.

This ambiguity is removed in the case of proton capture on $^7\text{Li}$ to the region of the isospin-mixed pair of states at about 16.6 MeV in $^8\text{Be}$, since the direct capture calculation peaks at about 10 MeV above the 16.6 MeV region.
This reaction, denoted here by $^7$Li(p,$\gamma_1$$^6$Be), should therefore provide a better test case both for the existence of a GDR built on highly excited states and for direct capture theory. Additionally, the direct calculation is more straightforward for $^7$Li(p,$\gamma_1$) than for $^{11}$B(p,$\gamma_19$), since the final states are bound to single-nucleon decay. The study of this reaction is the primary focus of this thesis. Additional investigations are reported for the two capture reactions, $^7$Li(p,$\gamma_0$) and $^7$Li(p,$\gamma_1$), and are used for comparison with the $^7$Li(p,$\gamma_1$$^6$Be) reaction.

A level diagram is shown in Fig.1 to illustrate more explicitly the processes occurring in the reaction denoted $^7$Li(p,$\gamma_1$$^6$Be). The incoming channel consists of a proton with energy $E_p$, incident upon the nucleus $^7$Li, $J^\pi=3/2^-$, and the outgoing channel consists of a $\gamma$-ray plus the recoiling $^8$Be nucleus, left in one of the excited states at $E_\gamma=16.63$ and 16.92 MeV. These states incidentally decay nearly 100% into two $\alpha$-particles, moving in opposite directions in the center-of-mass. This capture reaction at low energies and the isospin-mixed pair of states were studied in some detail by Marion and co-workers at the University of Maryland. They have presented evidence which indicates that the two states have mixed $T=0$ and $T=1$ isospin and are primarily single-particle plus core states, with the 16.63 MeV level being largely a $^7$Li + proton state, and the 16.92 MeV level being largely a $^7$Be + neutron state (Marion and Wilson, 1966). In addition, yield curves for proton capture to each state in the pair have been measured from 0.441-2.45 MeV (Sweeney and Marion, 1969), and it was seen that for off-resonance proton capture, the capture cross section to the 16.63 MeV state was roughly an order of magnitude larger than the capture cross section to the 16.92 MeV state. A model was then proposed using the shell model wave functions of Barker (1966), which gives a proton spectroscopic factor, $S$, of 0.470 for the 16.63 MeV state, and only
Figure 1. Level diagram for $^8\text{Be}$, $^7\text{Li} + p$ shown.
0.010 for the 16.92 MeV state.

The TUNL γ-ray spectrometer does not have sufficient energy resolution to independently confirm that the 16.92 MeV state is not populated in the proton capture reaction. For the data analysis, it was assumed that both states could be populated, and the data in this thesis are quoted as measuring the capture cross sections to the region of the isospin-mixed pair.
Chapter 2 Experimental Details

A. Beam Characteristics

The data reported in this thesis were taken at Triangle Universities Nuclear Lab (TUNL). A diagram of the lab is shown in Fig.2. To accelerate beams to energies from 3 to 17 MeV, a model FN tandem Van de Graaff accelerator was used. Various ion sources provided the proton beam for injection into the tandem. The unpolarized beams for the yield curves and angular distributions were produced by one of two direct-extraction negative ion sources (DENIS I or DENIS II). The unpolarized beams were chopped and bunched before injection into the tandem, and typical repetition rates for the bunched beam were about 5 MHz, with a typical on-target pulse width of about 2 nsec. The polarized proton beams used for the analyzing power experiments were produced by the TUNL Lamb-shift polarized ion source (Clegg et al., 1970). The polarization of the beam was measured after every run by making a quench-ratio measurement (Trainor et al., 1974), using a Faraday cup located at the center of the 90-90 magnet. The polarization varied between 60% and 80% over the course of the experiment, and the typical value was about 75% and quite steady during a given run. The assumed error in the polarization as determined from the quench ratio was less than about 5%. The polarized beams were pulsed by a three-stage bunching system (Wender et al., 1980). The first stage was a linear voltage ramp of approximately 100 V peak-to-peak applied to
Figure 2. TUNL laboratory.
the anode of the duoplasmatron in the polarized source. Additional bunching was provided by a two-stage double-drift buncher system located before the entrance of the tandem.

Unpolarized proton beams with energies from 18–30 MeV were obtained by injecting the beam of a single-energy (15 MeV) cyclotron into the tandem (Cyclo-Graaff) (Newson et al., 1974). The normal RF structure of the cyclotron beams gave bunched protons with a 25 MHz repetition rate.

After acceleration the beams were momentum analyzed by a pair of 90° magnets. Only protons of the correct energy, as selected by the magnetic field, were allowed through the magnets. The strength of the magnetic field, and thus the energy of the beam, was determined by using a nuclear magnetic resonance fluxmeter. The beams were next steered through the 70–70 switching magnet into the 30° left beam leg in target area 4 and focused on a thin foil target placed inside an evacuated brass target chamber. This chamber was cylindrical with a 15.5 cm diameter and 8 cm height. A drawing of the capture beam leg in the target area is shown in Fig.3. The beams passing through the target were collected in the beam dump, which consisted of an insulated 6 foot pipe with a tantalum end cap. The pipe was located in a hole drilled at a 30° angle through the 1.5 feet thick concrete wall and about 4 feet into the dirt outside the wall. The current impinging on the beam dump was read, monitored, and digitized using a current integrator. Typical target currents were about 50 nA. The limiting factor on the beam current was primarily the count rate in the γ-ray spectrometer, since high count rates caused pile-up problems and high accidental coincidence rates between the NaI and the shield. A small aperture tantalum collimator of 1/16 inch thickness was used to collimate the beam just prior to the target, and the typical aperture used was a circular hole of 0.125 inches diameter. The beams were steered and focused to keep the
Figure 3. Capture beam leg.
current on the collimator to a minimum (typically less than 1 nA).

A capacitive pick-off unit was used in the beam line to provide a timing signal from the bunched tandem beams. The unit consisted of a hollow cylinder of copper metal, as a capacitor, with a 1/16 inch wall, 1/2 inch outer diameter, and length of $2\frac{1}{2}$ inches. The signal was amplified at the beam line before being sent to the control room. For the Cyclo-Graaff experiments, a timing signal was obtained by the induction of a current in a coil of wire placed near the main RF oscillator of the cyclotron.

The 2α coincidence experiment was performed in the 52° scattering chamber in target area 1. The proton beams for this experiment were momentum analyzed with the 20-70 magnet (magnet #1 in Fig.2). The beams were collimated just prior to the target using a tantalum collimator with a square aperture of dimensions 0.120 by 0.120 inches. The beams passing through the target were collected with a standard beam dump.
B. NaI Detector and Electronics

The $\gamma$-rays from the $(p,\gamma)$ reactions were observed with a cylindrical 10 inch by 10 inch Bicron NaI crystal as shown in Fig.4. Six RCA-8575 photomultiplier tubes were used to collect the light from the scintillations in the crystal. The signals from the tubes were summed with a fan-in circuit and the output was clipped by a 160 nsec, 50 ohm clipping line, terminated with a 12 ohm resistor. The clipped signal, with about a 350 nsec width, was transmitted to the control room for further processing. A well-shaped NE110 plastic scintillator (Suffert et al., 1968) was positioned to cover the front and sides of the NaI and was used as an active anti-coincidence shield. The scintillations in this shield were viewed with 8 XP1031 photomultiplier tubes. The signals from the shield tubes were amplified separately, summed with a fan-in circuit, and amplified again. The output of the fan-in circuit was clipped by a 30 nsec, 50 ohm, shorted cable.

The shield and NaI were surrounded further by passive shielding, consisting of 10 cm of lead, approximately 20 cm of paraffin doped with lithium carbonate (50% lithium carbonate by weight), and a cadmium sheet across the front face. A lead collimator was used to collimate the $\gamma$-rays and was designed to just allow full illumination of the back face of the crystal by $\gamma$-rays from the target.

Using RG-8 cable to reduce attenuation, the summed signals from the NaI and shield were sent to the NaI and shield electronics set-up in the control room. A schematic diagram of these electronics is shown in Fig.5. The principle of these electronics was to send to the computer linear signals, one proportional to the $\gamma$-ray energy ($E_\gamma$) and another proportional to the time difference between the time pick-off and an event in the NaI crystal (TAC),
Figure 4. $\gamma$-ray spectrometer.
Figure 5. NaI and Shield electronics.
No. I and SHIELD ELECTRONICS

- PICK-UP LOOP
  - RF AMP
  - ZERO CROSSING DISC
  - TAC
  - STOP
  - START
  - TO ADC(TAC)
  - FOR CYCLOTRON EXPERIMENTS

- CAPACITIVE PICK-UP
  - VARIABLE GAIN AMP
  - CONSTANT FRACTION DISC
  - TAC
  - STOP
  - START
  - TO ADC(TAC)
  - FOR TANGEM (p,γ) EXPERIMENTS

- SHIELD
  - VARIABLE GAIN AMP
  - DISC
  - 200 ns
  - COIN (Acid)
  - LOGIC SHAPER & DELAY
  - TO ACCIDENTAL SCALER

- 11 μsec OPEN LINE
  - SHIELD
  - COIN
  - LOGIC SHAPER & DELAY
  - TO ROUTER (R2)

- NO. I
  - DISC
  - PILEUP GATE
  - GATE GEN.
  - TO COINCIDENCE SCALER
  - TO NO. I SCALER
  - TO ROUTER (RI)

- Fan OUT
  - TIMING FILTER AMP
  - DISC
  - GATE
  - FAST LINEAR GATE
  - SPEC AMP
  - TO ADC (LINEAR Eγ)

- DELAY
  - LINEAR
along with appropriate routing signals.

In more detail, the summed signal from the six NaI phototubes was fanned out into two signals. The first signal was sent to the linear input of a fast linear gate and then passed through a spectroscopy amplifier to give a linear signal to the ADC. The second signal from the fan-out was used to provide various logic signals. The signal was first passed through a fast amplifier to a discriminator. A gate was next used to produce a 10 μsec long signal which, by its leading edge, triggered a 400 nsec gate. This gate signal was used to open the fast linear gate for 400 nsec, allowing the 350 nsec linear signal to pass through. Thus, a signal large enough to trigger the discriminator opened the linear gate for 400 nsec and then held it closed (blocked) for 10 μsec. This 10 μsec block was implemented in an effort to reduce pile-up. The gate signal also provided a routing signal (R1) for use by the computer.

The shield electronics provided the computer with a routing pulse (R2) which indicated that the NaI linear signal had occurred in coincidence with a shield signal. These routing pulses were used by the computer logic to "reject" the corresponding linear NaI signals from the γ-ray spectrum and to store them in an additional spectrum, called the "rejected spectrum" (discussed in the next section). A sample rejected event would be one in which a cosmic ray caused a simultaneous scintillation in the shield and NaI. The shield signal was amplified, sent to a fast discriminator, and after being delayed, was sent to the input of a coincidence circuit, along with a NaI logic signal. The rejection routing signal (R2) was produced if there was a coincidence. The resolving time of the coincidence circuit was about 60 nsec. The rejection efficiency was a function, in particular, of the amplifier gain setting and of the trigger level of the fast discriminator. Another
coincidence circuit was used to provide a measure of the accidental coincidence rate, which is the rate of random coincidences between the NaI and the shield pulses. This was accomplished by delaying the shield signal 200 nsec relative to the NaI signal before this coincidence circuit. The data was later corrected for the accidental counting rate.

A time-to-amplitude converter (TAC) in these electronics produced the linear signal which was proportional to the time interval between the timing signal and the NaI signal (the TAC signal). The start signal for the TAC was provided by a fast logic signal from the NaI electronics. For \((p,\gamma)\) experiments using the tandem (without the cyclotron), the capacitive pick-off signal was sent to an amplifier and a discriminator before entering the stop input of the TAC. For \((p,\gamma)\) experiments using the Cyclo-Graaff, the signal from the pick-up loop was sent through a RF amplifier and a zero-crossing discriminator before entering the stop input. The TAC signal produced in either case was sent to an ADC.

The pick-off signal was itself monitored to see whether or not all (or nearly all) of the beam bunches were being detected by the electronics. If any beam bunches were not detected, the associated \((p,\gamma)\) data would not be stored into the proper spectrum in the computer. Additionally, if the discriminator in the pick-off circuit was set in the noise, too many bunches would be counted. The bunching system was tuned during the experiment to insure that the required number of bunches were detected. For a few cases when the beam was unstable, the number of bunches detected was counted in a scaler and used to renormalize the data upward in proportion to the percent of bunches missed by the electronics. Typically, since only 1 or 2% of the beam bunches were missed, this correction was small.

For the \((p,\gamma)\) experiments, silicon surface barrier detectors were used
as target thickness monitors. These detectors were placed at 160° relative to
the beam direction and were generally 2000 microns thick. The electronics
consisted simply of an ORTEC model 109A preamp, connected to a spectroscopy
amplifier. The particle spectra obtained from these detectors were stored in
the computer, and the peak due to proton elastic scattering from $^7$Li was used
to provide a relative normalization from run to run for the \((p,\gamma)\) angular
distribution data.
C. On-line Computer and Computer Interface

All of the data reported in this thesis were acquired using an on-line DDP-224 computer. A locally built computer interface provided the data path and controls for the transfer of data from the analog-to-digital converters (ADC's) and routers to the computer. The important signals for data storage for the $(p,\gamma)$ experiments were $E_\gamma$, TAC, R1, and R2. The linear signals $E_\gamma$ and TAC were connected to ADC's, and R1 and R2 entered a two-input router. The logic of the computer system used for data taking was such that if only R1 was present, the corresponding $E_\gamma$ signal was stored in the accepted data spectrum. If both R1 and R2 were present, $E_\gamma$ was stored in the rejected data spectrum. The associated TAC signal was also stored, and the data taking program allowed the setting of a window on the TAC spectrum. During the experiment, the window was set around a peak corresponding to prompt $\gamma$-rays from the target. If the TAC pulse occurred inside the window, the associated $E_\gamma$ signal was stored in the "in-the-window" spectrum. For a TAC pulse occurring below or above the window, the $E_\gamma$ signal was stored elsewhere. This time gating was used for both accepted and rejected events. The energy and TAC spectra were displayed on an oscilloscope as they were accumulated. After every run, the spectra were dumped on tape for later analysis. Sample spectra obtained are shown in the next section.

The computer also controlled and stored a number of scalers used for diagnostics. One scaler was used to count the output pulses from the current integrator, thus measuring the integrated incident beam charge for a given run. Another scaler counted this integrated charge gated by the dead time of the system, including the dead time from the 10 $\mu$sec gate and the dead time of the computer system. Other scalers counted NaI, shield, coincidence, and
accidental events as well as pulses from a real time clock. A final scaler counted the integrated charge gated by the dead time of the ADC used for the particle monitor storage.
D. NaI Spectra Data Reduction and Analysis

An accepted, in-the-window NaI spectrum for proton capture on $^7$Li is shown in Fig. 6. Also shown for comparison is the corresponding rejected, in-the-window spectrum (Fig. 7), and the accepted, but below-the-window, spectrum (Fig. 8). The first figure is the spectrum that was used for extracting the yields for the various $^7$Li capture peaks labelled in the figure. The shield rejection and time-of-flight window obviously provided a great increase in the quality of the spectra. The storage of above- and below-the-window spectra allowed the monitoring of the correct setting of the TAC window. In some cases, small peaks were seen in the out-of-window spectra which corresponded to $\gamma$-rays from the reactions $^7$Li($p,\gamma_0$) and $^7$Li($p,\gamma_1$). In such cases, the $\gamma_0$ and $\gamma_1$ yields were corrected for these extra counts. For the $^7$Li($p,\gamma_{16}$) case, no definite peaks were seen in the out-of-window spectra, so no corrections were made to the $\gamma_{16}$ yield.

