ANGULAR DISTRIBUTION AND ANGULAR CORRELATION MEASUREMENTS
IN Be$^9$ (d,p) Be$^{10}$, B$^{10}$ (d,p) B$^{11}$, AND Mg$^{24}$ (d,p) Mg$^{25}$

by
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ANGULAR DISTRIBUTION AND ANGULAR CORRELATION MEASUREMENTS

IN Be$^9$ (d,p) Be$^{10}$, B$^{10}$ (d,p) B$^{11}$, AND Mg$^{24}$ (d,p) Mg$^{25}$
Prior to 1950 strong forward peaking in the angular distributions of the protons in $(d,p)$ reactions had been observed by many investigators.\textsuperscript{1} The deuteron energy was usually very high (approximately 100 mev), and the emergent particles were confined to a cone peaked at zero degrees, with half angle of approximately ten degrees. Distributions of this sort were explained, chiefly by Serber, on the basis of a rather simple stripping model, and good agreement between theory and experiment was obtained in most cases. The theory developed by Serber, and modified by others, predicted a zero degree maximum in all cases. However, in 1950, Burrows et al. obtained angular distributions from $^{18}O(d,p)^{17}$ which did not agree with the Serber theory.\textsuperscript{2} The angular distribution of the protons which left $^{17}$O in its first excited state was well
behaved and had a maximum at zero degrees, but the angular
distribution of the protons which left $^{17}$ in its ground
state had a sharp decrease near zero degrees. In all the
theoretical work before this time no attempt was made to
distinguish between the different energy particle groups from
a \((d,p)\) reaction.\(^5\) The first theoretical attempt to take into
account the individual particle groups, and to allow for the
angular momentum and parity transfer in stripping reactions
was made by Butler.\(^3\) In the model of the stripping reaction
used by Butler, which was the same as that used in earlier
theories, the neutron and proton in the deuteron were assumed
to act independently once the deuteron reached the nuclear
surface. The neutron was absorbed and the proton served to
conserve energy and momentum in the reaction.

The process considered above is similar to the neutron
capture reaction.\(^1\) The essential distinction between a \((d,p)\)
stripping reaction and a pure neutron capture reaction is that,
in the former, the neutron can be absorbed into negative energy
states as well as positive energy states, while only positive
energy states are available to the latter. Most of the work
utilizing the \((d,p)\) stripping reaction is concerned with the
negative energy states. Let \(J_o\) be the angular momentum of the

\(^5\) The highest energy group leaves the residual nucleus
in its ground state, the next highest energy group leaves the
residual nucleus in its first excited state, etc.
target nucleus, $J_1$ the angular momentum of the excited state of
the residual nucleus, $J_2$ the angular momentum of the ground
state of the residual nucleus, and $l_n$ the orbital angular
momentum of the absorbed neutron. Then the reaction is
described as follows: the deuteron reaches the nuclear surface
of the target nucleus and separates into a neutron and proton,
the neutron is absorbed into the target nucleus forming a
resultant nucleus with angular momentum $J_1$. Then, for the
negative energy states considered here, the resultant nucleus
decays by gamma ray emission, by one or more transitions, to
the ground state of the residual nucleus which has angular
momentum $J_2$. The multipolarity of a gamma ray transition is
always denoted by $L$. The angular momentum $J_1$ of the excited
state of the residual nucleus can be formed in any way consis-
tent with the vector addition of the angular momenta involved
in the capture process. For a given value of $l_n$ the possible
values of $J_1$ are given by the following relation:

$$\left| J_0 + l_n + \frac{1}{2} \right|_{\text{min}} \leq J_1 \leq J_0 + l_n + \frac{1}{2}$$  \hspace{1cm} (1)

Also, for a given value of $J_1$, the possible values of $l_n$ which
can contribute to the reaction are given by:

$$\left| J_0 + J_1 + \frac{1}{2} \right|_{\text{min}} \leq l_n \leq J_0 + J_1 + \frac{1}{2}$$  \hspace{1cm} (2)

The contributing values of $l_n$ must be all even or all odd for
conservation of parity since the parity change in the reaction.
is determined by the orbital angular momentum of the absorbed neutron. For neutrons with even orbital angular momenta there is no parity change, and for neutrons with odd orbital angular momenta there is a parity change. For spin zero target nuclei (\(J_0 = 0\)), it can be seen from equation two that only one value of \(l_n\) can contribute, and from equation one that there are then only two possibilities for the angular momentum \(J_1\) of the level in the residual nucleus, \(l_n - \frac{1}{2}\) and \(l_n + \frac{1}{2}\). Thus, for spin zero target nuclei, a determination of \(l_n\) defines the parity of the level in the residual nucleus if the parity of the target nucleus is known, and limits to two the possible values of \(J_1\). For target nuclei with \(J_0\) greater than zero the parity is still uniquely defined, but the number of possible values of \(J_1\) can become quite large. For example, for \(J_0 = 3\), \(l_n = 2\), the possible values of \(J_1\) are \(1/2\), \(3/2\), \(5/2\), \(7/2\), and \(9/2\).

In Butler's theory only one level of the residual nucleus was involved in a particular distribution measurement. Butler found that the angular distributions were extremely sensitive to the orbital angular momentum \(l_n\) of the absorbed neutron. The maximum always occurred at zero degrees for \(l_n = 0\), and at successively larger angles for increasing \(l_n\). Butler was able to apply the theory successfully to the experimental data then available, and obtained an unambiguous determination of \(l_n\) in every case. Since 1950, many measurements of \((d,p)\) stripping reactions have been made,\(^1\),\(^5\),\(^6\) mostly at a deuterium bombarding
energy of eight mev, and a unique determination of $l_n$ was possible in almost all cases. Of especial merit was the work of Holt and Marsham, who made accurate angular distribution measurements in many nuclei.\textsuperscript{7,8,9,10,11} They used deuterons of eight mev bombarding energy obtained from the Liverpool cyclotron. Their measurements covered a great many nuclei from Li\textsuperscript{7} to Sr\textsuperscript{88}, and in almost all cases, unambiguous determinations of $l_n$ were possible. The values they obtained ranged from $l_n = 0$ to $l_n = 3$. In several instances a superposition of two or more $l_n$ curves was necessary in order to obtain good agreement between theory and experiment. Distributions requiring more than one $l_n$ value could have resulted from a reaction involving a single level of the residual nucleus, or possibly from two levels too closely spaced in energy to be resolved by the triple proportional counter used. If only one level of the residual nucleus was involved, then the $l_n$ values must necessarily have been all even or all odd for conservation of parity. However, if even and odd values of $l_n$ contributed to the same distribution, then more than one level of the residual nucleus must have been involved and at least two must have differed in parity.\textsuperscript{1} A few cases of almost isotropic distributions were observed which were presumably due to compound nucleus formation.\textsuperscript{8,9} These particular examples probably required a value of $l_n$ greater than three and thus would be expected to have had very small stripping cross sections.\textsuperscript{3}
The Butler theory involves matching of wave functions at the nuclear boundary and seems to have reasonable theoretical justification. However, in order to obtain a result free of undue mathematical complications, Butler finds it necessary to make rather sweeping approximations. The effect of the Coulomb field is ignored completely. It is also assumed that, once the deuteron reaches the nuclear surface its interaction with the proton of the deuteron is zero. The possibility of elastic deuteron scattering and resonant proton scattering is also neglected. Because of the neglect of the Coulomb field, Butler's theory is expected to yield the best results for deuteron bombarding energies well above the Coulomb barrier, and this is just what is observed experimentally. Bhattacharyya et al. have developed a Born approximation theory, which has little theoretical justification, but which yields a result very similar to Butler's. In both theories the interaction distance \( r_0 \) is the sum of the nuclear radius of the target nucleus and the range of nuclear forces. In the Butler theory an unambiguous determination of \( l_n \) can almost always be obtained if a value of \( r_0 \) is used given by: \( r_0 = (1.7 + 1.22 A^{1/3}) \times 10^{-13} \text{ cm.} \), while the theory of Bhattacharyya et al. usually requires a value of \( r_0 \) approximately 10^{-13} cm. larger than this.

Since the original work of Butler and Bhattacharyya et al., many authors have modified and extended the theory to take into account the Coulomb field interaction and the effect of
deuteron and proton scattering.\textsuperscript{1,13,14,15,16} The main effects of the Coulomb field interaction are to shift the peak of the stripping angular distribution toward backward angles, to broaden the peak, and to enhance the secondary maximum.

Neuma\textsuperscript{17} and Sorowitz and Messiah\textsuperscript{18} have developed theories of the deuteron stripping reaction which predict a polarization of the emergent protons. The theories of both Butler, and Shatia et al. predict the polarization to be identically zero. The polarization vector is normal to the plane of the reaction.\textsuperscript{17} Whether the polarization vector is directed up or down depends on the particular combination of the quantum numbers involved in the reaction. For spin zero target nuclei the polarization is directed in one sense for $J_0 = l_n - \frac{1}{2}$, and in the opposite sense for $J_0 = l_n + \frac{1}{2}$.\textsuperscript{17} Thus a measurement of the direction of polarization should determine the angular momentum $J_1$ for the case of spin zero target nuclei. However, it is found that a theory similar to Butler's, but taking into account the Coulomb interaction, also predicts a polarization of the emergent protons.\textsuperscript{16} Unfortunately the polarization predicted here is directed in a sense opposite to that predicted by Neuma, and Sorowitz and Messiah. Thus, before an unambiguous determination of spins can be made, it is necessary that the source of the polarization be known.

