7 The Many-Nucleon Problem

7.1 Phenomenology of Preequilibrium Nuclear Reactions

The exciton model of preequilibrium nuclear reactions provides a simple way to describe the continuum energy and angular distributions of particles emitted during energy equilibration in light particle induced reactions at incident energies of around 14 to 200 MeV. Because of its simplicity, its physical transparency, its utility, and its adaptability, the exciton model continues to be used in spite of the development of more microscopic and quantum mechanical models.

The TUNL code system, PRECO, has been used around the world (either alone or as modules in Hauser-Feshbach codes) in applied projects, in support of Radioactive Ion Beam studies, and in other basic physics research. Model and code development uses relatively simple physical concepts and appeals to available data to direct choices between alternative formulations and to provide values for key model parameters that cannot be obtained from independent sources.

The model, code and global input set are being refined and benchmarked against a broad range of experimental energy spectra from the literature to allow the reliable calculation of unmeasured or unmeasureable reaction spectra without the use of adjustable parameters. The present focus is on reactions with nucleons in the entrance and exit channels. Work in recent years has focused on incident energies up to around 30 MeV where the data are most sensitive to effects such as pairing and shell structure. In addition, a broader energy range has been used to study surface localization of the initial target-projectile interaction. Current work has involved verifying and refining the results on surface and collective effects in \( NN \) reactions, adding the excitation of giant resonance states in the calculation of inelastic scattering, and preparing for a new formal release of the code.

7.1.1 Surface Effects and Excitation of Strong Collective States

C. Kalbach Walker

The 1998-1999 TUNL progress report [Kal99] describes preliminary results on two related studies designed to clarify the issue of simultaneously reproducing the continuum energy spectra in the four \( NN \) reaction channels. The main emphasis was on the surface localization of the initial target-projectile interaction, comparing results for incident neutrons and incident protons. Results indicated more surface localization for incident neutrons. To aid in that study, a simple model for the excitation of strong spectroscopic collective states was added to the PRECO code system, and a provisional table of collective
state parameters for all the target nuclides in the project database was assembled. Early work this year involved checking and refining those results still using only a subset of the project database. This resulted in only minor changes to individual parameter values. Then, a set of model calculations was run and compared with the full database of energy spectra from the literature. This confirmed the utility of the work on collective states and surface effects but also indicated that additional strength was needed in many inelastic scattering spectra, particularly those for which giant resonance state excitation should contribute most strongly. This work has been written up and accepted for publication in Physical Review C.


7.1.2 Inclusion of Giant Resonance State Excitation

C. Kalbach Walker

Based on the results in Section 7.1.1, the excitation of isoscalar giant resonance (GR) states was included in the calculations for inelastic scattering. The collective state excitation model used for the spectroscopic collective states was also employed for the giant resonance states. For each type of GR excitation, systematic excitation energies, deformation parameters, and resonance widths were obtained from results in two review articles [Ber81, vdW91]. The deformation parameters are based on the energy-weighted sum rule (EWSR) for the appropriate \( \ell \)-value after subtracting contributions from the spectroscopic collective states (SCS). The EWSRs were evaluated for a spherical nucleus of constant density. Thus, the inclusion of GR excitations introduced no new free parameters into the calculations. The GR states considered and their parameter values are given in Table 7.1-1. The low-energy octopole (LEOR), giant quadrupole (GQR) and high-energy octopole (HEOR) resonances are included in subsequent model calculations, while the giant monopole resonance (GMR) is too weak to make a significant contribution and has been ignored.

<table>
<thead>
<tr>
<th>GR State</th>
<th>Transitions</th>
<th>Energy (MeV)</th>
<th>% EWSR used</th>
<th>Full EWSR (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEOR</td>
<td>1(h\omega) 3−</td>
<td>31A^{−1/3}</td>
<td>30% − SCS</td>
<td>1208A^{−5/3}</td>
<td>5</td>
</tr>
<tr>
<td>GQR</td>
<td>2(h\omega) 2+</td>
<td>65A^{−1/3}</td>
<td>100% − SCS</td>
<td>575A^{−5/3}</td>
<td>85A^{−2/3}</td>
</tr>
<tr>
<td>GMR</td>
<td>0+</td>
<td>18.7 − A/40</td>
<td>100%</td>
<td>23.4^{−5/3}</td>
<td>3</td>
</tr>
<tr>
<td>HEOR</td>
<td>3(h\omega) 3−</td>
<td>115A^{−1/3}</td>
<td>70%</td>
<td>1208A^{−5/3}</td>
<td>9.3 − A/48</td>
</tr>
</tbody>
</table>