Shown in the next figure (Fig. 9) is a plot of the same Li spectrum, labelling $^7$Li capture lines and possible contaminants and including the results of a multiple peak fitting program called MULFIT (S.E. King, 1980). The program MULFIT fitted simultaneously the peaks in the spectra to a standard $\gamma$-ray line shape obtained from $^3$H($p,\gamma$) spectra taken at TUNL with the same NaI spectrometer. Three variable parameters were used in the fit for each peak: the peak height, the peak centroid, and the peak width. For spectra taken at different angles but the same energy, the $^7$Li peak widths were held fixed. Since the first excited state of $^8$Be has a non-negligible width ($\Gamma = 1.5$ MeV), the $\gamma_1$ peak was fit with the standard line shape, convoluted with a Lorentzian line shape. Using MULFIT, the yields for $^7$Li($p,\gamma_0$), $^7$Li($p,\gamma_1$), and $^7$Li($p,\gamma_{16}$) were extracted from the spectra for
Figure 6. $^7\text{Li}(p,\gamma)$ spectrum. Used thick Li metal target. Shown are capture to ground state of $^8\text{Be}$ ($\gamma_0$), capture to first excited state ($\gamma_1$), and capture to isospin-mixed pair ($\gamma_{16}$).
The diagram represents the reaction $^{7}\text{Li}(p,\gamma)^{8}\text{Be}$ with a proton energy $E_p = 13\text{ MeV}$ and a laboratory angle $\theta_{\text{lab}} = 90^\circ$. The graph shows the counts plotted against the channel number.
Figure 7. \( ^7\text{Li}(p,\gamma) \) rejected, in-the-window spectrum.
Figure 8. $^7\text{Li}(p,\gamma)$ accepted, below-the-window spectrum.
Figure 9. $^7$Li(p,γ) spectrum with line-shape fitting. Shown are $^7$Li(p,γ₀), $^7$Li(p,γ₁), and $^7$Li(p,γ₁₀) and the predicted positions of various contaminant capture lines.
further analysis. Other observed peaks in the spectra were fit only to help
construct the background under the $\gamma_{16}$ peak, which was due largely to the
tails of higher energy peaks. Most of the data analysis described above was
performed with the TUNL VAX 11/780 computer.

Absolute cross sections for the data were determined in part from the
absolute efficiency of the NaI spectrometer for detecting $\gamma$-rays. This
efficiency was determined for 15 MeV $\gamma$-rays by measuring the $^{12}\text{C}(p,\gamma)$ thick
target yield curve over the 15.07 MeV resonance in $^{13}\text{N}$ and comparing to a
previous measurement of the number of $\gamma$-rays per proton (Marrs et al., 1975).
Measurements of the accept-reject ratio for the full energy $\gamma$-rays and the
shielding attenuation as a function of energy were used to extrapolate this
efficiency to other energies (Weller and Roberson, 1981). The ratio of the
full energy $\gamma$-rays (accepts-plus-rejects) divided by the total response of the
NaI (accepts and rejects integrated down to zero energy) is essentially
constant as a function of energy (Hayward), so it was not necessary to include
this term in the extrapolation to other energies.
E. 2α Coincidence Experiment, Detector Set-up, and Electronics

As discussed earlier, the final state in the \( ^7\text{Li}(p,\gamma_{16})^8\text{Be}^* \) reaction is actually a pair of isospin-mixed states in \(^8\text{Be}\). These states decay almost 100% (more than 99%) (Ajzenberg-Selove, 1979) into two α-particles. A pictorial representation of the reaction is shown in Fig.10. An alternate measurement of the cross section for \( ^7\text{Li}(p,\gamma_{16}) \) was provided by the 2α coincidence experiment, which detected the two decay α-particles in coincidence. Since the isospin-mixed pair does decay nearly 100% into 2 α-particles, and since the capture process involving a single γ-transition to these states is the only likely way of populating these states, the total cross section (\( \sigma_T \)) measured in the 2α reaction should be equal to the total cross section measured in the \( ^7\text{Li}(p,\gamma_{16}) \) reaction. Since measurements of \( p,\gamma_{16} \) angular distributions for \( E_p = 13-30 \text{ MeV} \) indicate that the γ-transitions are predominantly E1, the angular distribution of α-particles should be expandable in terms of Legendre polynomials of orders zero and two only (Sweeney and Marion, 1969). That is: \( \sigma(\theta) = A_0 P_0(\cos(\theta)) + A_2 P_2(\cos(\theta)) \). It was decided in our experiment to measure the α-particles at the zero of \( P_2 \), thus providing a direct measure of \( A_0 \) and \( \sigma_T (\sigma_T = 4\pi A_0) \).

The detectors used in the 2α coincidence experiment were silicon surface barrier detectors. Two sets of two detectors were used for the experiment, one set placed at a forward angle (at the zero of \( P_2(\cos(\theta)) \) in the center-of-mass system) and the other set placed at the predicted backward angle for the coincident α-particle. (A kinematics program was written, called DEKIN, to calculate the expected angles and energies for the coincident α-particles.) Each set consisted of a front detector and a back detector. The front detector was selected to be thick enough to stop the α-particles from the
Figure 10. Classical picture of $^7\text{Li}(p,\gamma_{16})^8\text{Be}^*\rightarrow2\alpha$. 
$^7\text{Li}(p, \gamma_{16})^8\text{Be}^* \rightarrow 2\alpha$

1. Incident channel

2. $\gamma$-ray emission

3. $\alpha$ decay

$p \rightarrow ^7\text{Li}$

$\gamma$-ray

$\text{RECOILING}^8\text{Be}^*$

$^4\text{He}$
decay of the isospin-mixed pair but thin enough to let higher energy α's and most protons pass through. The back detector of each set was 2000 microns thick and was operated in anti-coincidence with the front detector.

The electronics for the 2α experiment are shown in Fig.11. The thin, front detectors are labelled "E", and the thicker back detectors are labelled "V" for "veto". Fast preamps (ORTEC models 142A or 142B) were used for all four detectors. The electronics for sets 1 and 2 were identical. Set 1 was placed at the forward angle and set 2 was placed at the backward angle. The energy output from the E preamp was passed through a spectroscopy amplifier to produce a linear signal, called E₁ or E₂, which was sent to an ADC at the computer interface. Timing single channel analyzers were used as discriminators to create logic signals from both front and back detectors. These logic signals were fed to an overlap coincidence operated in the anti-coincidence mode such that an output was obtained only if an E signal was present without a V signal. The T outputs from the two E preamps were amplified and fed to two fast discriminators, which produced the start and stop signal for a combination time-to-amplitude converter and single-channel analyzer (TAC/SCA). The TAC output was a linear function of the time difference between the arrival of a particle in the forward detector (1) and the backward detector (2). This timing signal helped decrease background in the energy spectra (as discussed in more detail in the following section). The SCA-out signal from the TAC/SCA was a logic signal which occurred if the TAC signal was within the limits of the SCA window. This signal was run in coincidence with the output of the two other coincidence circuits to provide a gate signal allowing the E₁, E₂, and TAC pulses to be stored by the ADC's. The logic of the coincidences was such that, to obtain the gate signal, there must have been simultaneously a pulse in detector E₁ but not in V₁, a pulse in
Figure 11. 2α coincidence experiment electronics. The detectors labelled 1 were placed at the forward angle and the detectors labelled 2 were placed at the backward angle.
2a COINCIDENCE ELECTRONICS
$E_2$ but not in $V_2$, and a timing signal within the range of the SCA on the TAC. 

The spectra observed are discussed in detail in the following section.
F. 2α Spectra and Analysis

The two energy signals (E₁ and E₂) and the TAC signal produced by the electronics, gated as described in the previous section, were stored in the computer and dumped on tape in "event mode" for later analysis. The analysis program, using the TUNL off-line DDP-224 computer, generated two gated spectra, in addition to the normal ungated energy and TAC spectra. One gated spectrum was the TAC spectrum gated with windows on E₁ and E₂, called the "energy-gated TAC". The second spectrum was a summed E₁ plus E₂ spectrum gated by a window in the TAC spectrum and a window on E₂. The windows on these spectra were set as described below.

For a given incident beam energy, DEKIN was used to calculate the predicted energies of the α-particles from the 16.6 MeV region at the specified detector angles, and during the experiment each detector was energy calibrated using an 241Am α-particle source and a pulser. In the analysis, windows corresponding to the predicted energies were set on E₁ and E₂ to obtain the energy-gated TAC spectrum. A gated TAC spectrum for 10 MeV incident protons is shown in Fig.12. The region in the gated TAC spectra corresponding to coincidences between the α-particles had consistently a double-peaked nature, as seen in the figure, which was unexpected. This was believed to be due to a time jitter in the electronics, but since the background in the spectra was small, the final yield should not have been affected. Next an E₁+E₂ summed spectrum was obtained, gated by a window placed in the TAC spectrum surrounding the peak determined by the energy-gated TAC, and by a window placed in the E₂ spectrum surrounding the predicted α-particle energy. Gated and ungated summed spectra are shown in Fig.13. The gated spectrum shows a well-defined peak near the correct energy as predicted by the
Figure 12. Gated TAC spectrum for 2a coincidence experiment.
$^7\text{Li} \ (p, \gamma) ^8\text{Be}^*$

$E_p = 10.0 \text{MeV}$

Gated TAC spectrum

TAC Gate Region

(for $E_1 + E_2$)
Figure 13. Gated and ungated $E_1+E_2$ spectra for 2a coincidence experiment.
kinematics calculation. This peak was summed to obtain the yield for the \( 7\text{Li}(p,\gamma)^{8}\text{Be} \rightarrow 2\alpha \) reaction. Clearly the gating requirements were necessary in this experiment, due to the high background count rate relative to the proper \( 2\alpha \) coincidences.

Further analysis, performed with various gating windows, indicated that the windows in the initial analysis were properly set to detect the full number of coincidences in the data.

A potential problem that was checked involved the efficiency for detecting the second \( \alpha \)-particle in coincidence with the first. Since the capture \( \gamma \)-ray is not detected in this experiment, the excited \( ^8\text{Be} \) nucleus recoils in an unspecified direction after the proton capture and before decay into two \( \alpha \)-particles. Thus, depending on the direction of recoil, the \( \alpha \)-particles can come out at different lab angles for the same center-of-mass angle. In the experiment, the forward detector was tightly collimated, with a circular hole subtending an angle of \( 1.5^\circ \). Calculations were performed which estimated that the backward angle detector should subtend at least an angle of about \( 5.5^\circ \), both in and out of the reaction plane, to observe all of the possible \( \alpha \)-particles in coincidence with those in the forward detector. In the experiment, a circular collimator subtending \( 8.1^\circ \) was used for the backward detector. Although this was believed to be sufficient, an experimental check was made by observing the number of \( 2\alpha \) coincidences from the 16.6 Mev region as a function of the back angle, keeping the forward angle fixed. These experiments indicated that indeed the collimator size was adequate. They also indicated that the calculated angles for the two \( \alpha \)-particles were correct.
6. Targets

The targets used for the $^7\text{Li}(p,\gamma)$ experiments were thick, 10–20 mg/cm$^2$, foils of natural lithium, which were obtained by pressing lithium metal. After pressing, the foils were mounted on target rings and stored in mineral oil. Care was taken to reduce surface contamination of the targets, and they were not stored longer than a day in mineral oil before being used. When used, the targets were washed with pentane to remove the mineral oil and quickly pumped under vacuum in the target chamber. Speed was important to reduce oxidation of the lithium. These targets were too thick to measure with $\alpha$-particles from an $^{241}\text{Am}$ source, so cross sections were determined from thin targets or by comparing TUNL data to published data. The details of the absolute cross section determination and errors involved are discussed in Chapt.3.

Thin LiF targets were used for the $2\alpha$ coincidence experiment and also for the absolute cross section measurements of the $^7\text{Li}(p,\gamma_0)$ reaction. These targets were prepared by evaporation of natural LiF onto thin (20 $\mu$g/cm$^2$) aluminum foils mounted on target rings. The thicknesses of these targets were measured by comparing to the $(p,p_0)$ data of Gleyvod et al. (1965) and were typically about 250 $\mu$g/cm$^2$, implying a $^7\text{Li}$ thickness of about 70 $\mu$g/cm$^2$. These results were in agreement to within 10% of those determined from the energy loss of 5.477 MeV $\alpha$-particles from an $^{241}\text{Am}$ source. The targets were fairly strong, and it was not necessary to store them under vacuum.
Chapter 3 \( ^7\text{Li}(p, \gamma_{16})^8\text{Be} \) Experimental Results

A. Absolute Cross Section

Before discussing the determination of the absolute cross section for the \( ^7\text{Li}(p, \gamma_{16}) \) reaction, it is necessary to consider the effects of possible sources of background under the \( \gamma_{16} \) peak. The effects of \( ^{12}\text{C}(p, \gamma_1) \), \( ^{16}\text{O}(p, \gamma_0 + \gamma_1) \), and \( ^6\text{Li}(p, \gamma_2) \) (see Fig. 9 in Chapt. 2) are discussed in the following paragraphs.

Carbon was clearly present in the target, since fixed energy \( \gamma \)-rays were seen with energies of 15.11 and 12.71 MeV, which were presumably produced by the \( ^{12}\text{C}(p, p' \gamma) \) reaction. In addition, the particle monitor spectra showed a peak which was determined using kinematics to be due to protons elastically scattered from \( ^{12}\text{C} \). These two reactions provided an estimate of the amount of carbon present by comparison with published \( (p, p' \gamma) \) and \( (p, p_0) \) data. For the \( (p, p_0) \) case, the cross section data of Peele (1957) predicted a \( ^{12}\text{C} \) target thickness (for a typical case) of about 300 \( \mu \text{g/cm}^2 \). (In comparison, the \( ^7\text{Li} \) target thickness was between 10 and 20 \( \mu \text{g/cm}^2 \)). The absolute yields of \( \gamma \)-rays from both the 15.11 and 12.71 MeV states were difficult to determine precisely due to the large background in the \( \gamma \)-ray spectra at these energies. It was possible, however, to obtain an estimated yield from the 12.71 MeV state, and a comparison to the cross section data of Berghofer et al. (1976) indicated that the \( ^{12}\text{C} \) thickness in the targets was about 500 \( \mu \text{g/cm}^2 \). In the following
analysis, the value of about 500 \( \mu g/cm^2 \) was used as a rough upper limit.

The cross section for the reaction \(^{12}\text{C}(p, \gamma_1)\) has been reported in the literature only for small energy ranges. The reported 90° cross section is about 1 \( \mu b/sr \) for 3–9 MeV protons (Johnson, 1974), has a peak value of about 1.5 \( \mu b/sr \) at 22 MeV, in the region of the GDR, and is much smaller (less than 1/2 \( \mu b/sr \)) off the GDR. (Berghofer et al., 1976) The cross section is difficult to measure in the energy region of \( E_p = 10–20 \) MeV, due to the 15.11 and 12.71 MeV lines and the small cross section. Using a cross section of 1 \( \mu b/sr \), and a \(^{12}\text{C} \) thickness of 500 \( \mu g/cm^2 \), the \(^{12}\text{C}(p, \gamma_1)\) yield was predicted to be about 4% of the \(^{7}\text{Li}(p, \gamma_{16})\) yield for protons in the tandem energy region. This should be considered as a rough upper limit on the effects of \(^{12}\text{C}(p, \gamma_1)\). No correction was made to the data, but the estimate of 4% is included in the overall error in the \((p, \gamma_{16})\) cross section.

The particle monitor spectra indicated that \(^{16}\text{O} \) was also present in the target. A comparison of the proton elastic scattering yield from \(^{16}\text{O} \) to known cross section data (Skwiersky et al., 1974) gave, typically, an \(^{16}\text{O} \) thickness of about 70 \( \mu g/cm^2 \). Using this target thickness and the capture data of Harakeh et al. (1975), it was predicted that the \(^{16}\text{O}(p, \gamma_0 + \gamma_1)\) yield was about 1% of the \(^{7}\text{Li}(p, \gamma_{16})\) yield (for 16 MeV protons). This small effect was neglected in the analysis.

Since the targets were made of natural Li (7.5% \(^6\text{Li} \)), \(^6\text{Li} \) was known to be present. However, capture of protons by \(^6\text{Li} \) leading to the second excited state of \(^7\text{Be} \) has not been reported in the literature. For low energy protons, the yield for this reaction has been found to be less than 4% of the total yield of capture \( \gamma \)-rays to the ground and first excited states (Baskin and Carlson, 1955). It seems therefore quite likely that the effect of \(^6\text{Li}(p, \gamma_2)\) should be small.
The resolution (width) of the $\gamma_{16}$ peak could not be precisely determined from the spectra and was estimated by the measured $\gamma$-ray resolutions from the $^{14}_N(p,\gamma)$ reaction (Wender et al., 1981) and by the beam energy spread due to target thickness. On the basis of these estimates, a resolution of 7.0% (FWHM) was used in the peak fitting routine for the $\gamma_{16}$ peak. This resolution provided a good fit to the $\gamma_{16}$ peak as shown in Fig. 9 in Chapt. 2. However, since varying the width in the fitting procedure could cause changes in the yield without significantly changing the quality of the fit, an error of $\pm 15\%$ was included in the estimate of the error on the absolute cross section.