An alternative method for determining the value of $J_1$ is to measure the angular correlation of the protons and gamma rays from stripping reactions. The theory for this process
has been extensively treated by many authors. In all the theories cited, it is assumed that the neutron absorption process can be considered as a pure neutron capture reaction, and that the proton does not interact with the nucleus after the neutron has been captured. With this assumption, the entire process is separable into two parts: the angular distribution of the protons relative to the incident beam direction, and the angular distribution of the gamma rays relative to the direction of recoil of the nucleus after absorption of the neutron. Since the emergent proton direction is antiparallel to the direction of the recoil nucleus, the correlation angle, as measured experimentally, is the angle between emergent proton direction and the emergent gamma ray direction. Experimentally the protons are detected at a fixed angle relative to the incident beam direction and the intensity of the gamma rays, in coincidence with a particular proton group, is measured as a function of this angle. If there are no disturbing factors influencing the angular correlation, then a measurement of the angular correlation would probably determine the value of $J_1$ unambiguously in most cases, even for $J_0$ greater than zero. However, there are several factors which can markedly affect an angular correlation measurement. These are: (1) mixtures of channel spins; (2) mixtures of neutron orbital angular momenta; (3) mixtures of gamma ray multipolarities; (4) polarization of the emergent protons; (5) extra-nuclear influences on the
intermediate state. If $J_O = 0$ then only one channel spin is possible, $s = \frac{1}{2}$; but if $J_O > 0$, then the channel spin can have two values, $s = J_O + \frac{1}{2}$, and $s = J_O - \frac{1}{2}$. It has been shown that the two channel spins add incoherently, so that interference does not occur.\textsuperscript{23} Thus the angular correlation is simply the weighted average of the correlation functions calculated for the channel spins taken separately. Consequently, if the channel spin mixture is known, the angular correlation can be calculated explicitly. Alternatively, if the angular correlation is known, and the only mixtures involved are due to the channel spins, then the channel spin mixing ratio can be calculated. The neutron orbital angular momenta add coherently and interference does occur.\textsuperscript{23} Theoretically, since the values of $l_n$ leading to a particular level of the residual nucleus must differ by two units for conservation of parity, and since the relative cross sections for transitions having values of $l_n$ differing by two units are expected to differ by approximately two orders of magnitude,\textsuperscript{3} the effect on the angular correlation is expected to be small. Again the correlation can be calculated explicitly if the relative contributions of $l_n$ and $l_n + \epsilon$ are known, and alternatively, if the angular correlation is known, the relative contributions of the two $l_n$ values can be determined, assuming that there are no other mixtures involved in the reaction. The most serious source for a distortion of the measured correlation occurs for the mixing of multipoles in the gamma ray transition.\textsuperscript{26}
especially if the two lowest allowed multipole radiations are a magnetic L pole (2L) and an electric L+1 pole (2L+1). Here the multipolarities differ by only one unit, and it is often observed that electric L+1 pole radiation competes favorably with magnetic L pole radiation. A 10% admixture of electric L+1 pole radiation with magnetic L pole radiation can have a pronounced effect on the angular correlation (appendix B). It has been shown by Lloyd that the relative phases of the magnetic and electric radiation involved in a mixture can be chosen quite generally to be zero degrees or one hundred eighty degrees. 27 Whether the phase is zero degrees or one hundred eighty degrees is indeterminate except for a specific nuclear model. Thus the sign of the interference term in the angular correlation is unknown, and correlation functions must be calculated using both the plus and minus signs. It has been shown by Newns, 27 and Horowitz and Messiah, 28 that the polarization of the protons can distort the angular correlation. The magnitude of the polarization is difficult to estimate; however both Newns, and Horowitz and Messiah demonstrate that, for extreme cases of polarization, the anisotropy can be greatly reduced and in some cases reduced to zero. Horowitz and Messiah also show, for a particular model, that the correlation may no longer be symmetric about ninety degrees in the correlation angle, and that the symmetry angle can be changed by as much as twenty degrees. The influence of external fields on angular correlation
measurements has been investigated by many workers.\textsuperscript{25,29} The amount of the disturbance on the correlation depends critically on the mean life of the excited state of the residual nucleus and on the material in which the source is embedded. For the high energy gamma rays involved here the lifetime is expected to be short enough so that the influence on the correlation should be negligible.

It was the original aim to investigate the angular correlations and angular distributions in (d,p) stripping reactions for spin zero target nuclei with atomic number in the range 2-11 to 30 in order to assign spins and parities to the low lying levels in the residual nuclei. For spin zero target nuclei, the orbital angular momentum of the absorbed neutron, given by the angular distribution measurement, limits to two the possible values of the spin of the excited state which is formed by the absorbed neutron. For each spin possibility there are two possible correlation functions, one for electric, and one for magnetic radiation. Thus there are only four theoretical correlation functions to be compared with the experimental correlation. In most cases, measurements of this sort would yield unambiguous spin assignments, since the four correlations would generally be quite anisotropic and have anisotropies differing by amounts in excess of any expected experimental error. However, the above remarks are valid only if the reaction proceeds by a stripping process described very well by the Butler theory, and only if the contribution from
competing processes are negligible.

In initial investigations very strong structure was observed in the yield of protons versus deuteron bombarding energy for magnesium and silicon targets, indicating either very strong compound nucleus formation, or perhaps interference between stripping and some other process. Whatever the reason for the structure, the effect on the angular distributions was very pronounced, especially in the case of silicon. Angular correlation measurements were attempted for several levels in Mg^{25} and Si^{29}, but in almost all cases, the correlations were isotropic within 15% to 20%. Theoretically the anisotropies should almost always be much larger than this. Because of the structure in the yield curves and because of the failure to find sufficiently anisotropic correlations, it was decided to attempt similar measurements in lighter nuclei to test the validity of the angular correlation theory in cases more nearly satisfying the requirements of the theory. For this purpose the target nuclei chosen were Be^{9} and B^{10}. Angular correlation measurements were also made on the strongest level in Mg^{25}.

The experiments described in this thesis were performed utilizing the Duke University 4 mev Van de Graaf accelerator. The deuteron energies used were in the range 2.5 mev to 4.0 mev. The deuterons were selected from other particles in the beam by the Van de Graaf analyzing magnet which deflected the deuterons fifteen degrees. The energy spread of the beam at
the target was the order of a few kev.

Isotopically enriched $^{10}\text{B}$, in the form of a microscopic suspension in oil, was obtained from the Oak Ridge National Laboratory. The $^{10}\text{B}$ targets were prepared by painting the boron-oil suspension on one micron thick nickel backing and evaporating the oil in vacuum. The beryllium and magnesium targets were prepared by evaporating the pure metals onto thin nickel backings.
Chapter II
EXPERIMENTAL EQUIPMENT
The Target Chambers

For ease of operation in taking the angular distribution and angular correlation measurements it was convenient to have the charged particle detector outside the target chamber. The target chamber was a two inch by two inch brass cylinder with walls 1/32 of an inch thick. The angular distribution chamber had a 3/16 inch wide slot cut from minus fifteen degrees to one hundred forty degrees with respect to the incident beam. The angular correlation chamber had three holes, each 3/8 inch in diameter, centered respectively at twenty degrees, forty degrees, and eighty-five degrees with respect to the incident beam. The slot and holes were covered with one half mil mylar for a charged particle window. The mylar was glued to the chamber and glyptal was used to make a vacuum seal. The total
minimum absorber between the target and the crystal consisted of one half mil mylar, approximately two centimeters of air, and one micron of nickel (light tight and air tight cover for the crystal). This was equivalent to approximately four centimeters of air, or enough to stop 1.5 mev protons. In the investigation of $(d,p)$ reactions in this thesis the lowest energy protons encountered were approximately four mev, and these went through all the absorber without appreciable straggling in energy. In both chambers the incident deuterons were collimated by two tantalum discs with 1/16 inch holes spaced six inches apart. The collimation system was insulated from the target chamber proper by a lucite spacer so that the current measured was due only to the deuterons passing through the target. The targets were deposited on thin nickel backings supported by thin brass rings. The brass rings were bolted to an accurately centered brass rod which went through an O ring seal in one lid of the target chamber so that the target could be rotated without breaking the vacuum. The target chambers together with the collimator and target holder are shown in figure 1b.

In taking angular distribution measurements either a 1/16 inch or a 1/8 inch aperture was used over the charged particle detector. The aperture was centered in the slot so that the entire target could be seen from any part of the aperture. The distance from the target to the aperture was usually about 1.5 inches; thus the 1/16 inch and 1/8 inch apertures subtended
plane angles of 2.5 degrees and 5.0 degrees respectively and so the 
scattering of the angular distributions was small. The 
angular distributions were usually measured every five degrees 
from fifteen degrees to one hundred thirty degrees, although 
some measurements were made at zero degrees by inserting just 
enough tantalum between the target and mylar to keep the 
deuterons from hitting the mylar. In this way protons with Q 
values in excess of two mev could be measured with reasonable 
resolution. The zero angle was determined by sighting through 
the collimator and inscribing a line on the inside of the 
target chamber. The aperture of the crystal was then centered 
on this line so that the absolute angle should be known to 
something better than plus or minus two degrees. For angular 
correlation measurements the proton counter was kept fixed, 
usually at the peak of the stripping distribution, and the 
gamma counter was rotated. The gamma counter was a two inch by 
two inch NaI(Tl) cylinder and the distance between the front 
face of the gamma counter and target was three inches. The 
scattering of the angular correlation due to the finite solid 
angles of the detectors has been treated theoretically and 
the results together with applications are given in appendix C. 
The angular distribution table (Fig. 1b) was of rugged angle 
iron construction, with the rotating arm supported on roller 
bearings, and an angle scale graduated every five degrees 
through the entire three hundred sixty degree range. The legs 
were equipped with leveling screws so that the table could be
accurately leveled and centered with the target chamber. The angular distributions were taken in two parts, fifteen degrees to ninety degrees and ninety degrees to one hundred thirty degrees. The ninety degree point was repeated for purposes of normalization.

The Charged Particle Detectors

There are two types of charged particle detector which can be conveniently used in angular distribution and angular correlation measurements: the proportional counter and the scintillation counter. For the detection of low energy particles the proportional counter is probably more useful because it can be biased so that it is insensitive to gamma rays, while a scintillation counter gives approximately the same pulse height for protons and gamma rays of the same energy. However, the intrinsic resolution of a proportional counter is ten to twelve percent, while a scintillation counter with a properly mounted crystal gives an energy resolution of approximately three to four percent for four mev protons, and approximately 2.5% for eight mev protons. The effective resolution of a proportional counter can be greatly increased by inserting enough absorber to slow down the proton group to be measured so that it falls on the peak of the Bragg ionization curve. However, in the measurement of angular distributions where the proton energy changes as the angle of emission changes, and where the proton
group energies vary from four to twelve mev, a proportional counter would be rather inconvenient to use. Also, the entire proton spectrum can be easily measured at a particular angle with a scintillation counter, thus saving considerable time when the angular distributions of several proton groups from a $(d,p)$ reaction are to be measured. The scintillation counter is more suitable for coincidence measurements because of the relatively short pulses delivered by the scintillator.

Stoddart and Gove were the first to use a scintillation counter for the investigation of charged particle reactions. They studied the inelastic protons resulting from the bombardment of various elements with seven mev protons. Following Stoddart and Gove many others developed charged particle detectors of the same type.

NaI(Tl) is almost universally used as the scintillator in a charged particle scintillation spectrometer because of its large light output. This is the most important factor in determining the energy resolution of a scintillation counter, because the main spread in pulse height arises from the statistical fluctuation of the electrons from the photocathode of the photomultiplier tube used with the scintillator. Thus, the larger the light output a scintillator has, the smaller will be the fractional statistical fluctuation of the photoelectrons. Another important factor in determining the energy resolution is the non-uniformity of the photocathode. Since the energy resolution desired is 2.5%, a variation in the photocathode
sensitivity of one or two percent is too large. For this
reason it is best to use as small an area of the photocathode
as possible. This can be done for angular distribution measure-
ments where there is ample yield. For angular correlation
measurements, where large solid angles are necessary in order
to obtain high counting rates, the area used is a circle \( \frac{1}{2} \) inch
in diameter. Here it would seem better to have the crystal
somewhat removed from the photocathode so that the scintilla-
tions in different parts of the crystal illuminate the photo-
cathode in essentially the same way. This is discussed in more
detail below.

Both terphenyl and NaI(Tl) crystals were tried in many
mounting arrangements for the charged particle detector. NaI(Tl)
was always superior to terphenyl in energy resolution, but in
view of the ease with which terphenyl could be handled (sodium
iodide is hygroscopic), it was much more convenient where the
energy resolution requirements were not critical. The energy
resolution obtained with terphenyl varied from sample to
sample, but was generally approximately three fourths that of
NaI(Tl). At first, because of the non-uniformity of the photo-
cathode, it was thought necessary to mount the crystal some
distance from the photocathode. The first type mounting used
was a lucite light pipe one inch long with a reflecting cover
for the crystal. Then various light pipes varying in length
from \( \frac{1}{2} \) inch to one inch were tried. However, the best resolu-
tion was obtained with the crystal mounted directly on the
phototube. The decreased resolution with light pipes apparently resulted from a combination of poorer light transmission and more inefficient light collection. Various materials were tried for obtaining optical contact between the crystal and phototube. The best results were obtained with vaseline and special silicone fluid (obtained from National Radiac) for measurements with the crystal at atmospheric pressure. There was no appreciable difference between the two. However, for measurements with the crystal in vacuum, it was necessary to use some material which did not form bubbles between the crystal and phototube. For this purpose, bonding agent #R313 (obtained from Carl M. Biggs Co.) was very satisfactory.

Difficulty was encountered in obtaining a permanent mounting for a NaI(Tl) crystal. It appeared to be difficult to can a NaI(Tl) crystal in a chamber with a volume of air much larger than the crystal volume, and have it give good results for more than a week, unless some desiccant was inserted in the chamber. In the final arrangement, the crystal was not mounted directly on the phototube, but inside a lucite chamber which had a thin bottom, approximately 1/32 inch thick. The one micron thick nickel foil for the charged particle window was mounted on the aluminum cover with #R313 bonding agent, and the cover was sealed to the chamber with an O ring. The crystal was cleaved on both sides in a dry box. Phosphoric anhydride was used as a desiccant. The ½ inch diameter crystal ingot, from which the individual crystals were cleaved, was first
cleansed in alcohol so that the side walls of the cleaved crystals were reasonably clear. The crystal was sealed to the bottom of the chamber with vacuum dried vaseline. The vaseline was melted in vacuum and let stand for several hours in a molten state so that all water vapor was driven off. Some phosphoric anhydride was placed in the chamber as a dessicant. This arrangement gave as good energy resolution as any tried, and the crystal gave good results for several months. The crystals used were ½ inch in diameter and approximately 1 mm thick.

In addition to the pulse height spread resulting from the statistical fluctuation of the photoelectrons, and from the non-uniformity of the photocathode, there are several other factors which are important in determining the energy resolution obtainable from the overall equipment. The condition of the crystal surfaces is very important. The best results are obtained with cleaved crystals. It is necessary that the crystal surfaces be absolutely dry, since absorption of a small amount of water vapor drastically reduces the light output of the crystal. The pulse height spread can be reduced by suitably adjusting the voltages on the dynodes of the photomultiplier, but the improvement is slight and certainly minor compared with the other factors. The best results are obtained with the Dumont 6292 phototube. The only disadvantage of the Dumont tube is its slight non-linearity in pulse height versus energy. This is not serious except for very precise
energy measurements. The finite window width of the pulse height selector also contributes to the pulse height spread. The window width used is always one volt and pulse heights are measured as high as eighty volts, so that the window width, while not excessive, is always appreciable. Examples of proton spectra obtained using a NaI(Tl) scintillation counter, with enough absorber to stop the scattered deuterons, are given in figures 2, 3, and 4.

The NaI(Tl) scintillation counter can be used successfully in studying the proton spectra from (d,p) reactions so long as the energy levels of the residual nucleus are no closer together than 400 kev. This figure depends on the proton energy and will be somewhat smaller for low energy protons. The 400 kev figure applies to protons having energies of approximately 8 to 10 mev. In the investigation of nuclei with much smaller level spacing, it is necessary to use a magnetic analyzer for the protons. The energy resolution of a magnetic analyzer is five to ten times better than the energy resolution of a scintillation counter. However, the ease with which a scintillation counter can be manipulated makes it much more convenient for reactions for which the 2.5% energy resolution is sufficient. A much larger solid angle can be obtained with a scintillation counter than can be obtained with a magnetic analyzer. Thus, if an energy resolution of 2.5% is at all usable, the scintillation counter is a much more desirable instrument for use in angular correlation experiments.
Proton Spectrum

\[ \text{Mg}^{24}(d, p) \text{Mg}^{25} \]

[\( E_d = 3.5 \text{ MeV} \)]

[\( \theta_p = 40^\circ \)]

1 Volt Window

FIG. 2
Proton Spectrum

$^{28}\text{Si}^8 (d, p) ^{29}\text{Si}$

$E_d = 3.0$ Mev

$\theta_p = 30^\circ$

1 Volt Window

Fig. 3
Proton Spectrum
$^{32}\text{S} (d, p) ^{33}\text{S}$
$E_d = 2.5 \text{ MeV}$
$\theta_p = 50^\circ$
1 Volt Window

Counts

(8) (5) (4) (3) (2) (1) (0)

Pulse Height (Volts)
The Coincidence Circuit

Both the gamma rays and protons were detected by NaI(Tl) scintillators used with Dumont 6292 photomultipliers. The pulses from each detector were then sent through a cathode follower for driving a one hundred ohm cable approximately fifty feet long which fed an Oak Ridge type Al amplifier. The pulses were then fed into a differential pulse height selector, the output of which was split three ways. One lead triggered a univibrator which in turn ran a scaler and register for measuring the singles counts. The other two leads triggered blocking oscillators which were fed to a coincidence and accidental coincidence circuit. The outputs of the coincidence and accidental coincidence circuits each triggered a univibrator, scaler, and register combination for recording the total coincidence and accidental counts.

The photomultiplier arrangement was standard. The signal was taken from the last dynode of the photomultiplier rather than the anode since the Al amplifiers had a somewhat better response for positive pulses. The cathode follower was in the phototube base. The tube used for the cathode follower was a 6AC7 since this tube had a gain of approximately 0.9 when used in a cathode follower circuit and an output impedance of ninety ohms. The ninety ohm output impedance was a reasonable match for the one hundred ohm cable.

NaI(Tl) has a decay time of 0.25 microseconds, so that the pulses from the cathode follower had a rise time of 0.25
microseconds, since the RC constant in the grid circuit of the cathode follower was several microseconds. The clipping action of the AI amplifiers reduced this rise time to approximately 0.20 microseconds when the amplifier was used in the wide band position.