Although a large part of the background under the $\gamma_{16}$ peak was due to the tails of higher energy peaks and therefore could be accounted for reliably by the fitting program, there may have been additional background due, for example, to pile-up and improper beam alignment. Initial experiments showed that it was possible to produce a large additional background under the $\gamma_{16}$ peak by letting the beam impinge upon objects in the beam line, such as the target rings or the pick-off unit. Efforts were therefore made to keep this background as small as possible. The error in the absolute cross section introduced by this effect was estimated to be less than about 20%.

The $^{7}_Li(p,\gamma_{16})$ absolute cross section was determined at 13 MeV from the ratio of its yield to the $^{7}_Li(p,\gamma_0)$ yield and by knowing the $^{7}_Li(p,\gamma_0)$ absolute cross section (measured with a thin LiF target as discussed in Chapt. 4). The cross section determined in this manner was 0.613 $\mu$b/sr at 90° for $E_p = 13$ MeV. Using the measured angular distribution results at 13 MeV (Sec. C of this chapter), a total cross section of 7.10 $\mu$b was obtained. The absolute error on this cross section is about $\pm 20\%$, $-30\%$, including the errors discussed in the previous paragraphs and the error from the $^{7}_Li(p,\gamma_0)$ absolute cross section determination ($\pm 15\%$).
An alternate measurement of the $^7\text{Li}(p,\gamma_{16})$ absolute cross section was provided by the $2\alpha$ coincidence experiment, as described in Chapt.2. The value of $\sigma_T$ for $(p,\gamma_{16})$ at 13 MeV as determined by this experiment was 4.60 $\mu$b with an absolute error of $\pm16\%$. This uncertainty was determined from the statistical error ($\pm11\%$), the estimated error in the target thickness ($\pm10\%$), and the estimated error in the detector solid angle ($\pm5\%$). This cross section is 0.65 times the cross section obtained from the $(p,\gamma_{16})$ experiment, and the difference is just barely within the quoted errors. The two cross sections at 13 MeV were averaged, and a value of $\sigma_T=5.85$ $\mu$b was obtained. The absolute error on the average value, considering the previous discussion, should then be about 40\%.
B. Yield Curve Data

The 90° yield curve for the reaction $^7\text{Li}(p,\gamma)_{16}\text{Be}$ is shown in Fig.14 from 4 to 30 MeV. The closed dots represent the $\gamma$-ray data, taken with the NaI spectrometer. The absolute differential cross sections were obtained by normalizing the yield curve to the 90° cross section at 13 MeV, which was obtained from the averaged total cross section (5.85 µb as discussed in the previous section) by using the measured value of $a_2$. (Since $a_4$ is quite small and somewhat uncertain, it was not used to obtain this 90° cross section). The error bars are statistical only. The curve is the result of a direct capture calculation to be discussed in chapt.5. Gaps in the yield curve (at about 15 MeV and about 17.5 MeV) were regions where the presence of various $(p,p'\gamma)$ lines made it impossible to extract the yield for the $\gamma_{16}$ peak. Some identified sources for the various $(p,p'\gamma)$ lines were decays from the 15.11 MeV and 12.71 MeV states to the ground state of $^{12}\text{C}$. The lowest $(p,\gamma)$ data point was at 11.5 MeV, since below that energy the $\gamma_{16}$ peak could not be extracted, again due to the presence of various $(p,p'\gamma)$ lines in the spectra.

The $(p,\gamma)$ yield curve is very smooth throughout the region measured. The regions of apparent structure, such as the 3 points from 11.5 to 12.5 MeV, and the points from 18.5 to 20 MeV, may be due to small uncertainties in the data analysis procedure. In particular, for the 11.5-12.5 MeV region, there was some suggestion of a contaminant peak in the $\gamma$-ray spectra very near to the $\gamma_{16}$ peak, and these points should therefore be considered somewhat unreliable.

A yield curve for $\sigma_T$ was obtained from the 2a experiment for $E_p=4$ to 13 MeV. The 90° $\gamma$-ray cross sections were calculated from the measured $\sigma_T$ using the predicted values of $a_2$ from the E1-E2 direct capture calculation (chapt.5). (The angular distribution data for $E_p=13-30$ MeV indicate that the
Figure 14. 90° yield curve for $^7\text{Li}(p,\gamma_{16})$. Error bars represent the statistical errors associated with the data points. The solid curve is the result of the direct capture calculation.
$E_x$ (ABOVE 16.63 MeV STATE) (MeV)

$^7\text{Li}(p,\gamma_1)^8\text{Be}$

$\theta_{\text{lab}} = 90^\circ$

- $(p,\gamma)$ data
- $2\alpha$ data
direct model is quite reliable). The results were normalized to the averaged
cross section at 13 MeV and are shown with statistical error bars as the X's
in the figure. The yield curve shows a broad resonance-like shape, peaking at
about 25 MeV excitation energy in $^8$Be which is about 8 MeV above the final
states near 17 MeV. This energy is not, however, where a giant dipole
resonance would be expected, which is typically at about 20 MeV above the
final state in light nuclei (see, for example, the discussion of $^7$Li(p,$\gamma_0$) and
$^7$Li(p,$\gamma_1$) in Chapt.4).

A yield curve for $\sigma_T(p,\gamma_{16})$ (the angle integrated total cross section)
was obtained from the $(p,\gamma_{16})$ 90° yield curve from 11.5 to 30 MeV by using the
measured $a_2$ values (Sec. C of this chapter), which were assumed to vary
smoothly with energy. These values of $\sigma_T$, combined with those measured in the
2α experiment, were detailed balanced to obtain $\sigma_T(\gamma,p)$. The integrated yield
obtained was $\int \sigma_T(\gamma,p) \cdot dE = 10.3$ MeV·mb. This is about 9% of the classical E1
sum rule, which is 60 NZ/A = 120 MeV·mb for $^8$Be.
C. Angular Distributions of Cross Section and Analyzing Power

Angular distributions of cross section for the $^7\text{Li}(p,\gamma_{16})$ reaction were measured at seven angles from $30^\circ$ to $154^\circ$ for 8 energies between 12 and 30 MeV. In addition, the 14 MeV angular distribution was measured at 13 angles from $30^\circ$ to $154^\circ$. The measured angular distributions are shown in Fig.15. The error bars are statistical only.

The angular distributions of cross section were fit to the orthogonal basis of Legendre polynomials $P_k(\cos(\theta))$ according to:

$$\sigma(\theta) = A_0[1 + \sum_{k=1}^{n} a_k P_k(\cos(\theta))].$$

A fitting procedure was used which minimized the value of $\chi^2$, which is defined as:

$$\chi^2 = \sum \frac{(\sigma(\theta) - \sigma_{\text{fit}}(\theta))^2}{\Delta(\sigma)^2},$$

where $\sigma(\theta)$ is the experimental cross section, $\sigma_{\text{fit}}(\theta)$ is the value of the fit, and $\Delta(\sigma)$ is the uncertainty in the experimental cross section. The fits obtained are shown as the solid curves in the angular distribution figures. The values of $a_k$ obtained, and the values of $\chi^2$ for the fits, are reported in Table I. The fact that $\chi^2$ is often greater than 1 suggests that errors other than statistical are present in the data. The true error bars on the cross sections can be estimated by multiplying by $\sqrt{\chi^2}$. The data at 22 MeV have been fit only through $a_3$, since they were not of sufficient quality to obtain a reliable $a_4$.

A plot as a function of energy of the experimental $a_k$'s is shown in Fig.16. The error bars here are again statistical only. The curve represents the results of the direct capture calculations to be discussed in Chapt.5.

Angular distributions of analyzing power have been measured at 13, 14, and 16 MeV. The data at 13 and 14 MeV were taken at 7 angles each, while 13
Figure 15. Cross section angular distributions for $^7\text{Li}(p,\gamma_{16})$. Error bars represent the statistical errors associated with the data points. The solid curves are the result of the Legendre polynomial fits.
<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
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<td>28.16</td>
</tr>
</tbody>
</table>

Table I. $^7\text{Li}(p,\gamma_{16})$ $a_k$ Coefficients
Figure 16. $a_k$ coefficients from the Legendre polynomial fits for $^7\text{Li}(p,\gamma_{16})$. The error bars represent the statistical errors. The solid curves are the result of the direct capture calculation.
angles were measured at 16 MeV. The analyzing power, $A(\theta)$, is equal to:

$$\frac{1}{P} \frac{N_+ - N_-}{N_+ + N_-},$$

where $N_+$ denotes the number of counts with the beam spin "up", and $N_-$ denotes the number of counts with the spin "down", and $P$ denotes the beam polarization. The analyzing power data have been fit to the expression:

$$\sigma(\theta)A(\theta) = A \sum_{0}^{\infty} b_k P_k^1(\cos(\theta)),$$

where $P_k^1(\cos(\theta))$ is an associated Legendre polynomial of order $k$. The measured angular distributions of analyzing power along with the fits are shown in Fig. 17, and the values of $b_k$ obtained from the fits are given in Table II. The error bars quoted are statistical only.

The effects of the contaminants (discussed earlier in this section) on the analyzing power data can be shown to be small. For example, the reaction $^{12}\text{C}(p, \gamma_1)$ would produce an error in the asymmetry for $^{7}\text{Li}(p, \gamma_{16})$ of no greater than 0.01 assuming a rather large asymmetry in $^{12}\text{C}(p, \gamma_1)$ of 0.4.
Figure 17. Analyzing power angular distributions for $^7\text{Li}(p,\gamma_1\gamma_6)$. The error bars represent the statistical errors. The solid curves are the result of the associated Legendre polynomial fits. The dashed curves are the result of the direct capture calculation.
Table II. $^7\text{Li}(p,\gamma_{16})$ $b_k$ Coefficients

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.0</td>
<td>0.016±.011</td>
<td>-0.100±.008</td>
<td>-0.022±.006</td>
<td>-0.011±.005</td>
<td>1.64</td>
</tr>
<tr>
<td>14.0</td>
<td>0.026±.010</td>
<td>-0.049±.006</td>
<td>-0.025±.005</td>
<td>-0.001±.004</td>
<td>4.18</td>
</tr>
<tr>
<td>16.0</td>
<td>-0.003±.009</td>
<td>-0.093±.006</td>
<td>-0.013±.005</td>
<td>0.009±.005</td>
<td>1.35</td>
</tr>
</tbody>
</table>
Chapter 4  $^7\text{Li}(p,\gamma_0)$ and $^7\text{Li}(p,\gamma_1)$ Experimental Results

A. Yield Curves

The 90° yield curve for $^7\text{Li}(p,\gamma_0)$ has been measured at energies from 11.5 to 30 MeV using a thick Li metal target. The data obtained are shown in Fig.18. The absolute cross sections for the TUNL data were determined by normalizing to a measurement using a LiF target of known thickness. (This thickness was determined as discussed in Chapt.2). Due to the presence of the fluorine, only the capture yield to the ground state of $^8\text{Be}(\text{i.e.}^7\text{Li}(p,\gamma_0))$ was measured. The measurement gave the absolute $^7\text{Li}(p,\gamma_0)$ cross section at $E_p=12$ MeV, to an estimated accuracy of ±15%. This accuracy was determined from the error associated with the efficiency of the detector (±10%), the estimated error in the target thickness (±10%), and the statistical error for the $\gamma_0$ peak (±6%). The solid curve in the figure is a smoothed representation of the Stanford data as taken from a plot in the paper (Fisher et al., 1976) (and should therefore be considered only an approximation to the data). There has been no relative normalization of the data sets in the figure, and in the region of overlap, the absolute cross sections of the two data sets are in good agreement. The dashed curve and the dotted-and-dashed curve shown in the figure are the results of direct capture calculations (described in Chapt.5). The yield curve shows the broad concentration of strength typical of a GDR. In this case, the concentration of strength peaks at about 22 MeV excitation.
Figure 18. $90^\circ$ yield curve for $^7\text{Li}(p,\gamma_0)$. Error bars represent the statistical errors associated with the data points. For those points shown without error bars, the error was smaller than the size of the dot. The solid curve is a representation of the Stanford data. The dashed and dotted-and-dashed curves are the result of direct capture calculations which are discussed in Chapter 5, Section D.
energy in $^8$Be (about 5.5 MeV proton energy). Additionally, it should be noted that there is some suggestion of structure in the yield curves, which is also characteristic of a GDR. The total cross section has been summed over energy according to $\int \sigma_T(\gamma,p) \cdot dE_\gamma$ for comparison with the dipole sum rule for $^8$Be, where $\sigma_T(\gamma,p)$ is the total $(\gamma,p)$ cross section and was obtained from the $(p,\gamma)$ data using detailed balance. The total $(p,\gamma)$ cross section as a function of energy was obtained from the Stanford data for $E_p = 2-11$ MeV, and from the TUNL 90° yield curve, using measured values of $a_2$ (discussed in the following section) for energies from 11.5-30 MeV. The value obtained for the sum was 16.5 MeV-mb which is 13.8% of the classical sum rule prediction of 120 MeV-mb.

The 90° yield curve for proton capture to the first excited state of $^8$Be ($^7$Li$(p,\gamma_1)$) is shown in Fig.19. The absolute cross section for this yield curve was obtained from the ratio of the $\gamma_1$ to the $\gamma_0$ yield, using the $\gamma_0$ cross section measured with the LiF target. Because of the finite width of the first excited state, it was necessary in forming this ratio to integrate the entire line shape down to zero energy. The effect of the NaI detector efficiency, which is different for $\gamma_1$ than for $\gamma_0$ since $E_\gamma$ is different, was included in the cross section determination. The $\gamma_1$ cross section at 90° for $E_p = 12$ MeV determined in this manner was 3.58 mb/sr. The absolute uncertainty in this value includes the uncertainty in the $\gamma_0$ cross section (±15%) and the uncertainty in the ratio of $\gamma_1$ to $\gamma_0$ (±10%) giving a total uncertainty of ±18%. The solid curve in Fig.19 is again a smoothed representation of the Stanford data (Fisher et al., 1976). In this case, however, the Stanford data has been normalized down (multiplied by 0.610) to give agreement with our data at 11.5 MeV. This disagreement between the two data sets, which is greater than the predicted errors, was investigated by using MULFIT to fit the spectrum at 3.25 MeV reported in the Stanford paper. The results of MULFIT
Figure 19. $90^\circ$ yield curve for $^7\text{Li}(p,\gamma_1)$. Error bars represent the statistical errors associated with the data points. The solid curve is a representation of the Stanford data multiplied by 0.61. The dashed and dotted-and-dashed curves are the result of direct capture calculations which are discussed in Chapter 5, Section D.
$^7\text{Li} (p, \gamma)^{8}\text{Be}^*$

$\theta_{\text{lab}} = 90^\circ$

- TUNL data
- Stanford data
gave a ratio of the sums of $\gamma_0$ to $\gamma_1$ of 0.50, while the Stanford paper reports a ratio of 0.44. These numbers agree to within 12%, and it was concluded that MULFIT and the Stanford peak fitting program are in close agreement. The discrepancy between the TUNL data and the Stanford data for the $(p,\gamma_1)$ reaction has not been resolved.

As before, the dashed curve and dotted-and-dashed curve in the figure are the results of direct capture calculations.

The data show the giant dipole resonance built on the first excited state of $^8$Be, which peaks at about 7.5 MeV proton energy, which is about 24 MeV excitation energy, or about 21 MeV above the first excited state. The peak has thus been shifted upward relative to the $\gamma_0$ GDR by approximately the energy of the first excited state (2.94 MeV). The integrated cross section obtained for comparison with the sum rule was found to be 17.3 MeV·mb, using the normalized value of the Stanford data for $E_p=2-11.5$ MeV and the TUNL data for $E_p=11.5-30$ MeV. This value is 14.4% of the sum rule, 120 MeV·mb, which is very nearly the same as that exhausted in the case of the ground state GDR.
B. Angular Distributions of Cross Section and Analyzing Power

Angular distributions of cross section for both $^7\text{Li}(p,\gamma_0)$ and $^7\text{Li}(p,\gamma_1)$ have been measured at seven angles and at eight energies from 12–30 MeV and fitted with Legendre polynomials. Angular distributions of analyzing power for the two reactions have been measured at seven angles for 13 and 14 MeV and at thirteen angles for 16 MeV. These data were fit to associated Legendre polynomials.