A block diagram of the electronics is given in Figure 5. The notation is the following: photomultiplier (P.M.); cathode follower (C.F.); AI amplifier (Amp.); differential pulse height selector (D.P.H.S.); blocking oscillator (B.O.); coincidence circuit (C); accidental coincidence circuit (A); univibrator (U); scaler (S); register (R).

The differential pulse height selector was made by using a standard Oak Ridge type integral pulse height selector for determining the base line and another similar circuit biased above the first and in anti-coincidence with it. The grid of the anti-coincidence selector was biased above the grid of the base line selector by a battery which was adjustable from 1.5 volts to 7.5 volts. The differential pulse height selector was fast enough to respond to two pulses one microsecond apart.

The blocking oscillators were of conventional design. The circuit diagram of the blocking oscillator used is given in Figure 6. The pulse transformer used in the circuit was a Westinghouse #P 16 pulse transformer. Each blocking oscillator required a separate isolation tube for triggering because of the violence of the oscillation. With the Westinghouse #P 16 transformer, the circuit delivered a pulse triangular in shape
and 0.1 microseconds long at the base. The recovery time of
the circuit was approximately ten microseconds, thus it
responded satisfactorily to random pulses with an average
counting rate of approximately ten thousand counts per second.

The coincidence circuit was standard and utilized a 6SN6
gated beam tube. The circuit is given in Figure 7. With the
cathode biased 6.25 volts above ground, the circuit provided
excellent discrimination between singles and doubles. The
coincidence circuit itself was capable of much better resolving
time than 0.1 microseconds. Thus, the resolving time was
determined solely by the length of the pulses fed into it.
Since the blocking oscillator pulses were approximately 0.1
microseconds long, the resolving time would have been 0.1 micro-
seconds if the univibrator on the output of the 6SN6 had been
set to accept all pulses from the coincidence circuit. However,
since the blocking oscillator pulses were triangular, the
resolving time could be decreased by biasing the univibrator
to accept only pulses above a certain value. In this way the
resolving times of both the coincidence and accidental circuits
could be made roughly the same. The main limitation on the
resolving time of the coincidence circuit arose from the finite
rise time of the pulses which went to the differential pulse
height selector. Here the total delay of a pulse going through
the amplifier and differential pulse height selector depended
on the particular point on the rise at which the differential
pulse height selector was triggered. If the bias of an inte-
integral pulse height selector was varied throughout the rise of the pulse, the difference in time of the output pulses from the pulse height selector at the extreme ends of the rise would have equaled the rise time of the pulse. Since the rise time of the pulses was approximately 0.2 microseconds, and the desired resolving time was 0.1 microseconds or better, it was clear that an integral pulse height selector could not be used. The use of a differential pulse height selector eliminated most of this trouble since only that part of a pulse was selected which was near the top. Here then, the difference in time delay resulted only from a relatively small section of the rise and from imperfections in the window edges. With a differential window of four volts, the maximum variation amounted to approximately 0.05 microseconds.

The following procedure was used to check the coincidence circuit in order to make certain that there was negligible loss of coincidences. Pulses from a fast pulser were fed into each amplifier. Since the pulses into the amplifiers came from a single source, they were certainly in coincidence when they entered the amplifiers. The output of the coincidence circuit was used to measure the window widths. If the pulses were not in coincidence over the entire window, then the coincidence circuit would not have delivered pulses over the entire window. With this procedure the window widths, as measured by the coincidence circuit, were the same as the window widths measured using a single amplifier, when the biases of both
pulse height selectors were varied anywhere in the range twenty to sixty volts. The minimum usable resolving time for this voltage range was approximately 0.075 microseconds.

The accidental coincidence circuit was identical to the coincidence circuit, except that a delay of one microsecond was inserted in one input to eliminate all true coincidences. The resolving times of both the coincidence and accidental coincidence circuits were measured frequently, and were relatively constant over periods of several hours. However, the only parameter needed for calculation of the number of accidental coincidences in the coincidence channel was the ratio of the resolving times of the two circuits. This was constant to approximately ten percent over periods of many hours, and was insensitive to the counting rates in the channels so long as the counting rates did not exceed several thousand counts per second. The total number of true coincidence counts is given by:

\[ N(C) = N(C+A) + N(A)T(C)/T(A) \]

where:

- \( N(C) \) = number of true coincidences
- \( N(C+A) \) = total number of counts in coincidence circuit
- \( N(A) \) = total number of counts in accidental circuit
- \( T(C) \) = resolving time of coincidence circuit
- \( T(A) \) = resolving time of accidental circuit

Thus, even though the ratio of resolving may have varied by ten per cent, the error introduced in the true coincidence
counts was small so long as \( N(A) \) was much smaller than \( N(C) \). Practically, however, in order to obtain reasonable counting rates, \( N(A) \) was usually only three to four times smaller than \( N(C) \). In some cases \( N(A) \) was only twice as small as \( N(C) \).

It was essential to have a differential window in the proton channel in order to be certain that the coincidences measured were associated with only one proton group. It was also necessary to have a differential window in the gamma channel, both to minimize the time delay, and to keep the counting rate into the blocking oscillator down to a reasonable value.
Chapter III
EXPERIMENTAL PROCEDURE

Buechner investigated the proton spectra from many \((d,p)\) reactions with a high resolution magnetic analyzer.\(^5,6\) The proton groups from \(\text{Be}^9\), \(\text{B}^{10}\), and \(\text{Mg}^{24}\) were identified with those obtained from the magnetic analysis data of Buechner by plotting the pulse height against the supposed excitation energy as obtained from Buechner's work. The proton counter was linear enough so that the resulting curve was very nearly a straight line. It turned out that this method was fairly sensitive. If, due to poor resolution, one proton group was obscured, and a proton group on one side was plotted in its place, the resulting curve would have had a sharp break. This break would have been obvious even if the proton group had been only one hundred kev in error.

In taking angular distribution measurements a ten channel
analyzer was used to record the proton spectra. This analyzer was equipped with a precision pulser for accurate adjustment of the window widths. With this pulser the window widths could be set to plus or minus two per cent of the desired value. One volt windows were used exclusively. For isolated proton groups, the proton group was centered in the ten volt spread and an angular distribution was taken with the proton group kept centered as the angle was changed. For proton groups sufficiently isolated, the angular distribution was plotted by simply adding all the channels at each angle. In this way good statistics were obtained. For these isolated groups the contribution from background was subtracted in a straightforward manner. For groups which were not well isolated this procedure could not be used. Instead the following procedure was used for proton groups isolated in pairs. In all such cases a twenty volt spread was sufficient to completely cover both groups. At each angle, measurements were taken with the baseline of the analyzer set so that the upper proton group was centered in the ten channel spread. A measurement was taken at this setting, then the baseline lowered ½ volt and another measurement was taken. The baseline was then set ten volts below the first setting and the same procedure was repeated. In this way the proton groups were covered every ½ volt in a twenty volt region; thus the peak value was determined much more accurately than would have been possible with one volt increments. Here, then, the peak values themselves were
plotted in the angular distributions. The background was estimated when the groups were not sufficiently separated from neighboring groups for an accurate determination. The angular distributions were also corrected for the change in angle in going from the laboratory system to the center of mass system. This correction was rather small. Even for boron the maximum correction was five degrees. The distributions were also corrected for the variation of solid angle with emission angle in the center of mass system. Some difficulty was encountered, due to gamma ray background, in the measurement of distributions of protons with Q values of approximately three mev and smaller. The entire crystal was sensitive to both gamma rays and neutrons, while the proton sensitive portion was restricted by the relatively small aperture. The gamma ray background was considerably reduced, without seriously impairing the energy resolution, by enlarging the aperture to 1/8 inch diameter.

In the angular correlation measurements the proton counter was kept fixed and the gamma counter was rotated. The correlation angle was the angle defined by the target, the proton detector, and the gamma detector. The one hundred eighty degree position was determined by centering the gamma crystal in the appropriate proton window and reading the scale angle indicated by the pointer on the rotating arm. All successive angles were then measured from this reference point. The correlations were usually measured every ten degrees from ninety degrees to as close to one hundred eighty degrees as the
gamma counter could be set without hitting the entrance tube to the target chamber with the front face of the gamma crystal three inches from the target and a four volt window in the differential analyzer for the gamma channel set between twenty and thirty volts, the over-all efficiency of the system was such that one coincidence was recorded for every one thousand or two thousand proton counts. The efficiency was best for very high energy gamma rays because of the larger pair production cross section. In order to obtain the best discrimination against background gamma rays, the window was always set on the first pair peak or, in the case of low energy gamma rays, on the phototube. For most of the angular correlation measurements the procedure was the following. In order to average out any drifts in the amplifiers or phototube high voltage power supply the angular correlation was not taken with one rotation of the gamma counter. Rather, the measurements were taken with the counter rotated back and forth several times. The maximum time for the gamma counter to be held at a particular angle was ten minutes. A magnetic shield was used over the phototubes for the proton and gamma counters to minimize any variation of pulse height due to extraneous magnetic fields. With this experimental arrangement, it was extremely tedious to measure an angular correlation on proton groups of low excitation energy for a nucleus as heavy as magnesium, because of the very large gamma background from the numerous groups of higher excitation, and also from the gamma rays due to competing
reactions. Even in a nucleus as light as boron it was practical to measure an angular correlation only for the most intense groups.

The correlation angle to be compared with theory is not the angle between the direction of emission of the protons and the direction of emission of the gamma rays. The symmetry axis is defined by the direction of recoil of the target nucleus after capture of the neutron. The proton detector is used merely to fix this axis in space. Let \( \theta(\gamma R) \) be the angle between the direction of recoil of the nucleus and the direction of emission of the gamma rays. This is the correlation angle which appears in the theoretical formulae. Let \( E_d \) be the deuteron bombarding energy in the lab system, \( \theta(PR) \) the angle between the direction of recoil of the nucleus and the direction of emission of the protons, and \( \theta_p \) the angle between the direction of emission of the protons and the incident deuteron beam. The values of \( \theta(PR) \) appropriate to this thesis are given in the following table:

<table>
<thead>
<tr>
<th>Target</th>
<th>( E_d )(MeV)</th>
<th>( Q )(MeV)</th>
<th>( \theta_p )(degrees)</th>
<th>( \theta(PR) )(degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be(^9)</td>
<td>3.50</td>
<td>1.216</td>
<td>25</td>
<td>77</td>
</tr>
<tr>
<td>B(^{10})</td>
<td>3.90</td>
<td>2.474</td>
<td>20</td>
<td>76</td>
</tr>
<tr>
<td>B(^{10})</td>
<td>3.90</td>
<td>4.774</td>
<td>20</td>
<td>98.5</td>
</tr>
<tr>
<td>Mg(^{24})</td>
<td>2.98</td>
<td>1.699</td>
<td>35</td>
<td>110.5</td>
</tr>
<tr>
<td>Mg(^{24})</td>
<td>3.50</td>
<td>1.699</td>
<td>40</td>
<td>97.5</td>
</tr>
<tr>
<td>Mg(^{24})</td>
<td>4.00</td>
<td>1.699</td>
<td>40</td>
<td>96</td>
</tr>
</tbody>
</table>
The angular distribution of the protons which left $^{10}\text{Be}$ in its first excited state was measured by Fulbright et al. at a deuteron bombarding energy of 5.6 mev.\textsuperscript{5} Comparison with the theoretical Butler curves gave $l_n = 1$ for the absorbed neutron. The ground state of $^{9}\text{Be}$ had $J_o = 3/2$ odd parity, so the parity of the first excited state was uniquely determined as even. The possible values of $J_1$ were restricted by $l_n$ to be 0, 1, 2, or 3. Since $^{10}\text{Be}$ was an even-even nucleus, its first excited state was expected to have $J_1 = 2$, even parity. Evidence for $J_1 = 2$ was given by the following considerations. The $J_1 = 0, 1$ possibilities were eliminated by Cohen et al., who carried out angular correlation measurements at a deuteron bombarding energy of 0.34 mev, where stripping effects were expected to
Some of the correlations contained strong coefficients for the \( \cos^4 \theta \) term, which stated unambiguously that the first excited state of \( \text{Be}^{10} \) had an angular momentum of \( J_1 = 2 \) or larger, regardless of the mechanism involved in the reaction. Further restriction was provided by internal pair formation measurements which were consistent only with E1 (electric dipole), M1 (magnetic dipole), or E2 (electric quadrupole) radiation for the gamma transition from the first excited state of \( \text{Be}^{10} \) to its ground state. Since the ground state of \( \text{Be}^{10} \) had \( J_2 = 0 \), the internal pair formation measurements restricted the spin of the first excited state to \( J_1 = 2 \) or less. The combination of the above results for the angular correlation and internal pair formation measurements determined the spin of the first excited state of \( \text{Be}^{10} \) to be \( J_1 = 2 \). Thus the gamma transition was necessarily characterized by E2 radiation. The only undetermined parameters which characterized the reaction were the two possible values of the channel spin: \( S = 1 \) or 2. The theoretical correlation functions for these two values of the channel spin are given in figure 9 together with the experimental correlation. The correlation function for a channel spin mixture of 25% of

---

*This follows from the general theorem of angular distribution and angular correlation theory that the highest power of \( \cos \theta \) which can appear in the correlation or distribution function is given by \( 2J_1 \), \( 2J_1' \), or \( 2L \), whichever is the smallest.*
10\% S + 90\% S_0

= 0.11 \omega(\bar{r}) + \omega(r)

= 1 - \frac{4}{5} p_2

\omega is also called for

\nu_{\omega, \text{min}}^3 p_2, \ p_{10}^0 \text{ state}

'P_o' and state

'D_o' predicts 100\% \ S = 1

\frac{j_n = 3}{n} \rightarrow \text{isotropy}

\frac{j_n = 2}{n} \rightarrow \text{isotropy}

see Inglis
$\text{Be}^9(d,p)\text{Be}^{10}$

Group $P_1$

$P,Y$ Correlation

$E_d = 3.5$ Mev

$\theta_p = 25^\circ$

--- Theoretical

--- Exp.

$S = 1$

$0.25\% S_1 + 0.75\% S_2$

$S = 2$

Fig. 9

$1 - \frac{4}{3} P_2$

on $10^\circ S = 1$

$1 - \frac{2}{3} P_2$

$1 - 0.6 C^2 \theta$

$\theta(Degrees)$
$J = 1$ and 75% of $J = 2$ is also given for the purpose of comparison with the experimental correlation. The experimental correlation agreed fairly well with the correlation function calculated for the mixed channel spins. The Be$^9 (d,p)$ Be$^{10}$ reaction was almost ideal for testing the validity of angular correlation measurements in $(d,p)$ stripping reactions for light nuclei. The spins and parities of all the levels were known, the gamma ray transition could only have been E2, and the deuteron bombarding energy was well above the Coulomb barrier so that effects due to the Coulomb interaction should have been small.

The errors indicated in the figure are only statistical.

The Be$^{10} (d,p)$ Be$^{11}$ Reaction

The angular distributions of the protons which leave Be$^{11}$ in its ground state, second excited state, and fourth and fifth excited states are given in figures 10, 11, and 12. The usual notation is used for the proton groups; $P_0$ leaves Be$^{11}$ in its ground state, $P_1$ leaves Be$^{11}$ in its first excited state, etc.

Angular distribution measurements were made on groups $P_1$ and $P_2$; however these showed no agreement with the theoretical Butler distributions and, as such, were considered less desirable for angular correlation measurements. The angular distributions for $P_0$, $P_2$, and $P_{4,5}$ all showed good agreement with the theoretical curves. The chief differences between the theoretical and experimental curves were a shift of the
\[ \sigma (\theta) \]

Relative Scale

\[ B^{10} (d, p) B^{11} \]

Group \( P_0 \)

\( E_d = 3.90 \text{ Mev (Lab.)} \)

--- Butler Theory

0 Experimental

\[ \ell = 1 \]

Fig. 10
$\sigma(\Theta_p)$

Relative Scale

$B^{10}(d, P) B^{11}$

Group $P_2$

$Ed = 3.90$ Mev. (Lab)

- Butler Theory

$\circ$ exp.

$\ell = 1$

Fig. 11
$B^{10}(d, P) B^{11}$

Group $P_{4,5}$

$E_d = 3.90$ Mev (Lab.)

- Butler Theory

$\sigma(\Theta_p)$ Relative Scale

$\Theta_p$ (Degrees)
stripping peak toward backward angles and a broadening of the peak. These two effects were predicted theoretically when the effect of the Coulomb field was taken into account. The value of the nuclear radius \( r_0 \) used in the calculation of the theoretical curves, given in figures 10, 11, and 12, was chosen to be the same as that used by Evans and Parkinson, who carried out angular distribution measurements at a deuteron bombarding energy of 7.7 mev. The value used was \( r_0 = 5 \times 10^{-13} \) cm. In the work of Evans and Parkinson the agreement between theory and experiment was good; the value used for \( r_0 \) placed the theoretical peak at perhaps too large an angle. Thus the shift of the experimental peaks toward backward angles, in the present work at a deuteron bombarding energy of 5.90 mev, was probably due to an increased effect of the Coulomb interaction. The yield at large backward angles in the figures was probably due to compound nucleus formation. Groups \( P_0 \), \( P_2 \), and \( P_4, 5 \) all had angular distributions which, on comparison with the theoretical Butler curves, gave \( l_n = 1 \) for the orbital angular momentum of the absorbed neutron. This agreed with the work of Evans and Parkinson.

The ground state of \( \text{Bi}^{10} \) had \( J_0 = 3 \) even parity and the ground state of \( \text{Bi}^{11} \) had \( J_2 = 3/2 \) odd parity. The value \( l_n = 1 \) for the absorbed neutron defined the parity of the ground state, second excited state, and the fourth and fifth excited states of \( \text{Bi}^{11} \) as odd. The possible values of the angular momentum \( J_1 \) of these states was limited by the value \( l_n = 1 \) to
be \(J_1 = 3/2, 5/2, 7/2, \) or 9/2. The two possible values of the channel spin were \(S = 5/2\) and 7/2.

All the possible correlation functions for these values of \(J_1, J_n\), and \(S\) are given in table I, where only the two lowest allowed multipolarities for the gamma transition are considered for each pair of \(J_1\) and \(S\). The experimental correlation involving group \(P_2\) is given in figure 13 and is isotropic within plus or minus four percent. The experimental correlation for the composite group \(P_{4.5}\) is given in figure 14 together with the two theoretical correlations which agree most closely with it. The errors indicated in the experimental curves are purely statistical.