The angular distributions of cross section for $^7\text{Li}(p,\gamma_0)$, with the Legendre polynomial fits, are shown in Fig. 20. The $a_k$'s extracted in the fits are shown in Fig. 21 and listed in Table III along with the values of $\chi^2$ obtained in the fits. The dashed curve and the dotted-and-dashed curve shown are again the results of direct capture calculations. The error bars given are statistical only. Since $\chi^2$ for the Legendre polynomial fits is in general bigger than one it is apparent that there was some small additional uncertainty in the data (perhaps due to the peak fitting procedure). The exceptionally large $\chi^2$ at $E_p = 25$ MeV may indicate the presence of some problem in the data at this energy. Nonetheless, the values of $a_k$ obtained at 25 MeV seem quite reasonable when compared with the other energies (see figure), and indeed the entire data set shows a very smooth behavior as a function of energy.

Fisher et al. (1976) at Stanford have measured $a_k$ coefficients for $^7\text{Li}(p,\gamma_0)$ in small energy steps from 2 to 16 MeV protons. A smoothed representation of their results is shown in Fig. 21 as the solid curves. A comparison of the TUNL data with the Stanford results shows good overall agreement in $a_1$ (positive and slowly rising from 12–16 MeV), good agreement in $a_4$ (essentially zero), and reasonable agreement in $a_3$ (negative). There is,
Figure 20. Cross section angular distributions for $^7\text{Li}(p,\gamma_0)$. Error bars represent the statistical errors associated with the data points. The solid curves are the result of the Legendre polynomial fits.
\[ \text{\textsuperscript{7}Li}(p, \chi_0)\text{\textsuperscript{8}Be} \]

\[ E_p = 14.0 \text{MeV} \]
\[ E_p = 130.0 \text{MeV} \]
\[ E_p = 125.0 \text{MeV} \]
\[ E_p = 200.0 \text{MeV} \]
\[ E_p = 12.0 \text{MeV} \]
\[ E_p = 160.0 \text{MeV} \]

\[ \theta_{\text{c.m.}} \text{(deg)} \]

\[ 0 \rightarrow 120 \]

\[ 2.0 \rightarrow 0.0 \]

\(\phi^\text{CM} (\theta) \)
Figure 21. $a_k$ coefficients from the Legendre polynomial fits for $^7\text{Li}(p,\gamma_0)$. The error bars represent the statistical errors. The solid line is an approximate representation of the Stanford data (Fisher et al., 1970). The dashed and dotted-and-dashed curves are the result of direct capture calculations which are discussed in Chapter 5, Section D.
Table III. $^7\text{Li}(p,\gamma_0)$ $a_k$ Coefficients

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>0.229±.013</td>
<td>-0.217±.019</td>
<td>-0.117±.025</td>
<td>0.036±.031</td>
<td>1.28</td>
</tr>
<tr>
<td>12.5</td>
<td>0.260±.014</td>
<td>-0.211±.020</td>
<td>-0.107±.026</td>
<td>0.073±.033</td>
<td>2.73</td>
</tr>
<tr>
<td>13.0</td>
<td>0.241±.014</td>
<td>-0.302±.019</td>
<td>-0.111±.027</td>
<td>0.021±.032</td>
<td>2.74</td>
</tr>
<tr>
<td>14.0</td>
<td>0.337±.015</td>
<td>-0.350±.022</td>
<td>-0.177±.030</td>
<td>0.075±.036</td>
<td>1.72</td>
</tr>
<tr>
<td>16.0</td>
<td>0.434±.017</td>
<td>-0.403±.025</td>
<td>-0.291±.035</td>
<td>-0.109±.043</td>
<td>4.12</td>
</tr>
<tr>
<td>20.0</td>
<td>0.624±.012</td>
<td>-0.385±.019</td>
<td>-0.413±.028</td>
<td>-0.091±.030</td>
<td>3.22</td>
</tr>
<tr>
<td>25.0</td>
<td>0.711±.014</td>
<td>-0.423±.022</td>
<td>-0.505±.033</td>
<td>-0.130±.034</td>
<td>19.10</td>
</tr>
<tr>
<td>30.0</td>
<td>0.893±.014</td>
<td>-0.274±.025</td>
<td>-0.512±.035</td>
<td>-0.144±.033</td>
<td>4.33</td>
</tr>
</tbody>
</table>
however, less agreement in $a_2$. The Stanford data report a nearly constant $a_2$
with an average value of about $-0.05$ up to 16 MeV. The TUNL data clearly show
a negatively increasing $a_2$ of $-0.2$ to $-0.4$.

The analyzing power data for $^7\text{Li}(p, \gamma_0)$ are shown in Fig.22 along with
the results of the fits to the associated Legendre polynomials. The values of
$b_k$ obtained from the fits are shown in Table IV. The fits were of good quality
as indicated by the low values of $\chi^2$.

The angular distributions of cross section for $^7\text{Li}(p, \gamma_1)$ are shown in
Fig.23, along with the Legendre polynomial fits. The $a_k$'s extracted are shown
in Fig.24 and listed in Table V. The dashed curve and the dotted-and-dashed
curve are again the result of direct capture calculations. The error bars on
the data are statistical only, and the variances in $\chi^2$ indicate that in some
cases the error bars should have been somewhat larger. Note that at $E_p = 25$ MeV,
$\chi^2$ is large, as was true for the $\gamma_0$ case. The $a_k$'s, however, show a fairly
smooth energy dependence.

Fisher et al. (1976) at Stanford have also measured $a_k$'s from 2-16 MeV,
and in the region of overlap (12-16 MeV), there is quite good agreement with
the TUNL data. The solid curves in the figure are a smoothed representation of
their results.

The analyzing power angular distributions for $^7\text{Li}(p, \gamma_1)$ along with the
associated Legendre polynomial fits are shown in Fig.25, and the $b_k$'s obtained
are listed in Table VI. The fits appear to be of good quality and the $b_k$'s
obtained are all quite small.
Figure 22. Analyzing power angular distributions for $^7\text{Li}(p,\gamma_0)$. The error bars represent the statistical errors. The solid curves are the result of the associated Legendre polynomial fits. The dashed and dotted-and-dashed curves are the result of direct capture calculations which are discussed in Chapter 5, Section D.
### Table IV. $^7\text{Li}(p,\gamma_0)$ $b_k$ Coefficients

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.0</td>
<td>0.082±.011</td>
<td>-0.029±.008</td>
<td>-0.008±.006</td>
<td>0.000±.005</td>
<td>0.41</td>
</tr>
<tr>
<td>14.0</td>
<td>0.061±.012</td>
<td>-0.029±.008</td>
<td>-0.011±.006</td>
<td>0.000±.005</td>
<td>0.85</td>
</tr>
<tr>
<td>16.0</td>
<td>0.012±.011</td>
<td>-0.014±.007</td>
<td>-0.005±.006</td>
<td>0.013±.005</td>
<td>2.22</td>
</tr>
</tbody>
</table>
Figure 23. Cross section angular distributions for $^7\text{Li}(p,\gamma_1)$. The error bars represent the statistical errors associated with the data points. The solid curves are the result of the Legendre polynomial fits.
Figure 24. $a_k$ coefficients from the Legendre polynomial fits for $^7\text{Li}(p,\gamma)$. The error bars represent the statistical errors. The dashed and dotted-and-dashed curves are the result of the direct capture calculations which are discussed in Chapter 5, Section D.
Table V. $^7\text{Li}(p,\gamma_1) a_\chi$ Coefficients

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>0.173±.008</td>
<td>-0.274±.012</td>
<td>-0.041±.016</td>
<td>-0.021±.020</td>
<td>2.68</td>
</tr>
<tr>
<td>12.5</td>
<td>0.165±.008</td>
<td>-0.395±.012</td>
<td>-0.104±.016</td>
<td>0.053±.020</td>
<td>10.91</td>
</tr>
<tr>
<td>13.0</td>
<td>0.183±.008</td>
<td>-0.312±.011</td>
<td>-0.031±.016</td>
<td>0.013±.019</td>
<td>7.91</td>
</tr>
<tr>
<td>14.0</td>
<td>0.201±.009</td>
<td>-0.384±.012</td>
<td>-0.074±.017</td>
<td>0.012±.022</td>
<td>0.74</td>
</tr>
<tr>
<td>16.0</td>
<td>0.238±.009</td>
<td>-0.449±.014</td>
<td>-0.169±.019</td>
<td>0.034±.024</td>
<td>0.21</td>
</tr>
<tr>
<td>20.0</td>
<td>0.358±.006</td>
<td>-0.500±.008</td>
<td>-0.193±.012</td>
<td>-0.052±.014</td>
<td>1.24</td>
</tr>
<tr>
<td>25.0</td>
<td>0.458±.007</td>
<td>-0.459±.011</td>
<td>-0.217±.016</td>
<td>-0.022±.017</td>
<td>16.50</td>
</tr>
<tr>
<td>30.0</td>
<td>0.588±.006</td>
<td>-0.504±.010</td>
<td>-0.377±.015</td>
<td>-0.099±.015</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 25. Analyzing power angular distributions for $^7\text{Li}(p,\gamma_1)$. The error bars represent the statistical errors. The solid curves are the result of the associated Legendre polynomial fits. The dashed and dotted-and-dashed curves are the result of the direct capture calculations which are discussed in Chapter 5, Section D.
Table VI. $^{7}\text{Li}(p,\gamma_1)$ $b_k$ Coefficients

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.0</td>
<td>0.021±.006</td>
<td>0.041±.004</td>
<td>0.013±.003</td>
<td>-0.013±.003</td>
<td>2.50</td>
</tr>
<tr>
<td>14.0</td>
<td>0.023±.006</td>
<td>0.033±.004</td>
<td>0.015±.003</td>
<td>-0.002±.003</td>
<td>0.57</td>
</tr>
<tr>
<td>16.0</td>
<td>0.018±.005</td>
<td>0.021±.003</td>
<td>0.010±.003</td>
<td>0.005±.002</td>
<td>4.67</td>
</tr>
</tbody>
</table>
Chapter 5 Direct and Semidirect Calculations

A. Introduction

The details and results of our direct and semidirect model calculations are discussed in this chapter. This section gives a brief introduction to the direct and direct-semidirect capture models and discusses the applicability of these models.

The direct capture model has been discussed extensively in the literature (see, for example, Lane (1959)). In this model, an incident nucleon moves in the potential of the target nucleus and then radiates a photon while falling directly into the final state. No intermediate, or compound nuclear, state is formed in this "one-step" process. The final state consists of a core plus single-particle state, where the single-particle is the incoming particle, in addition to the emitted (free) $\gamma$-ray. The core is identical to the target. The T-matrix element computed in actual direct calculations is written $\langle u_b | d^L | \chi \rangle$, where $u_b$ represents the radial wave function of the captured particle in the field of the core (the final state), $\chi$ represents the wave function of the initial continuum state of the particle in the field of target, and $d^L$ is the radial part of the electro-magnetic transition operator, where $L$ is the multipolarity of the radiation.

Direct capture calculations have been compared with experimental capture data for various cases (Cvetkovic and Whetstone, 1972, Weller and Roberson,
1980, and Rolfs, 1973). For low-energy (< 2 MeV) incident nucleons, interesting
work was done by Rolfs (1973), who performed calculations which assumed that
the capture data could be described as contributions from compound nuclear
states interfering with the smoothly varying direct capture background. In
fact, one of the main characteristics of direct capture is such a smooth
variance as a function of energy. The result obtained by Rolfs shows
remarkable agreement between the direct capture calculations and the
"background" cross sections between the low energy resonances.

At higher energies (up to 20 MeV) however, the situation changes
dramatically. Here it is found that the direct cross section is often much
smaller than the capture data and does not predict the observed structure in
the yield curves (Brown, 1964). The data in fact show large and broad resonant
effects, which have been successfully described as giant multipole resonances.
In particular, the giant dipole resonance (GDR) is seen in most capture
reactions leading to the ground state and occurs at an excitation energy in
the compound nucleus of about 80/A^{1/3} MeV in heavy nuclei and about 20 MeV in
light nuclei (Hayward, 1970). In the region of the GDR, the cross sections
calculated for direct E1 capture are typically a factor of about 5-10 less
than the data. At energies above the resonance, direct capture should again
describe the general trend of the data.

Since the early capture work showed that a direct-only capture model was
unable to predict the capture data in the region of the GDR, the semidirect
model (Brown, 1964, and Clement et al., 1965) was suggested to describe the
effects of the GDR and has since been expanded to allow for the possibility of
other giant resonances.

In the semidirect model, a nucleon is incident upon a target nucleus,
which is able to oscillate in various collective modes. The particle is then
inelastically scattered (or "captured") into a bound single-particle state, simultaneously exciting a collective oscillation in the nucleus (typically the GDR). This collective state can then decay either by re-emission of the incident nucleon (which accounts for almost all of the decay width) or by $\gamma$-ray decay (which is enhanced due to the collective nature of the compound state). The model, then, is designed to calculate the cross section for the capture process, with a nucleon entering the nucleus and a $\gamma$-ray emitted from the collective state. The term "semidirect" arises from the fact that, although the lifetime of collective excitation, as determined from the width according to $\hbar/\Gamma$, is much larger than the time for a direct process, it is much less than that of a typical compound nuclear state. This short lifetime implies that the decay process occurs, with emission of a $\gamma$-ray, before the excitation can mix into the surrounding compound nuclear states (Brown, 1964).

Actual capture calculations first compute T-matrix elements, and in the direct-semidirect (DSD) model, the semidirect term is added to the direct capture matrix element. The DSD matrix element is thus given by:

$$
\langle u_b | d^L | \chi \rangle + \frac{1}{E - E_R + i \Gamma/2} \langle u_b | h^L(r) | \chi \rangle,
$$

where $E_R$ and $\Gamma$ give the resonance energy and width (determined generally by experiment) of the giant resonance to be calculated. The form factor, denoted by $h^L(r)$, is the radial part of the nucleon-nucleus interaction which excites the collective excitation (Weller and Roberson, 1980). Various expressions have been suggested for this form factor (Brown, 1964, Clement et al., 1965, and Potokar, 1973).
B. Direct Capture Model Calculations

Since the purpose of this dissertation is to investigate the existence of giant resonances built on highly excited states, the experimental data will be first compared with direct capture calculations. Any discrepancies in this comparison should indicate the need for including the semidirect (collective) term in the calculations.

Direct calculations have been performed in this investigation using the fortran code RADCAP (Cotanch, 1978). (The actual code used was a version modified by Mitev (1980) to include the exact electromagnetic transition operator). The details of the theory used in the code, the parameters used, and the conversion of the results of the code to cross sections are described in the following paragraphs.

The incident channel (proton plus $^7$Li target in this case) was described in the program by the wave function ($\Psi$) of an continuum proton moving in the optical potential of $^7$Li. The potential used (listed in Table VII) was the global energy–dependant fit to (p,p) data for light nuclei (A<17) obtained by Watson et al. (1969). This global potential does not necessarily give the "best fit" to the scattering data for $^7$Li at every energy, but since our direct capture calculations need to be valid for 3 to 30 MeV incident protons, it was desirable to use a slowly–varying (with energy) optical potential. This potential does provide a reasonable fit to the available (p,p) data, although the published data for $^7$Li(p,p) is scanty. Therefore, the optical potential used was believed to be reasonable, but the parameters should be considered somewhat uncertain (or adjustable).

The final state in the capture process is generally assumed to be a bound state, although calculations can be made for capture reactions in which
Table VII. Watson Optical Potential

\[ V_R = 60.0 + 0.4 (Z/A^{1/3}) + 27.0 [(N-Z)/A] - 0.3 E_{cm} \]

\[ V_{so} = 5.5 \]

\[ r = r_{so} = r_{c} = 1.15 - 0.001 E_{cm} \]

\[ a_R = a_{so} = 0.57, \quad a_I = 0.5 \]

\[ W_s = W_s(E) + 10.0 (N-Z)/A \]

where: \[ W_s(E) = 0.64 E_{cm} \quad \text{for} \quad E_{cm} < 13.8 \text{ MeV} \]

\[ 9.60 \text{ MeV} - 0.06 E_{cm} \quad \text{for} \quad E_{cm} > 13.8 \text{ MeV} \]

\[ W_V = 0.0 \]
the final state is a continuum state (Halderson and Philpott, 1981). The bound final state in our calculation was described by the wave function \( u_b \) for a bound proton in a Woods-Saxon well. The shape parameters \((x, a)\) used for the real and spin-orbit wells were obtained from Watson's potential, but the real potential strength, \( V_0 \), was adjusted by the program to give the experimental binding energy of the single-particle.