The best agreement between the experimental correlation involving group \(P_2\) and the theoretical correlation functions was obtained for \(S = 5/2, J_1 = 3/2\), for either M1 or E2 radiation. It would have been possible to have obtained agreement through a suitable mixture of M1 and E2 radiation for \(S = 5/2, J_1 = 5/2\) and for \(S = 7/2, J_1 = 5/2\). Agreement would have been impossible for \(J_1 = 7/2\) except for a rather fortuitous mixture of the channel spins. For \(J_1 = 9/2\) the anisotropies involved were quite large; thus the appropriate mixture of M3 and M4 radiation which was needed to produce isotropy was unlikely. Because of the nature of the measurement, and because of the possibilities of mixtures, none of these spins could be ruled out completely; however the most likely assignment to this level was \(J_1 = 3/2, S = 5/2\).
Chalk River $\Delta h = \frac{3}{2}$ cal/c

\[
\omega = 1 + \left[ \frac{0.08 + 0.333 S}{1 + S^2} \right] \frac{p_n}{p_n^2 + 2N^4}
\]

\[
S^2 = \left| \frac{E_n}{M_1} \right|
\]

\[
1 - 0.25 c^2 = 0.09
\]

\[
1 - 0.14 + 0.06
\]

N0

So N0 $\Delta h = \frac{3}{2}$
<table>
<thead>
<tr>
<th>S</th>
<th>J&lt;sub&gt;1&lt;/sub&gt;</th>
<th>M</th>
<th>W((\phi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1.08</td>
<td>5/2 3/2</td>
<td>M1</td>
<td>1 + 0.185cos^2(\phi)</td>
</tr>
<tr>
<td>5/2 3/2</td>
<td>E2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>-1.37</td>
<td>5/2 5/2</td>
<td>M1</td>
<td>1 + 0.572cos^2(\phi)</td>
</tr>
<tr>
<td>-1.62</td>
<td>5/2 5/2</td>
<td>E2</td>
<td>1 - 0.226cos^2(\phi)</td>
</tr>
<tr>
<td>+3.06</td>
<td>5/2 7/2</td>
<td>E2</td>
<td>1 + 0.542cos^2(\phi)</td>
</tr>
<tr>
<td>+3.7</td>
<td>5/2 7/2</td>
<td>M3</td>
<td>1 + 0.654cos^2(\phi)</td>
</tr>
<tr>
<td>-1.1</td>
<td>7/2 5/2</td>
<td>M1</td>
<td>1 - 0.143cos^2(\phi)</td>
</tr>
<tr>
<td>+0.05</td>
<td>7/2 5/2</td>
<td>E2</td>
<td>1 + 0.079cos^2(\phi)</td>
</tr>
<tr>
<td>-0.16</td>
<td>7/2 7/2</td>
<td>E2</td>
<td>1 - 0.507cos^2(\phi)</td>
</tr>
<tr>
<td>-0.17</td>
<td>7/2 7/2</td>
<td>M3</td>
<td>1 - 0.576cos^2(\phi)</td>
</tr>
<tr>
<td>+0.46</td>
<td>7/2 3/2</td>
<td>M3</td>
<td>1 + 0.891cos^2(\phi)</td>
</tr>
<tr>
<td>7/2 9/2</td>
<td>E4</td>
<td>1 + 0.073cos^2(\phi)</td>
<td></td>
</tr>
</tbody>
</table>

M = multipolarity  
S = channel spin  
J<sub>1</sub> = spin of excited state in B<sup>11</sup>  

ANGULAR CORRELATION FUNCTIONS FOR B<sup>10</sup>(d,p)B<sup>11</sup>  

TABLE I
$B^{10}_{(d,p)}B^{11}$
Group P2
P,$\gamma$ Correlation
$E_d = 3.90$ Mev
$\theta_p = 20^\circ$

Fig. 13
\[ \frac{3}{2} \sqrt{1 - \frac{3.06R}{3.2}} \]

\[ \frac{3}{2} \sqrt{1 - \frac{4.09R}{3.2}} \]

So

\[ J = \frac{2}{5} \leq 10\% \quad S = \frac{3}{2} \]
$W(\Theta)$

$J_I = \frac{9}{2}, M3$

$J_I = \frac{9}{2}, E4$

$J_I = \frac{5}{2}, M1$

$J_I = \frac{5}{2}, E2$

$B^{10}(d, p)B^{11}$

Group $P_{4,5}$

$P, \gamma$ Correlation

$E_d = 3.90$ MeV

$\Theta_p = 20^\circ$

--- Theoretical

--- Exp.

Fig. 14

$1 + 5 \cos^2 \theta$

$1 + 0.30 \cos \theta$
Neither the angular distributions nor the angular correlations of the two groups comprising the composite group $P_{4,5}$ could have been measured separately because of the inadequate energy resolution of the proton detector. However, the two groups were resolved by Buechner who used a magnetic analyzer. The protons were detected at ninety degrees and Buechner found, at a deuteron bombarding energy of 1.51 Mev, that group $P_4$ was ten times more intense than group $P_5$. Thus the angular distribution and angular correlation measurements reported in this thesis, which were carried out at a deuteron bombarding energy of 3.90 Mev, were probably due mainly to group $P_4$. For the composite group $P_{4,5}$, the best agreement between the experimental and theoretical correlations was obtained for $S = 5/2$, $J_1 = 5/2$, M1 radiation, or $S = 5/2$, $J_1 = 7/2$, E2 radiation. The difference between the theoretical correlation functions was too small to be detected experimentally by present techniques. It would have been possible to obtain agreement through a suitable mixture of M3 and E4 radiation for $S = 7/2$, $J_1 = 9/2$ but the agreement would have been somewhat fortuitous. The only other possible mixtures of radiations or channel spins would have yielded the same values of $J_1$ which were indicated above, i.e., $J_1 = 5/2$ or 7/2.

The tentative spin assignments for $B^{11}$ are then $J_1 = 3/2$ odd parity for the second excited state and $J_1 = 5/2$ or 7/2 odd parity for the composite fourth and fifth excited states. It is interesting to compare these results with the results obtained
Corel 4 + 5 may not be formed in the same ratio in x? - 1 dp.
from $\alpha$-$\gamma$ and $\gamma$-$\gamma$ angular correlation studies in the $\text{Li}^7(\alpha,\gamma)\text{Be}^{11}$ reaction. From these studies the second excited state is assigned $J^*_2 = 5/2$ and the composite fourth and fifth excited state is assigned $J^*_1 = 3/2$ all odd parity. These assignments are not in agreement with the values deduced from the stripping data except for the parity. However, because of the possibility of mixtures of channel spins and multipolarities the disagreement cannot be considered serious. At present there is some serious disagreement between the results of the $\text{Li}^7(\alpha,\gamma)\text{Be}^{11}$ reaction and the $\text{B}^{10}(d,p)\text{B}^{11}$ stripping reaction for the first and third excited states of $\text{Be}^{11}$. The 7.7 Mev stripping data gives $l_n = 1$ for both the first and third excited states, thus restricting the possible spin values to 3/2, 5/2, 7/2, or 9/2. However, the results of the $\text{Li}^7(\alpha,\gamma)\text{Be}^{11}$ reaction give $J^*_1 = 1/2$ for both levels. A measurement of the anisotropy of the angular correlation involving each level would seem worthwhile, since the presence of an anisotropy, however small, immediately eliminates the possibility of $J^*_1 = 1/2$. For $J^*_1 = 1/2$ the angular correlation must necessarily be isotropic.

The $\text{Mg}^{24}(d,p)\text{Mg}^{25}$ Reaction

The angular distributions obtained for the protons leaving $\text{Mg}^{25}$ in its eighth excited state (3.40 Mev excitation) are given in figures 15, 16, and 17 for deuteron bombarding energies of 2.98 Mev, 3.50 Mev, and 4.00 Mev respectively. The angular distribution at a deuteron bombarding energy of 2.98 Mev was
$\sigma(\theta_p)$ Relative Scale

$\text{Mg}^{24}(d, p) \text{Mg}^{25}$

Group P8

$E_d = 2.98$ Mev

- O exp.

Fig. 15
$\text{Mg}^{24} (d, P) \text{ Mg}^{25}$

Group $P_8$

$E_d = 3.5$ Mev

$\sigma(\theta_p)$

$\theta_p$ (Degrees)

FIG. 18
Mg$^{24}$ (d, P) Mg$^{25}$

Group $P_8$

$E_d = 4$ Mev (Lab)

- Butler Theory
- exp.

FIG. 17
anomalous, with a suggestion of a peak at a proton angle of forty degrees, and a pronounced rather broad peak at a proton angle of eighty degrees where the stripping cross section was expected to be small. Angular distributions taken with bombarding energies just above and below a deuteron bombarding energy of 2.95 Mev were not anomalous, although the back angle yield was more than half the yield at stripping peak. The angular distribution at a deuteron bombarding energy of 3.50 Mev showed very good agreement with theory, but the curve was not extended to further back angles because the data was not reliable. However, the data indicated that the back angle yield was approximately half the yield at the stripping peak. The best over-all agreement was obtained for a deuteron bombarding energy of 4.00 Mev. Here the back angle yield fell off rapidly. This indicated that the yield from compound nucleus formation was small. Even for a bombarding energy of 4.00 Mev the shift of the stripping peak toward backward angles and the broadening of the peak were quite large. Comparison with the results for the $^2\text{H}(d,p)^3\text{He}$ reaction showed that these effects were much more pronounced in the case of $^2\text{H}(d,p)^3\text{He}$. This was presumably due to the increased Coulomb effect for $^2\text{H}$. The angular distributions given in figures 15, 16, and 17 were not corrected for background. The contribution from background was difficult to estimate since the proton group fell on the tail of the background from gamma rays and neutrons. However, the background was probably not more than twenty per cent of the yield at the minimum cross section of each distribution.
Mg\textsuperscript{24} (d,\textit{p}) Mg\textsuperscript{25}

Group P8

\textit{P,\textit{Y}} Correlation

\(E_d = 2.98\) Mev

\(\Theta_{\text{p}} = 85^\circ\)

- Theoretical
- Exp.

\[ W(\Theta) \]

\[ \Theta_{\text{v,\textit{p}}} \text{(Degrees)} \]

\(J_2 = \frac{5}{2}\)

\(J_2 = \frac{1}{2}\)

\[ \text{Fig. 18} \]
Mg$^{24}$ (d,p) Mg$^{25}$
Group P8
P,γ Correlation
E$_{d}$ = 3.50 Mev
θ$_p$ = 40°

--- Theoretical
--- Exp.