The electromagnetic operators, \( d^L \), used in the calculations were exact (not the long-wavelength approximation) and are given by:

\[
d^L = \frac{(2L+1)!!}{(L+1)k_r^{L+1}} \left( j_L(k_r) - k_r j_{L+1}(k_r) \right)
\]

(Eisenberg and Greiner, 1970). In the long-wavelength approximation, \( kr \ll 1 \), the EL operator is simply given by \( r^L \).

After calculation of the wave functions as a function of \( r \), the radial matrix element \( \langle u_b | d^L | \chi \rangle \) was calculated by numerical integration. The integration was done from \( r=0 \) to \( r=40 \) fm, with a step size of 0.15 fm. At 40 fm the bound state wave function has become sufficiently small to be neglected.

The following notation was used for the calculations. The capture reaction is denoted by \( a(x, \gamma)c \), where \( a \) is the total angular momentum of the target nucleus, \( x \) is the spin of the incident particle, and \( c \) is the total angular momentum of the final state. In addition, \( b \) denotes the spin of the \( \gamma \)-emitting (intermediate) state. Other definitions that will be used are \( L \), which is the multipolarity of the \( \gamma \) radiation, \( I_a \) and \( j_a \), which are, respectively, the orbital and total angular momentum of the particle in the incident channel, and \( I \) and \( j \), which are, respectively, the orbital and total angular momentum of the single-particle in the final state. \( I_c \) is defined as the Clebsch-Gordan coefficient connecting the isospins:

\[
I_c = C(T_a T_{az}, 1/2 t_z | T_c T_{cz})
\]

where \( T_a \), \( T_{az} \) are the total isospin and \( z \)-projection
for the target $a$, $T_{G}$, $T_{c}$, and $T_{2}$ are the total isospin and $z$-projection for the final state $c$, and $t_{z}$ is the $z$-projection of the isospin for the incident nucleon.

In our calculations as performed by RADCAP, the target spin is assumed to be zero, and therefore the final state angular momentum $c$ is just the single particle angular momentum $j$. The T-matrix elements for target spin zero are calculated from the radial matrix elements from RADCAP according to:

$$ T_{G} = i^{l_{a} - l - L} C(j_{1/2}, L, 0, j_{a} 1/2) \frac{CNORM}{2 j_{a} + 1} e_{L}^{2} \langle u_{b} | d^{L} | z \rangle, $$

where $e_{L}$ is the recoil effective charge for the given multipolarity (Hayward, 1970). The effective charge for electric multipoles is given in general as $e_{L} = (A_{1}^{2} Z_{1} + (-1)^{L} Z_{2} A_{1}^{L}) / (A_{1} + A_{2})^{L}$ (Buck and Pilt, 1977), where 1 refers to the projectile and 2 refers to the target. The factor CNORM is calculated by RADCAP and is defined as: $197.3289 \frac{kr}{137.036 E_{a} k_{a}} 2^{1/2, L} B_{L}^{2}$, where

$$ B_{L}^{2} = \frac{L+1}{(2L+1)L} \frac{2^{2L}}{((2L-1)!!)^{2}}. $$

For the equations for $a_{k}$, $b_{k}$, and $c_{T}$ which follow we have assumed that the capture process depends on the core only in providing the average potential and on the final state parentage to the target core plus a single nucleon. Therefore, the true equations (target spin $a$) are simple factors times the target spin zero equations. It is possible, then, to write the target spin "a" total cross section in terms of the T-matrix elements for target spin zero ($T_{G}$) as:

$$ \sigma_{T} = 4 \pi A_{0} \sum_{j} S_{j} \sum_{j_{a}} \frac{\hat{a}_{2}^{2} |T_{G}|^{2}}{j_{a}} \sum_{j} S_{j} = \sum_{j} S_{j}, $$

where $\hat{a}_{2} = (2x+1)^{1/2}$ and $a$ and $c$ are the true target and final state spins. $S_{j}$ is the spectroscopic factor describing the final single-particle state. The $a_{k}$ and $b_{k}$ coefficients for target spin $a$ are calculated from:

$$ a_{k} = \frac{\sum_{j} S_{j} \frac{1}{2} S_{j} a_{k}^{2} A_{k}}{\sum_{j} S_{j} \frac{1}{2} S_{j} A_{k}^{2} \sum_{j_{a}} \frac{\hat{a}_{2}^{2} |T_{G}|^{2}}{j_{a}}} $$

and
\[ b_k = \sum_{j} \frac{I^2 S_{1} \bar{B}_k}{I^2 S_{1} \sum_{j} \frac{1}{2} |T_G|^2}. \]

In the j-j coupling scheme (used in this thesis), where \(f_a + s = j_a\) and \(j_a + a = b\), \(\bar{A}_k\) and \(\bar{B}_k\) are calculated from \(T_G(f_a, j_a)\) using the expressions:

\[
\bar{A}_k = \sum_{j' \neq j} (-1)^{a-c+1-x+k+j-j'} \hat{\hat{\ell}} \hat{\hat{j}} \hat{\hat{j'}} \hat{\hat{\ell'}} \hat{\hat{L}} \hat{\hat{b}} \hat{b'} \hat{2}_a \hat{2}_b, \]

\[
W(L b L'b', c k) \cdot \text{Re}(T_{G_T G}^*) \]

and

\[
\bar{B}_k = \frac{3 \sqrt{2 \times 2}}{[(x+1) k (k+1)]} \sum_{j' \neq j} (-1)^{a-c+1+j'\hat{\hat{j'}}} \hat{\hat{\ell'}} \hat{\hat{\ell}} \hat{\hat{\hat{j'}}} \hat{\hat{\hat{j}}} \hat{\hat{\hat{b'}}} \hat{\hat{b}} \hat{2_a} \hat{2_b}, \]

\[
W(L b L'b', c k) \cdot \text{Re}(iT_{G_T G}^*), \]

where \(\sum\) \(= \frac{1}{2} [1+(-1)^{L+p+L'+p'k}],\) and \(p\) equals the mode of the \(\gamma\) radiation (i.e., \(p=1\) for electric, \(p=0\) for magnetic). (See Weller and Roberson (1980) for more discussion). The sum over \(t\) and \(t'\) means over \(pp'LL'bb'\) \((j'\) and \(j'). It should be noted that since the \(T_G\) are the target spin zero matrix elements, \(\bar{A}_k\) and \(\bar{B}_k\) must also be calculated using \(a=0\) and \(c=j\).
C. Comparison with \(^{7}\text{Li}(p,\gamma_{16})\) Data

A direct capture calculation, as described in the previous section, has been performed for the reaction \(^{7}\text{Li}(p,\gamma_{16})\) for comparison with the experimental data. The target in this case is \(^{7}\text{Li}\), which has \(J^m=3/2^-\), the incident particle is a proton, and the final states are the two \(2^+\) isospin-mixed levels in \(^{8}\text{Be}\). As discussed earlier in this thesis, the reported values (Sweeney and Marion, 1969) for the proton spectroscopic factors for these states are \(S=0.470\) for the 16.63 MeV level and \(S=0.010\) for the 16.92 MeV level. These values are consistent with experimental evidence which indicates that the 16.63 MeV state is predominantly a single proton plus \(^{7}\text{Li}\) core, while the 16.92 MeV state is predominantly a single neutron plus \(^{8}\text{Be}\) core (Marion and Wilson, 1966). Thus, the 16.92 MeV state should not be excited in the direct capture process, since the direct cross section is directly proportional to \(S\). The very small effect of this state has therefore been neglected in our calculations. The 16.63 MeV state is a mixture of \(T=0\) and \(T=1\) isospin and \(p_{1/2}\) and \(p_{3/2}\) single-particle states. Using the equations given by Marion and co-workers, we have calculated the separate spectroscopic factors for the \(p_{3/2}\) and \(p_{1/2}\) states. Equation 19 in Marion et al. (1967) gives: 
\[|16.63\rangle=0.772|T=0\rangle + 0.636|T=1\rangle,\]
and from Table III in Sweeney and Marion (1969) we have the coefficients of fractional parentage (\(\text{cfp}_j\)) for \(j=1/2\) or \(3/2\), and \(T=0\) or \(T=1\). Therefore,
\[\text{cfp}_{3/2}=0.772(0.4316)+0.636(0.4864)=0.6425,\]
and
\[\text{cfp}_{1/2}=0.772(0.2003)+0.636(0.1319)=0.2385.\]
The spectroscopic factors used in our direct capture calculations are given by \(S=n\cdot\text{cfp}^2\), where \(n\) is the number of available nucleons. In \(^{8}\text{Be}\), \(n\) is 4, so we have finally, \(S_{1/2}=0.228\) and \(S_{3/2}=1.651\). These values were compared with the
calculations of Cohen and Kurath (1967), and it was seen that the cfp’s were in quite good agreement. These values of S therefore seem reliable, but may be subject to some uncertainty, since they have not been determined experimentally.

For the target spin zero calculation as performed by RADCAP, the reaction is described as a 1/2+ projectile incident upon a 0+ core, going to a final state which is partly \( p_{3/2} (3/2^-) \) and partly \( p_{1/2} (1/2^-) \). For our calculation, direct capture involving both E1 and E2 radiation has been considered. The allowed E1 and E2 capture matrix elements can be determined by examining the angular momentum and parity changes. Since we used the \( j-j \) coupling scheme, the contributing matrix elements can be labeled by the \( \ell_a \) and \( j_a \) for the projectile and by the multipolarity of the outgoing radiation (L). The notation used for the amplitude of the matrix element was \( \ell_j \)(L) and the phase \( \phi \). Since E1 radiation has \( J=1 \) and must change the parity, the appropriate E1 capture matrix elements are: \( s_{1/2}, d_{3/2}, \) and \( d_{5/2} \) for the \( p_{3/2} \) component of the final state, and \( s_{1/2} \) and \( d_{3/2} \) for the \( p_{1/2} \) component. Since E2 radiation has \( J=2 \) and must not change the parity, the E2 capture matrix elements are: \( p_{1/2}, p_{3/2}, f_{5/2}, \) and \( f_{7/2} \) for the \( p_{3/2} \) component, and \( p_{3/2} \) and \( f_{5/2} \) for the \( p_{1/2} \) component.

The equations for \( \bar{A}_k \) and \( \bar{B}_k \) obtained are then, for the \( p_{3/2} \) component (assuming only E1 and E2 radiation):

\[
\bar{A}_1 = 1.732 \ s_{1/2}(E1)p_{1/2}(E2)\cos(\phi_{p_{1/2}} - \phi_{s_{1/2}}) \\
+ 2.449 \ s_{1/2}(E1)p_{3/2}(E2)\cos(\phi_{p_{3/2}} - \phi_{s_{1/2}}) \\
- 1.095 \ d_{3/2}(E1)p_{1/2}(E2)\cos(\phi_{p_{1/2}} - \phi_{d_{3/2}}) \\
+ 1.239 \ d_{3/2}(E1)p_{3/2}(E2)\cos(\phi_{p_{3/2}} - \phi_{d_{3/2}}) \\
+ 5.217 \ d_{3/2}(E1)f_{5/2}(E2)\cos(\phi_{f_{5/2}} - \phi_{d_{3/2}}) \\
- 1.138 \ d_{5/2}(E1)p_{3/2}(E2)\cos(\phi_{p_{3/2}} - \phi_{d_{5/2}})
\]
\[ + 0.9128 \, d_{5/2} (E1) f_{5/2} (E2) \cos (\varphi_{f_{5/2}} - \theta_{d_{5/2}}) \\
+ 8.606 \, d_{5/2} (E1) f_{7/2} (E2) \cos (\varphi_{f_{7/2}} - \theta_{d_{5/2}})\]

\[ \overline{A}_2 = 0.6325 \, s_{1/2} (E1) d_{3/2} (E1) \cos (\varphi_{d_{3/2}} - \theta_{s_{1/2}}) + 2.324 \, s_{1/2} (E1) d_{5/2} (E1) \cos (\varphi_{d_{5/2}} - \theta_{s_{1/2}}) + 0.800 \, d_{3/2} (E1) \]

\[ - 1.470 \, d_{3/2} (E1) d_{5/2} (E1) \cos (\varphi_{d_{5/2}} - \theta_{d_{3/2}}) - 1.200 \, d_{5/2} (E1) \]

\[ - 1.134 \, p_{1/2} (E2) f_{5/2} (E2) \cos (\varphi_{f_{5/2}} - \theta_{p_{1/2}}) + 1.145 \, p_{3/2} (E2) f_{5/2} (E2) \cos (\varphi_{f_{5/2}} - \theta_{p_{3/2}}) - 1.296 \, p_{3/2} (E2) f_{7/2} (E2) \cos (\varphi_{f_{7/2}} - \theta_{p_{3/2}}) + 0.6122 \, f_{5/2} (E2) \]

\[ + 1.039 \, f_{5/2} (E2) f_{7/2} (E2) \cos (\varphi_{f_{7/2}} - \theta_{f_{5/2}}) + 2.041 \, f_{7/2} (E2) \]

\[ \overline{A}_3 = 1.309 \, s_{1/2} (E1) f_{5/2} (E2) \cos (\varphi_{f_{5/2}} - \theta_{s_{1/2}}) + 3.703 \, s_{1/2} (E1) f_{7/2} (E2) \cos (\varphi_{f_{7/2}} - \theta_{s_{1/2}}) + 1.859 \, d_{3/2} (E1) p_{3/2} (E2) \cos (\varphi_{p_{3/2}} - \theta_{d_{3/2}}) + 2.650 \, d_{3/2} (E1) f_{5/2} (E2) \cos (\varphi_{f_{5/2}} - \theta_{d_{3/2}}) - 2.342 \, d_{3/2} (E1) f_{7/2} (E2) \cos (\varphi_{f_{7/2}} - \theta_{d_{3/2}}) + 2.683 \, d_{5/2} (E1) p_{1/2} (E2) \cos (\varphi_{p_{1/2}} - \theta_{d_{5/2}}) + 3.036 \, d_{5/2} (E1) p_{3/2} (E2) \cos (\varphi_{p_{3/2}} - \theta_{d_{5/2}}) - 2.434 \, d_{5/2} (E1) f_{5/2} (E2) \cos (\varphi_{f_{5/2}} - \theta_{d_{5/2}}) - 2.869 \, d_{5/2} (E1) f_{7/2} (E2) \cos (\varphi_{f_{7/2}} - \theta_{d_{5/2}}) \]

\[ \overline{A}_4 = 4.276 \, p_{1/2} (E2) f_{7/2} (E2) \cos (\varphi_{f_{7/2}} - \theta_{p_{1/2}}) + 3.665 \, p_{3/2} (E2) f_{5/2} (E2) \cos (\varphi_{f_{5/2}} - \theta_{p_{3/2}}) \]
\[ \bar{B}_1 = 1.732 \ s_{1/2}(E1) p_{1/2}(E2) \sin(\phi_{p_{1/2}} - \phi_{s_{1/2}}) \\
- 1.225 \ s_{1/2}(E1) p_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{s_{1/2}}) \\
+ 0.5477 \ d_{3/2}(E1) p_{1/2}(E2) \sin(\phi_{p_{1/2}} - \phi_{d_{3/2}}) \\
- 2.479 \ d_{3/2}(E1) p_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{d_{3/2}}) \\
+ 2.608 \ d_{3/2}(E1) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{d_{3/2}}) \\
- 0.5692 \ d_{5/2}(E1) p_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{d_{5/2}}) \\
+ 2.738 \ d_{5/2}(E1) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{d_{5/2}}) \\
- 4.303 \ d_{5/2}(E1) f_{7/2}(E2) \sin(\phi_{f_{7/2}} - \phi_{d_{5/2}}) \\
\]

\[ \bar{B}_2 = 0.3162 \ s_{1/2}(E1) d_{3/2}(E1) \sin(\phi_{d_{3/2}} - \phi_{s_{1/2}}) \\
- 0.7746 \ s_{1/2}(E1) d_{5/2}(E1) \sin(\phi_{d_{5/2}} - \phi_{s_{1/2}}) \\
+ 1.225 \ d_{3/2}(E1) d_{5/2}(E1) \sin(\phi_{d_{5/2}} - \phi_{d_{3/2}}) \\
- 0.7071 \ p_{1/2}(E2) p_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{p_{1/2}}) \\
- 0.3780 \ p_{1/2}(E2) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{p_{1/2}}) \\
+ 0.9545 \ p_{3/2}(E2) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{p_{3/2}}) \\
+ 0.4320 \ p_{3/2}(E2) f_{7/2}(E2) \sin(\phi_{f_{7/2}} - \phi_{p_{3/2}}) \\
- 1.212 \ f_{5/2}(E2) f_{7/2}(E2) \sin(\phi_{f_{7/2}} - \phi_{f_{5/2}}) \\
\]

\[ \bar{B}_3 = 0.4364 \ s_{1/2}(E1) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{s_{1/2}}) \\
- 0.9258 \ s_{1/2}(E1) f_{7/2}(E2) \sin(\phi_{f_{7/2}} - \phi_{s_{1/2}}) \\
- 0.6197 \ d_{3/2}(E1) p_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{d_{3/2}}) \\
+ 0.2208 \ d_{3/2}(E1) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{d_{3/2}}) \\]
\[ + 1.171 \, d_{3/2}(E1)f_{7/2}(E2)\sin(\phi_{f_{1/2}} - \phi_{d_{3/2}}) \]
\[ + 0.8944 \, d_{5/2}(E1)p_{1/2}(E2)\sin(\phi_{p_{1/2}} - \phi_{d_{5/2}}) \]
\[ + 0.2530 \, d_{5/2}(E1)p_{3/2}(E2)\sin(\phi_{p_{3/2}} - \phi_{d_{5/2}}) \]
\[ - 1.217 \, d_{5/2}(E1)f_{5/2}(E2)\sin(\phi_{f_{5/2}} - \phi_{d_{5/2}}) \]
\[ + 0.2390 \, f_{5/2}(E2)f_{7/2}(E2)\sin(\phi_{f_{7/2}} - \phi_{f_{5/2}}) \]

\[ \bar{B}_4 = -1.069 \, p_{1/2}(E2)f_{7/2}(E2)\sin(\phi_{f_{7/2}} - \phi_{p_{1/2}}) \]
\[ + 0.9163 \, p_{3/2}(E2)f_{5/2}(E2)\sin(\phi_{f_{5/2}} - \phi_{p_{3/2}}) \]
\[ - 0.4320 \, p_{3/2}(E2)f_{7/2}(E2)\sin(\phi_{f_{7/2}} - \phi_{p_{3/2}}) \]
\[ + 1.212 \, f_{5/2}(E2)f_{7/2}(E2)\sin(\phi_{f_{7/2}} - \phi_{f_{5/2}}) \]

For the \( p_{1/2} \) component:

\[ \bar{A}_1 = 3.464 \, s_{1/2}(E1)p_{3/2}(E2)\cos(\phi_{p_{3/2}} - \phi_{s_{1/2}}) \]
\[ + 0.6928 \, d_{3/2}(E1)p_{3/2}(E2)\cos(\phi_{p_{3/2}} - \phi_{d_{3/2}}) \]
\[ + 6.235 \, d_{3/2}(E1)f_{5/2}(E2)\cos(\phi_{f_{5/2}} - \phi_{d_{3/2}}) \]

\[ \bar{A}_2 = -2.000 \, s_{1/2}(E1)d_{3/2}(E1)\cos(\phi_{d_{3/2}} - \phi_{s_{1/2}}) \]
\[ - 1.000 \, d_{3/2}^2(E1) \]
\[ + 1.000 \, p_{3/2}(E2) \]
\[ + 0.8571 \, p_{3/2}(E2)f_{5/2}(E2)\cos(\phi_{f_{5/2}} - \phi_{p_{3/2}}) \]
\[ + 1.714 \, f_{5/2}^2(E2) \]

\[ \bar{A}_3 = -3.464 \, s_{1/2}(E1)f_{5/2}(E2)\cos(\phi_{f_{5/2}} - \phi_{s_{1/2}}) \]
\[ - 4.157 \, d_{3/2}(E1)p_{3/2}(E2)\cos(\phi_{p_{3/2}} - \phi_{d_{3/2}}) \]
\[ - 2.771 \, d_{3/2}(E1)f_{5/2}(E2)\cos(\phi_{f_{5/2}} - \phi_{d_{3/2}}) \]
\[ A_4 = -6.857 \, P_{3/2}^2(E2) f_{5/2}(E2) \cos(\phi_{f_{5/2}} - \phi_{p_{3/2}}) \\
- 1.714 \, f_{5/2}^2(E2) \]

\[ B_1 = -1.732 \, s_{1/2}(E1) P_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{s_{1/2}}) \\
- 1.386 \, d_{3/2}(E1) P_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{d_{3/2}}) \\
+ 3.118 \, d_{3/2}(E1) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{d_{3/2}}) \]

\[ B_2 = -1.000 \, s_{1/2}(E1) d_{3/2}(E1) \sin(\phi_{d_{3/2}} - \phi_{s_{1/2}}) \\
+ 0.7143 \, P_{3/2}(E2) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{p_{3/2}}) \]

\[ B_3 = -1.155 \, s_{1/2}(E1) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{s_{1/2}}) \\
+ 1.386 \, d_{3/2}(E1) P_{3/2}(E2) \sin(\phi_{p_{3/2}} - \phi_{d_{3/2}}) \\
- 0.2309 \, d_{3/2}(E1) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{d_{3/2}}) \]

\[ B_4 = -1.714 \, P_{3/2}(E2) f_{5/2}(E2) \sin(\phi_{f_{5/2}} - \phi_{P_{3/2}}) \]

It should be noted that \( a_1(b_1) \) and \( a_3(b_3) \) contain only \( E1 \) and \( E2 \) interference terms, while \( a_2(b_2) \) contain only terms proportional to \( (E1)^2 \) or \( (E2)^2 \), and \( a_4(b_4) \) contain only terms proportional to \( (E2)^2 \). Our analysis has neglected M1 capture.

The effective charges for \( 7Li + p \) are \( e_1 = 1/2 \) for electric dipole radiation and \( e_2 = 0.813 \) for electric quadrupole radiation. In addition, the isospin Clebsch, \( I_C \), is 1/2 for both final state isospins, \( T=0 \) and \( T=1 \).

The bound state wave function calculation for the 16.63 MeV state (binding energy 0.63 MeV) gave a well-depth, \( V_0 \), of 52.9 MeV for a \( p_{3/2} \) proton about a \( 7Li \) core. For a \( p_{1/2} \) proton, the calculation gave \( V_0 = 64.6 \) MeV. These are reasonable well depths in comparison with Watson's optical model potential.
(V₀ about 60 MeV).

The resulting E1-E2 direct capture calculation for ⁷Li(p,γ₁₆) shows quite remarkable agreement with the data. The solid curve in Fig.14 (chapt. 3), which is the result of the E1-E2 direct capture calculation, shows that there is very good agreement with the shape of the yield curve data. In particular, the position of the broad peak in the yield curve at about 8 MeV is described very well. Even more importantly, the calculation has been renormalized only by a factor of 1.27, indicating good agreement with the absolute magnitude of the data. These results are in marked contrast with measurements of nucleon capture reactions leading to ground or low-lying states. Typically for these cases, the direct calculations give absolute cross sections which are approximately an order of magnitude less than the data and often have the wrong shape as a function of energy. Two somewhat typical examples are the reactions ⁷Li(p,γ₀) and ⁷Li(p,γ₁), which will be discussed in some detail in Sec. D of this chapter.

Studies have been made to determine the dominant factors influencing the energy dependence of the calculated cross sections. The predominant matrix element was found to be d_{5/2} (E1) capture to the p_{3/2} component of the bound state. This term accounted for approximately 80% of the total calculated cross section, and it has been analyzed as a function of energy. Shown in Fig.26 is the calculated total d_{5/2} capture cross section as a function of energy. A possible explanation for the initial rise in the capture cross section is that the coulomb barrier is being crossed. The energy of the coulomb barrier is defined as: E_c = \frac{1}{c} \frac{1}{4\pi} \frac{Ze^2}{R}, where R is the nuclear radius (given by \( r_0 A^{1/3} \)), Z-e is the projectile charge, and Z-e is the target charge. For protons on ⁷Li, E_c = 4.6 MeV, corresponding closely with the rise in the capture cross section. A more detailed study can be made by examining the
Figure 26. Calculated $d_{5/2}(E1)$ direct capture cross sections for $^7\text{Li}(p,\gamma_{16})$. 
$^7\text{Li}(p,\gamma_{16})$

d$_{5/2}$ capture 
cross sections

$\sigma_\text{T} (\mu b)$

$E_p$ (MeV)

Watson optical model

Watson optical model with $W_S = 0$
Figure 27. d-wave proton penetrabilities for $^7\text{Li} + p$. 
$^7\text{Li} + p$

d-wave proton penetrabilities

$p_2$

$E_p$ (MeV)
d-wave proton penetrabilities as a function of energy as shown in Fig. 27. These do show a fast rise from 3 MeV and upwards, but in contrast with the data, they continue to rise above 10 MeV.

In an attempt to describe the peaking and subsequent decrease in the $d_{5/2}$ capture term, Fig. 28 shows the $90^\circ$ $d_{5/2}$ proton scattering cross section (nuclear part only) and the $d_{5/2}$ total reaction cross section, calculated with the optical model used in the direct calculation (Watson et al., 1969). The corresponding $d_{5/2}$ scattering phase shifts were investigated, and a plot of the $d_{5/2}$ real phase shifts ($\delta_R$) and damping parameters ($\gamma$) is shown in Fig. 29. Shown in Fig. 30 are the corresponding complex scattering amplitudes ($C = (\gamma e^{2i\delta_N} - 1)/2i$). Although the phase shifts may correspond to some broad peaks in the scattering cross section, they do not exhibit any truly resonant behavior, since the scattering amplitudes do not show a loop in the complex plane. (For a more complete discussion of phase shifts, scattering amplitudes, and resonances, see, for example, Duval et al. (1967)).

From this phase shift investigation, and also from the fact that the $d_{5/2}$ capture yield peaks at a different energy than the $d_{5/2}$ scattering cross section, it is apparent that the peak in the capture yield is not due to resonances in the continuum channel.

The effect that the reaction cross section (represented by the imaginary surface potential $W_s$) has on the capture yield curve was investigated by setting $W_s = 0.0$ in the calculations. The results on the $d_{5/2}$ capture yield are shown in Fig. 26 as the dashed curve. Comparing with the "normal" direct calculation (solid curve) shows that the imaginary potential does indeed have a large effect. In particular, the absolute cross sections for $W_s = 0$ are larger by a factor of about 2 throughout most of the calculated energy region, and the peak in the yield curve has been shifted up in energy by about 3 MeV.
Figure 28. Calculated $d_{5/2}$ scattering and reaction cross sections for $^7\text{Li} + p$. 
Figure 29. Calculated $d_{5/2}$ real phase shift and damping parameter for $^7\text{Li} + p$. 
Figure 30. Calculated $d_{5/2}$ real and imaginary scattering amplitudes for $^7\text{Li} + p$. 
$^7\text{Li} + p$

Watson optical model

d$_{5/2}$ scattering amplitude
(Fig. 28 shows the effect that \( W_s = 0.0 \) has on the scattering cross sections). It is apparent therefore that the absorption of protons in the incident continuum channel does affect the shape of the capture yield. However, even with \( W_s = 0.0 \), the capture yield still shows a decrease at higher energies. It has thus been assumed that the decrease in the cross section for \( p \) above 8 MeV is due largely to the nature of the overlap of the incoming channel wave function with the state formed by the electromagnetic operator acting on the final state. In any case, the initial rise and peaking in the yield, followed by a gradual decrease, are typical characteristics of direct capture calculations.

Fig. 16 in chapt. 3 shows a plot as a function of energy of the \( a_k \) coefficients obtained from the Legendre polynomial fits, along with the predictions of the E1-E2 direct capture model (shown as the solid curve). (The fact that the experimental data at 12 and 12.5 MeV may be affected by a contaminate has already been discussed in chapt. 3). From the figure, it is seen that the calculation predicts rather well the general trend of the data. In the \( a_1 \) coefficient, the calculation predicts a larger value than the data but does correctly describe the positive and increasing trend. For \( a_2 \), the agreement is quite good, showing the initial rise (up to 20 MeV) and the relatively constant region from 20 to 30 MeV. The calculated \( a_3 \) is somewhat larger in magnitude than the data but still predicts the correct sign and negatively increasing energy dependence. The agreement in \( a_4 \) is quite good, giving near zero from 12-16 MeV, and small and negative for 20-30 MeV. This non-zero value of \( a_4 \) at the higher energies is indicative of the increasing presence of E2 radiation.

The results for the angular distributions of analyzing power are somewhat in contrast with the unpolarized results. Fig. 17 in chapt. 3 shows the angular distributions of \( A(\theta) \), with the dashed curves representing the
direct E1-E2 capture calculation. There is clearly a disagreement between the data and calculation, which is quantized by looking at the $b_k$ coefficients shown in Table VIII. Here it is seen that the $b_2$'s in particular, and the $b_1$'s to a lesser extent, are not well described. The data give values of $b_2$ between $-0.05$ and $-0.10$, while the calculation gives $b_2$ values which are very nearly zero.

The calculation was checked at the energy of 15 MeV to find the cause for $b_2=0.0$. (Since the $b_k$'s are nearly constant from 13-16 MeV, any energy in this region should be typical). Separating the effects of the two different components of the final state, a $b_2$ of $-0.033$ was obtained for the $p_{3/2}$ component calculation, while a $b_2$ of $+0.141$ was obtained for the $p_{1/2}$ component calculation. These two numbers, when weighted properly for angular momentum and spectroscopic factors, combine to give the reported value near zero. The fact that the data give a larger, negative value of $b_2$ may suggest that the $p_{1/2}$ bound state component of the 16.63 MeV state is not as large as given by the shell model calculations reported by Sweeney and Marion (1969). Setting the $p_{1/2}$ component to zero gives: $b_1=+0.071$, $b_2=-0.033$ (as discussed above), $b_3=-0.031$, and $b_4=-0.003$. These values are in good agreement with the data for $b_3$ and $b_4$ and give better agreement in $b_2$ than the original calculation, but give worse agreement in $b_1$. The effects on the $a_k$ coefficients of removing the $p_{1/2}$ component were also investigated and found to be negligible.

Since the assumption of no $p_{1/2}$ component was still unable to describe the data very well, the details of $b_2$ for the $p_{3/2}$ component calculation were investigated. Assuming only E1 radiation, the $E_2$ equation used in the $p_{3/2}$ component calculation is written in terms of various matrix elements as

$$E_2 = 0.3162 a_{1/2} d_{3/2} (E1) \sin (\theta_{d_{3/2}} - \theta_{a_{1/2}})$$
Table VIII. $^7\text{Li}(p,\gamma_\gamma)$ $b_k$ Coefficients Compared with Direct Capture Calculations

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$\chi^2$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.0</td>
<td>0.016±.011</td>
<td>-0.100±.008</td>
<td>-0.022±.006</td>
<td>-0.011±.005</td>
<td>1.64</td>
<td>Exp.</td>
</tr>
<tr>
<td>13.0</td>
<td>0.038</td>
<td>-0.003</td>
<td>-0.013</td>
<td>-0.001</td>
<td></td>
<td>Calc.</td>
</tr>
<tr>
<td>14.0</td>
<td>0.026±.010</td>
<td>-0.049±.006</td>
<td>-0.025±.005</td>
<td>-0.001±.004</td>
<td>4.18</td>
<td>Exp.</td>
</tr>
<tr>
<td>14.0</td>
<td>0.040</td>
<td>0.001</td>
<td>-0.017</td>
<td>-0.002</td>
<td></td>
<td>Calc.</td>
</tr>
<tr>
<td>16.0</td>
<td>-0.003±.009</td>
<td>-0.093±.006</td>
<td>-0.013±.005</td>
<td>0.009±.005</td>
<td>1.35</td>
<td>Exp.</td>
</tr>
<tr>
<td>16.0</td>
<td>0.040</td>
<td>0.001</td>
<td>-0.017</td>
<td>-0.002</td>
<td></td>
<td>Calc.</td>
</tr>
</tbody>
</table>
\[-0.7746 \, s_{1/2}(E1)d_{5/2}(E1)\sin(\phi_{d_{5/2}} - \phi_{s_{1/2}}) \]
\[+ 1.225 \, d_{3/2}(E1)d_{5/2}(E1)\sin(\phi_{d_{5/2}} - \phi_{d_{3/2}}).\]

Analyzing separate terms in this expression gives a \(b_2\) (normalized) of 0.027 for the first term (\(s_{1/2}\) and \(d_{3/2}\) interference), –0.103 for the second term (\(s_{1/2}\) and \(d_{5/2}\) interference), and 0.043 for the third term (\(d_{3/2}\) and \(d_{5/2}\) interference). (Note that the sum of these numbers is equal to –0.033.)