Figure 19
\( ^{24}\text{Mg} (d, p) ^{25}\text{Mg} \)

Group P8

P, \( \gamma \) Correlation

\( E_d = 4.00 \text{ MeV} \)

\( \theta_p = 40^\circ \)

- Theoretical
- Exp.

W(\( \theta \))

\( J_2 = \frac{1}{2} \)

\( J_2 = \frac{3}{2} \)

Fig. 20
Angular correlation measurements were taken at the deutron
bombarding energies of 2.98 Mev, 3.50 Mev, and 4.00 Mev. These
are given in figures 18, 19, and 20, together with the expected
theoretical correlations. The 3.40 Mev state in Mg$^{25}$ decayed
both to the ground state and first excited state. The ratio
of intensities for the two transitions were 16 to 39 respectively
for the transition to the ground state and the first excited
state. For a particular region in the gamma spectrum, however,
it was difficult to estimate the relative intensities. Thus,
it was known only that the ground state transition was weaker,
and that it was probably weaker than is indicated by the above
intensity ratios since the window on the gamma channel was set
on the peak of the gamma spectrum in coincidence with the proton
detector. The ground state of Mg$^{25}$ had $J_2 = 5/2$ even parity,
and the first excited state had $J_2 = 1/2$ even parity. The or-
bital angular momentum of the absorbed neutron was determined
to be $l_p = 1$ by the angular distribution of the protons, so that
the angular momentum and parity of the 3.40 Mev state were
$J_1 = 1/2$ or $3/2$ odd parity. Both gamma transitions were E1 so
that the correlations for the two transitions were

$$W(\theta) = 1 - 1/7 \cos^2 \theta, \quad W(\theta) = 1 - 3/5 \cos^2 \theta$$

for the ground state and first excited state respectively. The
expected experimental correlation should have been a weighted
sum of the above theoretical correlations. The first excited
state correlation should have had a weight two or three times
the weight of the ground state transition. The correlation taken
at a bombarding energy of 2.96 MeV agreed reasonably well with the correlation for the ground state transition. This was not the correlation expected. However, the proton angular distribution was anomalous and the proton detector was placed at 80 degrees with respect to the incident beam, so that stripping effects were not expected to predominate. The correlation was taken chiefly to see what correlation could be expected when most of the yield was presumably from compound nucleus formation. The correlations taken at deuteron bombarding energies of 3.50 and 4.00 MeV showed the expected character. The angular distributions indicated large stripping contributions, especially at 4.00 MeV. The presence of an anisotropy immediately eliminated the possibility of $J_1 = 1/2$ for the 3.40 MeV state. The agreement between theory and experiment was as good as could have been expected in view of the uncertainty of the relative contributions of the gamma rays from the two competing transitions. Since $J = 0$ for the ground state of $^{24}$Mg there was only one possible channel spin, $S = 1/2$. Both gamma transitions were presumably E1,6 and higher multipoles were expected to be much weaker. Thus there was no possibility of mixtures of either channel spins or multipolarities.

Newns,17 and Horovitz28 and Messiah showed that the presence of proton polarization could strongly influence angular correlation measurements in stripping reactions. The magnitude of the polarization, and thus its importance in angular
correlation measurements, could not be calculated. However,
Newns showed in an extreme case that an angular correlation could
be made completely isotropic. Morowitz and Messiah showed, on
the basis of a different model, that in extreme cases the cor-
relation might not be symmetric about ninety degrees in the cor-
relation angle, and that the symmetry angle might be changed
by as much as twenty degrees. However, it seemed unlikely that
the position of the proton could change the shape of the
anisotropy distribution magnitude by as large a factor.

The possibility of a
large anisotropy due to compound nucleus formation seemed ruled
out because the experimental distribution at a deuteron energy
of 4.00 Mev indicated that the contribution from compound
nucleus formation was small.
Chapter V
SUMMARY

All of the angular correlations obtained from $^{9}\text{Be}(d,p)^{10}\text{Be}$, $^{10}\text{B}(d,p)^{11}\text{B}$, and $^{24}\text{Mg}(d,p)^{25}\text{Mg}$ can be explained satisfactorily by comparison with theory. There is a strong indication that, when the angular distribution of the protons indicates strong stripping, the angular correlations can be compared with theory to yield useful information. Newns\textsuperscript{17} and Horowitz and Messiah\textsuperscript{26} showed that the presence of proton polarization could strongly influence angular correlation measurements in stripping reactions. The magnitude of the polarization and thus its importance in stripping reactions could not be calculated. However, Newns showed in an extreme case that an angular correlation could be made completely isotropic. Horowitz and Messiah showed, on the basis of a different model, that in extreme cases the correlation might not be symmetric about 90 degrees in the correlation angle,
and that the symmetry angle could be changed by as much as 20 degrees. Another result of the polarization calculations was that the correlation would no longer be necessarily isotropic in the azimuthal angle. This affords a means for detecting the presence of proton polarization. The angular correlation obtained from $^{9}Be(d,p)^{10}Be$ was not quite symmetric about 90 degrees in the correlation angle. This might indicate some polarization or it might simply be due to poor statistics. The angular correlation measurements carried out by Cohen, et al. in $^{9}Be(d,p)^{10}Be$, at a deuteron bombarding energy of 0.84 Mev, showed little agreement with the stripping correlation. This was reasonable since, at this low bombarding energy, the reaction was expected to proceed mainly by compound nucleus formation. The results from the $^{10}B(d,p)^{11}B$ reaction showed much better agreement with two of the theoretical correlations than with any others. The results from stripping did not agree with the results from the $^{7}Li(\alpha,\gamma)^{11}B$ reaction, however more work must be done in both of these reactions and in other reactions leading to $^{11}B$ before either can be rejected. The results from $^{24}Mg(d,p)^{25}Mg$ indicated that useful information could be obtained from $(d,p)$ reactions with targets of intermediate Z even when the deuteron bombarding energy was not above the Coulomb barrier. However, much more work must be done with target nuclei with Z as high and higher than Mg before any definite statement can be made. The angular correlation of the protons and gamma rays involving the first excited state of $^{29}Si$ was measured by Allen in the
reaction $^{28}\text{Si}(d,p)^{29}\text{Si}$, at a deuteron bombarding energy of eight or nine Mev. Reasonable agreement was obtained with theory. Thus, for all the work which has been done so far, the indications are that the measurements of angular correlations in stripping might yield useful information in the study of low lying level of nuclei.
APPENDICES
Appendix A

FORMULAS FOR CALCULATION OF (d, p) STRIPPING ANGULAR DISTRIBUTIONS

(A) Butler theory

The formula (equation 34 in reference three) given in Butler's article can be put into a form which is much more useful for numerical calculation. The general form of the modified equation is given below and the coefficients are evaluated for the special cases $l_n = 0, 1, 2$, and $3$. All energies are in the center of mass system. In general the best value to use for the nuclear radius parameter is: $r_0 = (1.7 + 1.32A^{1/3})10^{-13}$. The general form of the angular distribution equation is:

$$
\sigma(\theta_i) = G(\theta_i) \left| A \frac{r_s r_0}{\sqrt{2} \sigma_0} \int_{l_n} \frac{1}{l_n + \frac{1}{2}} \left( 2 \tau_0 \right) + B \int_{l_n} \frac{1}{l_n + \frac{1}{2}} \left( \frac{Z \tau_0}{\sqrt{2} \tau_0} \right) \right|^2
$$

$$
\int L_n(2 \tau_0) = \left( \frac{\pi}{2 \sigma_0} \right) \int_{l_n} \frac{1}{l_n + \frac{1}{2}} \left( 2 \tau_0 \right)
$$
Where:

$$A = \sum_{i=0}^{l_n} \frac{(l_n+i)!}{i!(l_m-i)!} \left\{ \frac{1}{(k_5 r_0)^i} + \frac{i-l_n}{(k_5 r_0)^{i+1}} \right\}$$

$$\beta = \sum_{i=0}^{l_n} \frac{(l_m+i)!}{i!(l_m-i)!} \frac{1}{2^i} \left( \frac{1}{k_5 r_0} \right)^i$$

For $l_n = 0$, 1, 2, and 3 the values of $A$ and $B$ are:

$l_n = 0$

$$A = 1 \quad ; \quad B = 1$$

$l_n = 1$

$$A = 1 \quad ; \quad B = 1 + \frac{1}{k_5 r_0}$$

$l_n = 2$

$$A = 1 + \frac{1}{k_5 r_0} \quad ; \quad \beta = 1 + \frac{3}{k_5 r_0} + \frac{3}{(k_5 r_0)^2}$$