Without the \(d_{3/2} - d_{5/2}\) interference term, this calculation would then give good agreement with the data for \(b_2\). Since interference between \(d_{3/2}\) and \(d_{5/2}\) requires the presence of a finite spin-orbit potential, the sensitivity of \(b_2\) to the spin-orbit potential \(V_{so}\) was investigated. The optical potential originally used in the direct calculation contained a \(V_{so}\) of 5.5 MeV. Since this potential was a global fit to many light nuclei, it is therefore likely to be reasonable. However, due to the lack of polarization data for \(^7\text{Li} + p\) for \(E_p\) less than 50 MeV, the value of \(V_{so} = 5.5\) MeV has not been determined precisely. The potential \(V_{so}\) was adjusted in the \(p_{3/2}\) component direct calculation, and the following values of \(b_2\) were obtained: for \(V_{so} = 5.5\) MeV, \(b_2 = 0.033\); for \(V_{so} = 0.0\) MeV, \(b_2 = 0.085\); for \(V_{so} = 2.7\) MeV, \(b_2 = 0.061\); and for \(V_{so} = 8.4\) MeV, \(b_2 = 0.012\). Note that for \(V_{so}\) equal to or less than about 2.7 MeV, there is quantitative agreement with the data. The effects due to varying \(V_{so}\) on the other \(b_k\) and \(a_k\) coefficients was also investigated. There was a negligible effect on \(a_1 - a_4\) and only very small effects on \(b_1\), \(b_3\), and \(b_4\).

These results show that at least a part of the difference between the experimental and calculated \(b_2\) may be due to an incorrect spin-orbit potential. This effect, combined with the effect from varying the \(p_{1/2}\) component of the bound state, may be sufficient to explain the data.

In conclusion, it has been shown for the reaction \(^7\text{Li}(p, \gamma)_{16}\) that a
direct capture calculation including the effects of both $E_1$ and $E_2$ radiation provides good overall agreement with the yield curve, both in terms of shape and absolute cross section, and good agreement with the angular distributions. There is a disagreement with the analyzing power data, but this disagreement can be reduced by a reasonable adjustment of various parameters in the calculation.
D. Comparison with $^7\text{Li}(p,\gamma_0)$ and $^7\text{Li}(p,\gamma_1)$ Data

Direct El-E2 capture calculations have been performed for the reactions $^7\text{Li}(p,\gamma_0)$ and $^7\text{Li}(p,\gamma_1)$ in an investigation of two aspects of these reactions: first, to show that the direct calculation is quite inadequate to describe the data in the region of the GDR (this is the typical case for a capture reaction); and secondly, to check the agreement of the calculation with the data at excitation energies above the GDR.

The coefficients of fractional parentage (cfp) of Cohen and Kurath (1967) have been used to describe the single-particle nature of the final states in $^8\text{Be}$. They describe the ground state as a $p_{3/2}$ single-particle plus core state, with a spectroscopic factor of $S=2.8981$. The first excited state in $^8\text{Be}$ (at 2.94 MeV) is described as a mixed $p_{3/2}$ and $p_{1/2}$ single-particle state, with $S=1.1188$ for the $p_{3/2}$ component and $S=0.7509$ for the $p_{1/2}$ component. These two numbers give a total spectroscopic factor of $S=1.869$ for the first excited state. These calculated spectroscopic factors were compared to the experimental values of $S=2.84$ for the ground state and $S=1.70$ for the first excited state, as obtained from the stripping reactions (Azimov et al., 1976). The calculated values of Cohen and Kurath are therefore consistent with the data.

The optical model potential used in both cases was initially the same as that used for the $^7\text{Li}(p,\gamma_{16})$ calculation (Watson et al., 1969). However, in the use of this potential a problem occurred which is discussed in the following paragraphs.

For the bound state calculation for the $^8\text{Be}$ ground state, which has a binding energy of 17.255 MeV, the use of the Watson radius parameter of $r_0=1.135$ gave a well-depth, $V_0$, of 88.2 MeV. This is somewhat larger than the
value of about 60 MeV used by Watson for the continuum channel. Since the use of two significantly different well depths in the initial and final state calculations is not strictly valid (the average nuclear potential should not be time-dependent), it was believed that the results of the calculation might be unreliable. As a solution to this problem, the radius parameter was changed to $r_0 = 1.45$ fm, both in the incident channel and the bound state calculation. This value of $r_0$ gave for the bound state a value of $V_0 = 65.2$ MeV, which is in much closer agreement with the real well-depth in Watson's potential. Of course, in this process the radius parameter has been forced to a value which does not agree with Watson's potential, but at least approximately the same potential is used for both the bound state and continuum calculations. Two calculations were then performed, one with the original unmodified potential (hereafter called the "unmodified" calculation) and the other with the modified potential (hereafter called the "symmetric" calculation).

The results of the two direct calculations were checked with the data at higher energies (20–30 MeV), since direct capture should be the dominant effect in the data at these energies. For the unmodified calculation, it was found that the calculated absolute cross section was approximately four times larger than the data at 30 MeV. However, for the symmetric calculation, very good agreement with the data was obtained for 25–30 MeV. The fact that these adjustments in the optical potential can cause such large changes in the absolute cross section suggests that the detailed results of our direct capture calculations are somewhat uncertain.

The details of the yield curve are shown in Fig.18 of chapt.4, along with the symmetric calculation (dashed line) and the unmodified calculation (dotted-and-dashed line). A clear difference is seen in the figure between the two calculations, with the symmetric calculation giving a good description
of the data for $E_p = 20$--$30$ MeV. Whichever calculation is used, it is clear that neither calculation can correctly predict the shape or the magnitude of the data in the region of the GDR ($E_p$ about 3--10 MeV). The small size of the calculation relative to the data (about 20% for the symmetric calculation) is typical of direct capture calculations in the region of the GDR built on the ground state.

Angular distributions were calculated for $^7\text{Li}(p,\gamma_0)$ assuming $E1$ and $E2$ radiation. The results of the calculations, in terms of the Legendre polynomial coefficients, $a_k$, are shown in Fig.21 of chapt.4, with the dashed line giving the symmetric calculation results, and the dotted-and-dashed line representing the unmodified calculation. The general trends of the two calculations as a function of energy are similar and agree with the general trend of the data. In the region of the GDR (up to at least 15 MeV), it might be expected that the direct model would not be completely adequate to describe the data, but there is, nonetheless, qualitative agreement. The Stanford data (Fisher et al., 1976), which include the region of the GDR, are shown as the solid curves in Fig.21, and the calculations give reasonable agreement with $a_1$, $a_3$, and $a_4$. However, there does appear to be a significant difference in terms of magnitude and energy dependence for $a_2$. This may indeed be a failure of the direct model in the GDR region, but, as discussed in chapt.4, the Stanford and the TUNL data for $a_2$ do not agree very well in the region of overlap, so it is possible that there are some problems in the data. Above the observed GDR, where we certainly expect the direct model to provide a good description of the reaction, there is reasonable agreement with the data, although neither calculation gives agreement within the error bars.

The angular distributions of analyzing power and the corresponding calculations for $^7\text{Li}(p,\gamma_0)$ are shown in Fig.22 in chapt.4, where the solid
curves give the fit to associated Legendre polynomials, the dashed curves show
the symmetric calculation results, and the dotted-and-dashed curves show the
unmodified calculation results. Shown in Table IX are the $b_k$ coefficients
from the data and the two calculations. The results indicate that the
unmodified calculation is in reasonable agreement with the data, but the
symmetric calculation does not provide very good agreement.

An investigation of the calculated $b_k$ coefficients was undertaken to
provide an indication of their sensitivity. For $b_1$, $b_2$, and $b_3$ it was
discovered that there existed a large amount of cancellation between different
terms in the expansions of the $b_k$'s in terms of matrix elements.

Specifically, for $b_2$ we can write:

\[
b_2 = 0.3162 \ s_{1/2}(E1)d_{3/2}(E1)\sin(\phi \ 3/2 - \phi \ 1/2)
- 0.7746 \ s_{1/2}(E1)d_{5/2}(E1)\sin(\phi \ 5/2 - \phi \ 1/2)
+ 1.225 \ d_{3/2}(E1)d_{3/2}(E1)\sin(\phi \ 5/2 - \phi \ 3/2)
\]

where the E2 terms have been neglected since they are considerably smaller.

At 15 MeV, the unmodified calculation gives for the first term: $b_2 = 0.025$, for
the second term: $b_2 = -0.125$, and for the third term: $b_2 = +0.065$. (These do in
fact add up to the total $b_2$ of $-0.034$). In this case, we see that all three
terms have a significant effect on $b_2$, and because of cancellation, the final
value is smaller in magnitude than the individual terms. This result is
similarly true for $b_1$ and $b_3$ (although the expansion is more complicated due
to many significant E1 and E2 mixing terms). It is therefore not surprising
that the generally small calculated values of $b_k$ are quite sensitive to the
details of the calculation. This sensitivity is seen in the difference between
the results of the unmodified and symmetric calculations.

For the direct calculation for capture to the first excited state of $^8\text{Be}$
($^7\text{Li}(p,\gamma_1)$), a situation exists somewhat similar to that of the $(p,\gamma_0)$
Table IX. $^7\text{Li}(p,\gamma_0)$ $b_k$ Coefficients Compared with Direct Capture Calculations

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$\chi^2$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.0</td>
<td>0.082±.011</td>
<td>-0.029±.008</td>
<td>-0.008±.006</td>
<td>0.000±.005</td>
<td>0.41</td>
<td>Exp.</td>
</tr>
<tr>
<td>13.0</td>
<td>0.081</td>
<td>-0.053</td>
<td>-0.022</td>
<td>-0.001</td>
<td></td>
<td>Unmod.</td>
</tr>
<tr>
<td>13.0</td>
<td>0.152</td>
<td>-0.021</td>
<td>-0.092</td>
<td>-0.013</td>
<td></td>
<td>Symm.</td>
</tr>
<tr>
<td>14.0</td>
<td>0.061±.012</td>
<td>-0.029±.008</td>
<td>-0.011±.006</td>
<td>0.000±.005</td>
<td>0.85</td>
<td>Exp.</td>
</tr>
<tr>
<td>14.0</td>
<td>0.089</td>
<td>-0.043</td>
<td>-0.025</td>
<td>-0.001</td>
<td></td>
<td>Unmod.</td>
</tr>
<tr>
<td>14.0</td>
<td>0.153</td>
<td>-0.022</td>
<td>-0.099</td>
<td>-0.015</td>
<td></td>
<td>Symm.</td>
</tr>
<tr>
<td>16.0</td>
<td>0.012±.011</td>
<td>-0.014±.007</td>
<td>-0.005±.006</td>
<td>0.013±.005</td>
<td>2.22</td>
<td>Exp.</td>
</tr>
<tr>
<td>16.0</td>
<td>0.102</td>
<td>-0.029</td>
<td>-0.029</td>
<td>-0.001</td>
<td></td>
<td>Unmod.</td>
</tr>
<tr>
<td>16.0</td>
<td>0.139</td>
<td>-0.023</td>
<td>-0.100</td>
<td>-0.016</td>
<td></td>
<td>Symm.</td>
</tr>
</tbody>
</table>
calculation. In detail, for the bound state wave function (consisting of both $p_{1/2}$ and $p_{3/2}$ single-particle components), the determined well-depth was $V_0 = 99.5$ MeV for the $p_{1/2}$ component, and $V_0 = 82.9$ MeV for the $p_{3/2}$ component, using the given well parameters $r_o$ and $a_o$ from Watson's potential. These values of $V_0$ are somewhat large, and it was again decided to perform a calculation with a "symmetric" potential. For this symmetric calculation, the radius parameter was changed to $r_o = 1.4$, and the spin-orbit potential, $V_{so}$, in the bound state calculation was set to zero to give the same $V_0$ for both the $p_{1/2}$ and the $p_{3/2}$ states. This calculation then gave for the bound state well-depth $V_0 = 65.9$ MeV, in much better agreement with Watson's real well-depth.

The 90° yield curve for $^7$Li$(p, \gamma_1)$ along with the symmetric (dashed curve) and unmodified (dotted-and-dashed curve) direct calculations is shown in Fig. 19 in chapt. 4. As was true for the $^7$Li$(p, \gamma_0)$ reaction, a large absolute difference is seen between the two calculations. However, in contrast to the $^7$Li$(p, \gamma_0)$ case, the unmodified calculation gives better agreement with the data at higher energies (where we expect direct to be more nearly correct). A possible explanation of the situation is that, since the observed GDR built on the first excited state is centered at a higher excitation energy and is broader in energy, its high energy tail may still be significant for $E_p = 20-30$ MeV. This would suggest that the symmetric calculation might in fact be correctly describing the direct capture, and that semidirect capture may provide the additional capture strength necessary to give agreement with the data at the higher energies. In order to test this suggestion, it would be necessary to extend the 90° yield curve to proton energies above 30 MeV.

Whichever calculation is used, it is true that both calculations fail to
describe the data in the GDR region.

Fig. 24 in chapt. 4 shows a plot of the $a_k$'s obtained from the Legendre polynomial fits to the data, along with the results of the symmetric (dashed line) and the unmodified (dotted-and-dashed line) calculations. The $a_k$'s appear to give a preference for the unmodified calculation, but the discussion given above concerning the location and width of the GDR also applies here. The important point, still, is that a direct calculation with reasonable parameters can provide a satisfactory description of the data above the main strength of the GDR.

Also shown in Fig. 24 in chapt. 4 are the Stanford $a_k$'s (Fisher et al., 1976) for $^7\text{Li}(p,\gamma_1)$. These data include the region of the GDR built on the first excited state. Interestingly, the direct calculations give good agreement for all coefficients $a_1 - a_4$. For example, the initial positive value of $a_2$ (at about 5 MeV) followed by a fast decrease to a negative value (for 8-12 MeV) is described very well by the unmodified calculation.

It should be noted at this point that qualitative agreement between the measured $a_k$'s and those calculated with a direct model is not surprising even in the region of the GDR. It has been shown (Mavis, 1977, and Weller and Roberson, 1980, and references therein) that the relative phases $\phi_{a_j}$ and the $a_k$'s do not change dramatically over the GDR and are in fact not much different from the off-resonance values. A partial explanation for the fact that the GDR appears to have little effect on the $a_k$'s for the two capture reactions $^7\text{Li}(p,\gamma_0)$ and $^7\text{Li}(p,\gamma_1)$ may be that since the $a_k$'s are all fairly small, large percent changes in any $a_k$ would appear as only a small change in magnitude of the $a_k$. For example, if a given E1 matrix element were to double in value due to the presence of a GDR, the total cross section due to that matrix element would be increased by a factor of 4. However, the $a_1$
coefficients would only double, assuming that the relative phases and E2 matrix elements remained unchanged. If $a_4$ were small, for example about 0.05, then doubling to give 0.10 would probably not appear to be significant in comparison to our direct calculations.

The analyzing power results for $^7\text{Li}(p,\gamma_1)$ are shown in Fig. 25 of chapt. 4, along with the symmetric (dashed lines) and unmodified (dotted-and-dashed lines) calculations. Although neither calculation provides a precise fit to the data, the unmodified calculation does give reasonable agreement with the data, while the symmetric calculation gives considerably worse agreement. To quantize the level of agreement, the calculated and experimental $b_k$'s are shown in Table X. The unmodified calculation gives good agreement for $b_1$, $b_3$, and $b_4$, although it is somewhat incorrect for $b_2$, especially at 16 MeV. The symmetric calculation fails somewhat for $b_1$, $b_2$, and $b_3$. It is true in this case, as for the $^7\text{Li}(p,\gamma_0)$ case, that the calculated $b_k$'s are quite sensitive to the parameters in the calculation, so that it may be possible to fit the data better by adjusting these parameters.

In conclusion, a direct capture calculation with reasonable parameters can provide a satisfactory description of the $^7\text{Li}(p,\gamma_0)$ and $^7\text{Li}(p,\gamma_1)$ reactions, in terms of total cross sections and angular distributions of cross sections and analyzing powers, for the energy regions above the GDR. In the region of a GDR, the calculated angular distributions can still give qualitative agreement with the data, but the absolute cross sections are significantly too small.
Table X. $^7$Li$(p, \gamma_1) b_k$ Coefficients Compared with Direct Capture Calculations

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$\chi^2$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.0</td>
<td>0.021 ± 0.006</td>
<td>0.041 ± 0.004</td>
<td>0.013 ± 0.003</td>
<td>-0.013 ± 0.003</td>
<td>2.50</td>
<td>Exp.</td>
</tr>
<tr>
<td>13.0</td>
<td>0.015</td>
<td>0.052</td>
<td>0.006</td>
<td>0.001</td>
<td></td>
<td>Unmd.</td>
</tr>
<tr>
<td>13.0</td>
<td>-0.081</td>
<td>0.111</td>
<td>0.027</td>
<td>0.001</td>
<td></td>
<td>Symm.</td>
</tr>
<tr>
<td>14.0</td>
<td>0.023 ± 0.006</td>
<td>0.033 ± 0.004</td>
<td>0.015 ± 0.003</td>
<td>-0.002 ± 0.003</td>
<td>0.57</td>
<td>Exp.</td>
</tr>
<tr>
<td>14.0</td>
<td>0.014</td>
<td>0.061</td>
<td>0.007</td>
<td>0.001</td>
<td></td>
<td>Unmd.</td>
</tr>
<tr>
<td>14.0</td>
<td>-0.090</td>
<td>0.107</td>
<td>0.028</td>
<td>0.001</td>
<td></td>
<td>Symm.</td>
</tr>
<tr>
<td>16.0</td>
<td>0.018 ± 0.005</td>
<td>0.021 ± 0.003</td>
<td>0.010 ± 0.003</td>
<td>0.005 ± 0.002</td>
<td>4.67</td>
<td>Exp.</td>
</tr>
<tr>
<td>16.0</td>
<td>0.014</td>
<td>0.072</td>
<td>0.009</td>
<td>0.001</td>
<td></td>
<td>Unmd.</td>
</tr>
<tr>
<td>16.0</td>
<td>-0.109</td>
<td>0.099</td>
<td>0.033</td>
<td>0.002</td>
<td></td>
<td>Symm.</td>
</tr>
</tbody>
</table>
E. Direct-Semidirect Calculations

A brief introduction to the semidirect capture model was given in Sec. A of this chapter. The details of our calculations are discussed in this section.

For the DSD calculations performed for this thesis (Kitazawa, 1980), a real volume form factor was used of the type suggested by Potokar (1973). Specifically, the form factor was written:

\[ 4 \cdot V_1 \text{for} \frac{1}{1+e^{-(t-r)/\alpha}} \]

where \( V_1 \) is the isospin symmetry potential well-depth, \( f \) is the fraction of the sum rule exhausted by the appropriate giant resonance, and \( \alpha \) is the ground state correlation factor for the target nucleus. In one sense, \( V_1, f, \) and \( \alpha \), which all are constants affecting the total cross section, can be considered as parameters determinable from the fit of the DSD calculation to the data of the giant resonance. However, there are some restrictions on these parameters. \( V_1 \) can be obtained from \( (p,n) \) data. For example, the global fit of Watson et al. (1969) to light nuclei gives an isospin symmetry term of \( 27 \left( \frac{N-Z}{A} \right) \text{MeV} \), so a number of near 27 MeV should be used for \( V_1 \). (It is customary when performing DSD calculations to report \( 4 \cdot V_1 \), which is 108 MeV in this case). Typically, a giant dipole resonance exhausts about 100% of the sum rule (in all channels), so \( f \) should be about 1. (\( f \) is often somewhat less than 1 for light nuclei). The ground state correlation factor varies as a function of atomic mass \( A \) and approaches 1 for light nuclei (Leonardi, 1972).

The calculations in this thesis have used \( \alpha = 1.0 \).

Other parameters needed for the calculation include an optical model potential for the incident nucleon plus target nucleus state (\( ^7 \text{Li} + p \) in this case). As for the direct capture calculations, the potential of Watson et al.
(1969) was used. Additionally, the bound final states in $^8$Be were calculated with a Woods-Saxon well as described earlier in this chapter for the direct capture case.

For an initial check of the DSD calculation for a typical GDR, and to obtain some typical parameters for a GDR, a DSD calculation was performed for the reaction $^7$Li$(p,\gamma_0)$. Since the "symmetric" direct calculation (with $r_0=1.45$) gave better agreement with the data at higher energies than the "unmodified" calculation (see Sec. D), it was decided to use the symmetric potential for the DSD calculation. The result of the calculation is shown in Fig.31, along with the yield curve data at $90^\circ$. The calculation gives good overall agreement in the region of the GDR, although at higher energies, the calculated cross section is somewhat too large. To obtain this overall agreement, it was necessary to adjust some of the parameters for the semidirect term. The parameters used for the calculation shown in the figure were: $V_1=50$ MeV, $f=0.60$, $\alpha=1.0$, $\Gamma=4.5$ MeV, and $E_{\text{res}}=20.5$ MeV. Of interest is the fact that the symmetry potential has been decreased by about a factor of 1/2, but it should be noted that $V_1$, $f$, and $\alpha$ have equivalent effects in terms of the calculation, so that any set of these parameters would fit the data equally well, provided that the product $V_1 f \cdot \alpha$ is kept constant. A value of $f=0.60$ is typical for light nuclei (Hayward, 1970).

As the next step, a DSD calculation for $^7$Li$(p,\gamma_{16})$ was performed, using as a reasonable approximation the resonance parameters used in the $^7$Li$(p,\gamma_0)$ calculation, except of course for $\Gamma$ and $E_{\text{res}}$. For simplicity, only the $p_{3/2}$ component of the bound state was included in the calculation (the effects of the $p_{1/2}$ component are small), but the other continuum and bound state parameters were the same as those used in the direct calculations of Sec. C.

Since there was no obvious GDR peak in the $^7$Li$(p,\gamma_{16})$ data, it was
Figure 31. 90° yield curve for $^7$Li(p,γ₀) including the results of the DSD calculations.
necessary to predict, using some reasonable method, the resonance energy and
width that might be expected for a GDR built on the isospin-mixed pair in
$^8\text{Be}$. The value of $E_{\text{res}}$ was simply chosen to be 20 MeV above the final 16.6
MeV state ($E_{\text{res}}=20+16.6=36.6$ MeV), which is a typical value for light nuclei.
The width, $\Gamma$, was less easy to predict precisely. In general, a giant
resonance width is largely determined by two different mechanisms. One
mechanism involves decay into a continuum nucleon plus core state
(single-particle escape), where the process is governed in part by the barrier
penetration. The width of the GDR determined from this mechanism is denoted as
$\Gamma_p$ in this thesis. The other important mechanism involves damping of the GDR
into nearby multiple particle-hole configurations. The width from this
mechanism is denoted as $\Gamma_d$. The effect of the $\gamma$-ray decay on the width is
negligible. In medium weight and heavy nuclei, the damping process is
dominate, while for light nuclei the single-particle escape process is almost
totally dominate (Danos and Greiner, 1965). For proton capture to $^8\text{Be}$ the
escape process is thus expected to give most of the observed 4.5 MeV width for
the ground state GDR. The width of a GDR built on the 16.6 MeV state can then
be estimated by extrapolating the width of the ground state GDR to higher
energies.

To investigate the behavior of $\Gamma_d$ as a function of energy, the
expression of Danos and Greiner (1965) was used. Specifically, $\Gamma_d=\Gamma_0 E^g$,
where $\Gamma_0$ is a constant and $g$ is a number calculated by Danos and Greiner to
be about 1.8. This energy dependence is due to the density of $2p-2h$
configurations as a function of energy. Assuming that $\Gamma_d$ is about half of $\Gamma$
for the $\gamma_0$ GDR (2.25 MeV) would give $\Gamma_d=6.4$ MeV for a GDR at 36.6 MeV. This
value of $\Gamma_d$ for the $\gamma_{16}$ GDR is probably a considerable overestimate since $\Gamma_d$
for the $\gamma_0$ GDR is probably much less than 2.25 MeV.
The situation for $\Gamma_p$ is considerably different. This width can be written for a given partial wave $L$ as $2P_L\gamma^2$, where $P_L$ is the penetrability and $\gamma^2$ is the reduced width, giving the overlap of the GDR with the continuum state. Assuming that d-wave capture is predominate for both $^7\text{Li}(p,\gamma_0)$ and $^7\text{Li}(p,\gamma_{16})$ (as is often true in light nuclei (Snover et al., 1980)), and that $\gamma^2$ is roughly the same for both reactions, we may write, approximately, $\Gamma_p(E) = P_2(E)$. Since the d-wave proton penetrability is almost 10 times larger at the expected position of a $\gamma_{16}$ GDR ($E_p=20-25 \text{ MeV}$) than at the position of the $\gamma_0$ GDR ($E_p=5 \text{ MeV}$), $\Gamma_p$ should be about 40 MeV for a $\gamma_{16}$ GDR. From these arguments, we would expect $\Gamma \approx \Gamma_p \approx 40 \text{ MeV}$.

DSD calculations have been performed for $^7\text{Li}(p,\gamma_{16})$ using various widths, and the results are shown in Fig.32. All the calculations shown have been normalized by the factor of 1.27 to give better absolute cross section agreement in the low energy region. The results for $\Gamma=10 \text{ MeV}$ clearly do not describe the experimental results. For $\Gamma=20 \text{ MeV}$, a curve is obtained which does not actually fit the data, but gives the shape of a small broad resonance between 20 and 30 MeV that may be present in the data. These results indicate that if a GDR is present, it must have a width of at least 20 MeV or be significantly reduced in strength. Also shown in the figure are the results for the predicted width, $\Gamma=40 \text{ MeV}$. Since the effect of this resonance on the calculation is not very dramatic, it is difficult to conclude whether or not the yield curve data suggest such a resonance. The data is reproduced fairly well either with a pure direct calculation or with a calculation which adds a broad resonance (DSD).

The effects on the angular distributions of adding a semidirect term were checked. The $a_k$'s obtained for various calculations are shown in Table XII. at 15 and 25 MeV. The first row gives the $a_k$'s obtained from a direct
Figure 32. 90° yield curve for $^7\text{Li}(p,\gamma_{16})$ including the results of the DSD calculations.
Table XI. $^7\text{Li}(p,\gamma_{16}) a_k$ Coefficients from DSD

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0</td>
<td>0.450</td>
<td>-0.503</td>
<td>-0.167</td>
<td>-0.011</td>
<td>$p_{3/2}$ only, direct</td>
</tr>
<tr>
<td>15.0</td>
<td>0.451</td>
<td>-0.502</td>
<td>-0.169</td>
<td>-0.010</td>
<td>DSD, $\Gamma=40$</td>
</tr>
<tr>
<td>15.0</td>
<td>0.462</td>
<td>-0.497</td>
<td>-0.173</td>
<td>-0.011</td>
<td>DSD, $\Gamma=20$</td>
</tr>
<tr>
<td>25.0</td>
<td>0.863</td>
<td>-0.478</td>
<td>-0.499</td>
<td>-0.092</td>
<td>$p_{3/2}$ only, direct</td>
</tr>
<tr>
<td>25.0</td>
<td>0.800</td>
<td>-0.523</td>
<td>-0.462</td>
<td>-0.073</td>
<td>DSD, $\Gamma=40$</td>
</tr>
<tr>
<td>25.0</td>
<td>0.725</td>
<td>-0.563</td>
<td>-0.420</td>
<td>-0.058</td>
<td>DSD, $\Gamma=20$</td>
</tr>
</tbody>
</table>
calculation which neglected the $p_{1/2}$ component of the bound state. Shown in
the next two rows are two DSD calculations, with $\Gamma = 40$ and $\Gamma = 20$ MeV. Both
assume for simplicity only the $p_{3/2}$ component of the bound state. A
comparison of these $a_k$'s indicates that the angular distributions are not
very sensitive to the addition of the semidirect term.

Similarly, Table XII shows the results of the calculations for the $b_k$
coefficient. The first row gives the results of the direct calculation with
the $p_{3/2}$ component only, and the second and third row give the two DSD
calculation results. Again, the results are rather insensitive to the
addition of the semidirect term.

The results of these direct-semidirect calculations indicate that it is
difficult in this reaction to establish the presence of a GDR which has a
width greater than about 20 MeV. The difficulty is due to the limited
sensitivity of the $a_k$'s, $b_k$'s, and $90^0$ yield curve to the addition of such a
broad semidirect term.
Table XII. $^7\text{Li}(p,\gamma_{16})$ $b_k$ Coefficients from DSD

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0</td>
<td>0.070</td>
<td>-0.034</td>
<td>-0.032</td>
<td>-0.003</td>
<td>$p_{3/2}$ only, direct</td>
</tr>
<tr>
<td>15.0</td>
<td>0.061</td>
<td>-0.040</td>
<td>-0.030</td>
<td>-0.003</td>
<td>DSD, $\Gamma=40$</td>
</tr>
<tr>
<td>15.0</td>
<td>0.054</td>
<td>-0.046</td>
<td>-0.030</td>
<td>-0.003</td>
<td>DSD, $\Gamma=20$</td>
</tr>
</tbody>
</table>
Chapter 6 Summary and Conclusions

The $90^\circ$ yield curve has been measured from $E_p = 4$ to $30$ MeV for the
reaction $^7\text{Li}(p,\gamma_{16})^8\text{Be}^*$, where the final state is the region of the
isospin-mixed pair of levels in $^8\text{Be}$. Angular distributions of cross sections
for this reaction have been measured at nine beam energies from 12 to 30 MeV.
Angular distributions of analyzing power have been measured at 3 energies. The
yield curve data for this reaction do not exhibit any pronounced peaking at
the expected energy for a giant dipole resonance built on the 16 MeV states.
Furthermore, a simple direct capture model calculation, including E1 and E2
radiation, is sufficient to give a good description of the data. In
particular, the peaking in the yield curve at about $E_p = 8$ MeV and the absolute
cross section are described very well by the direct calculation.

To investigate the possibility of a GDR built on the isospin-mixed pair,
DSD calculations were performed for the reaction $^7\text{Li}(p,\gamma_{16})$. Although no
obvious GDR is suggested by the yield curve data, the DSD calculations
indicate that a GDR could be consistent with the data if it were at least 20
MeV wide. The energy dependence of the d-wave proton penetrabilities
indicates that the width for a GDR built on the isospin-mixed pair of states
might be about 40 MeV. The DSD calculations show that it would be very
difficult to determine the existence of a GDR with such a large width.
Therefore, there would seem to be little utility in calling such a resonance a
"giant resonance".

These results are in contrast with the two capture reactions, \( ^7\text{Li}(p,\gamma_0) \) and \( ^7\text{Li}(p,\gamma_1) \). The 90° yield curves for these two reactions have been measured at beam energies from 11.5 to 30 MeV. Our results combine with results from other work (Fisher et al., 1976) to provide 90° yield curves for \( E_p = 2 \) to 30 MeV. Additionally, angular distributions of cross sections and analyzing powers have been measured at various energies from 12 to 30 MeV. In the region of the observed GDR's (about 5 MeV for \( \gamma_0 \) and about 8 MeV for \( \gamma_1 \)), the direct capture model is not sufficient to describe the data for either reaction. In particular, the calculated cross sections are too small and do not have the correct energy dependence. Above the regions of the GDR's, the direct model can provide a reasonable description of the data.

Direct-semidirect (DSD) calculations have been performed for the reaction \( ^7\text{Li}(p,\gamma_0) \). The inclusion of an El semidirect term provides a good description of the overall shape and magnitude of the yield curve.
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