$l_n = 3$

$$A = 1 + \frac{3}{k_5 r_0} + \frac{3}{(k_5 r_0)^2} \quad ; \quad B = 1 + \frac{6}{k_5 r_0} + \frac{15}{k_5 r_0} + \frac{15}{(k_5 r_0)^2}$$
where:

\[ \zeta(\Theta_p) = \left( \frac{1}{k^2 + a^2} - \frac{1}{k^2 + (a + b)^2} \right)^2 \]

\[ k = \frac{1}{4} k_d^2 + k_p^2 - k_d k_p \cos \Theta_p \]

\[ Z = k_d^2 + \left( \frac{m_0}{m_{0+1}} \right)^2 k_p^2 - 2 \left( \frac{m_0}{m_{0+1}} \right) k_d k_p \cos \Theta_p \]

\[ k_d = \sqrt{\frac{2m_d}{\hbar^2}} E_d \quad k_d = 9.52 \times 10^{24} \text{E}_d \text{(mev)} \text{cm}^{-2} \]

\[ k_p = \sqrt{\frac{2m_p}{\hbar^2}} E_p \quad k_p = 4.82 \times 10^{24} \text{E}_p \text{(mev)} \text{cm}^{-2} \]

\[ k_s = \sqrt{\frac{2m_n}{\hbar^2}} E_m \quad k_s = 4.83 \times 10^{24} \text{E}_m \text{(mev)} \text{cm}^{-2} \]

\[ a^2 = 5.19 \times 10^{-4} \text{cm}^{-2} \quad (a + b)^2 = 269.0 \times 10^{24} \text{cm}^{-2} \]
and:

\( N_0 = \text{mass number of target nucleus} \)

\( m_p = \text{mass of proton} \)

\( m_d = \text{mass of deuteron} \)

\( m_n = \text{mass of neutron} \)

\( E_d = \text{kinetic energy of deuteron} \)

\( E_p = \text{kinetic energy of proton} \)

\( E_n = \text{kinetic energy of absorbed neutron} = E_d - E_p - 2.236 \text{ mev} \)

(B) The theory of Bhatia et al. yields a result which, except for constant multiplicative factors, is identical to the first term in Butler's equation. Then, dropping constant factors, the result is:

\[
\sigma(\theta_p) = G(\theta_p) \left| \frac{1}{\sqrt{2\pi}r_0} \int_{\theta_0,\theta_0} (Zr_0) \right|^2
\]

All symbols here have the same meaning as in section (A), except that the value of \( r_0 \) used in the Bhatia formula should be:

\( r_0 = (2.7 + 1.22A^{1/3}) \times 10^{-13} \text{ cm} \).
Angular Distributions (Butler Theory)

\[ \sigma(\theta_p) \]

Relative Scale

\[ \ell = 1 \]
\[ \ell = 0 \]
\[ \ell = 2 \]
\[ \ell = 3 \]

\[ E_d = 3.50 \text{ Mev} \]
\[ Q = 2.00 \text{ Mev} \]
\[ \rho = 5.3 \times 10^{-13} \text{ cm} \]

Fig. 21
Appendix B

ANGULAR CORRELATION FUNCTIONS FOR (d,p) STRIPPING REACTIONS

(A) The correlation function for single contributing \( j_{\text{max}} \) of the channel spin \( (s) \), the neutron orbital momentum \( l_n \), and the gamma ray multipolarity \( (l) \) is given by:

\[
W(\theta) = \sum_{l=0}^{j_{\text{max}}} \frac{2 l_n (l_n + 1)}{2 l_n (l_n + 1) - \delta(l + 1)} F_l (l_n S J_i) F_l (L J_2 J_i) P_l (\cos \theta)
\]

where:

- \( J_1 \) = angular momentum of intermediate state
- \( J_2 \) = angular momentum of final state

If the gamma ray transition involves a mixture of \( l \) and \( l + 1 \) pole radiation then the correlation is given by:

\[
W(\theta) = W_1 (\theta) + 2 J W_2 (\theta) + J^2 W_3 (\theta)
\]

where:

\[
W_1 (\theta) = \sum_{l=0}^{j_{\text{max}}} \frac{2 l_n (l_n + 1)}{2 l_n (l_n + 1) - \delta(l + 1)} F_l (l_n S J_i) F_l (L J_2 J_i) P_l (\cos \theta)
\]
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<th>$J_1$</th>
<th>$J_2$</th>
<th>$W(\theta)$ for D</th>
<th>$W(\theta)$ for Q</th>
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<td>1</td>
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<td>3/2</td>
<td>1</td>
<td>1</td>
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<td>$1 + x^2$</td>
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<td>7/2</td>
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<tr>
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<td>1/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/2</td>
<td>3/2</td>
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<td>7/2</td>
<td>$1 + 0.47x^2$</td>
<td>$1 + 1.50x^2 - 2.25x^4$</td>
</tr>
</tbody>
</table>

$x = \cos^2 \theta$, D = dipole radiation, Q = quadrupole radiation

$J_1$ = spin of intermediate state

$J_2$ = spin of final state

ANGULAR CORRELATION FUNCTIONS FOR SPIN ZERO TARGET NUCLEI

TABLE II
\[ B_0^9 \]
\[ S = 1, \quad b = 1, \quad j = 2, \quad h = 2, \quad I = 0 \]
\[ \frac{1}{1 + c^2 \theta} \]
\[ S = 2, \quad b = 1, \quad j = 2, \quad h = 2, \quad I = 0 \]
\[ \frac{1}{1 - 0.6 c^2 \theta} \]
\[ W_2(\theta) = (-1)^{J_1-J_2} \left( \frac{2J_1+1}{2J_1} \right)^{1/2} X \]

\[
\sum_{J_2 \geq J_1} \frac{2L_n(L_n + 1)}{2L_n(L_n + 1) - J_2(J_2 + 1)} G_J(LL'J_2J_1) F_J(L_n S J_1) P_{_0} (c_a \theta) \]

\[ W_3(\theta) = \sum_{J \geq 0} \frac{2L_n(L_n + 1)}{2L_n(L_n + 1) - J(J + 1)} F_J(L_n S J_1) F_J(L'L_2 J_1) P_{_0} (c_a \theta) \]

and \( \delta^2 = \) relative intensity of the magnetic L pole and electric L+1 pole; \( L' = L + 1 \).

Correlation functions must be calculated for both the + and - signs for the interference term \( 2J_1 W_2(\theta) \) since the proper sign is not known theoretically except for some specific nuclear model. The functions \( F_{_0} \) and \( G_{_0} \) are tabulated in the review article of Biedenharn and Rose and are in the proper form for that tabulation.
M1 - E2 Mixture in (d, p)^2
Angular Correlation

\[ X = \text{Fractional Admixture of E2} \]

\[ A = \frac{W(0^\circ) - W(90^\circ)}{W(90^\circ)} \]

\[ J_0 = 3, \quad j_1 = \frac{5}{2}, \quad j_2 = \frac{3}{2} \]

\[ l_n = 1 \]

\[ S^+ \]

\[ S^- \]
Appendix C

FINITE SOLID ANGLE CORRECTION IN CORRELATION MEASUREMENTS

The correction for the large solid angle necessary in angular correlation measurements has been treated by many authors.\textsuperscript{36,37,38} The results below were taken from Rose.

The results of Rose are rigorous for cylindrical detectors with axes directed radially from the source and account for the less than one hundred per cent efficiency of the gamma detector. However, Klema and McGowan applied Rose's results to the case of a gamma-gamma correlation using essentially the same geometry as was used in the stripping correlations reported here. The results of Klema and McGowan indicated, for the geometry used here, that a good approximation would be obtained if the detectors were considered one hundred per cent efficient. This approximation makes the calculation of the correction much easier, and the formulae given below incorporate
The correlation function for a given process is given by:

\[ W(\theta) = \sum_{j=0}^{\text{max} \theta} \alpha_j \rho_j (\text{c.o.d.}) \]

where the correlation is normalized so that: \( \alpha_1 = 1 \). Then, after correction is made for the solid angle, the formula is modified to:

\[ W(\theta) = \sum_{j=0}^{\text{max} \theta} (Q_1 j) (Q_2) \alpha_j \rho_j (\text{c.o.d.}) \]

The subscripts 1 and 2 refer to the two detectors.

The attenuation coefficients \( Q_j \) are given by:

\[ Q_j = \frac{P_{j-1}(x) - x P_j(x)}{(j+1)(1-x)} \]

where:

\[ \gamma = \text{half plane angle subtended at front face of crystal} \]

\[ x = \cos \gamma; \quad q_0 = 1 \]

and the \( P_j \) are the Legendre polynomials of order \( \gamma \). For the angular correlation measurements in this thesis the values of \( \gamma \) are: \( \gamma_1 = 11 \) degrees, and \( \gamma_2 = 18 \) degrees. For this geometry the values of the attenuation coefficients are:

\[ (Q_0)_1 = (Q_0)_2 = 1 \]

\[ (Q_3)_1 = 0.973; \quad (Q_3)_2 = 0.928 \]

\[ (Q_4)_1 = 0.907; \quad (Q_4)_2 = 0.772 \]

So for terms up to \( P_4(\cos \theta) \), the corrected correlation function is:

\[ W(\theta) = 1 + 0.901 \alpha_2 P_2(\text{c.o.d.}) + 0.70 \alpha_4 P_4(\text{c.o.d.}) + \ldots \]
The correction is fairly small for correlation functions for which $\gamma_{\max} = 2$, but becomes quite large for higher order terms. All of the angular correlations involved in this thesis have $\gamma_{\max} = 2$ so the correction is small, and in fact is within the statistical error in all cases.
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