Table 7.1–1: Summary of the parameters for the giant resonance states whose excitation is considered for inclusion in exciton-model calculations.
A new set of calculations, this time with the inclusion of the giant resonance states, was performed and compared with the full project database of roughly 150 spectra. Including GR excitations makes a small but helpful improvement in the agreement between calculation and experiment. As a result, the exciton model and its associated reaction models as developed and embodied in the code PRECO-2000 are now able to successfully describe the energy spectra in all four \( NN \) reaction channels for a wide variety of targets and incident energies while using a single, consistent set of model input. In particular the calculations can account for the relative emission intensities in these four channels. This is a major achievement for any pre-equilibrium model. Sample spectra for inelastic scattering on heavy deformed targets are shown in Figure 7.1–1. These spectra have consistently been some of the most difficult spectra to reproduce, and most of the other spectra in the project database show significantly better agreement. The figure shows the importance of surface effects and both spectroscopic and GR collective excitations in achieving the current level of agreement. This work has been written up along with the work of Section 7.1.1 and has been accepted for publication in Physical Review C. The preprint contains many comparisons between model calculations and the experimental spectra.

![Figure 7.1–1: Effect of recent changes in the model calculations on their agreement with experiment for two of the more difficult spectra to reproduce. The points and bars show the data [Tak92, Bab94, Mar89]. The lower dashed curves show the results of previous calculations, while the upper dashed curves include enhanced surface localization of the initial interaction for incident neutrons and the excitation of spectroscopic collective states. The solid curves also include the excitation of giant resonance states whose contributions are shown separately as dotted curves.](image)

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7.1.3 Users Manual for PRECO-2000

C. Kalbach Walker

A new formal release of the PRECO code system is overdue and has been requested by potential users. Thus, following completion of the work on surface and collective effects, the process of developing a revised users manual was begun. The last formal users manual was made available in 1992 so that eight years worth of physics studies and code improvements need to be pulled together and summarized.

The current users manual, like its predecessors, will contain a review of all the applicable physics, a description of the code structure, an explanation of the required input and its various options, a summary of the available output options, and a list of important variables used in the code. It will also contain a description of the recommended global input set, much of which is contained as default values for the various input parameters. Finally, a FORTRAN listing of the code as well as sample input and output files will be provided. A first draft of the manual is nearing completion.
7.2 Nuclear Data Evaluations

7.2.1 Data Evaluation Activities

J.L. Godwin, J.H. Kelley, C. Nesaraja, J.E. Purcell, G. Sheu, D.R. Tilley, and H.R. Weller

The Nuclear Data Evaluation Group at TUNL is a part of the United States Nuclear Data Network and the International Nuclear Structure and Decay Data network (NSDD), and is responsible for evaluations in the mass range $A = 3$–$20$. The TUNL group published reviews for $A = 3$ and $A = 4$ in 1987 and 1992, respectively, and was assigned the additional responsibility of continuing evaluation activities for $A = 5$–$20$ following the retirement of F. Ajzenberg-Selove (Univ. of Pennsylvania) in 1990. Since that time, TUNL has published reviews for $A = 16$–$17$ in 1993, $A = 18$–$19$ in 1995, and $A = 20$ in 1998. A review of the $A = 5$–$7$ nuclides, being performed in collaboration with G.M. Hale of Los Alamos National Laboratory and H.M. Hofmann of the Universität Erlangen-Nürnberg, is presently underway. Preliminary versions of $A = 5$, $A = 6$, and $A = 7$ were issued in February 1998, January 2000 and May 2000, respectively. A review paper, “Energy Levels of Light Nuclei, $A = 5$–$7$” is being prepared for submission to Nuclear Physics A. In late 1998, the TUNL group was asked by NSDD to provide minimal coverage of the $A = 2$ nuclides as well. This assignment entails only the production of ENSDF files; no “Energy Levels of Light Nuclei” publication is planned for $A = 2$.

Table 7.2–1: Current publication status of $A = 3$–$20$ Evaluations.

<table>
<thead>
<tr>
<th>Nuclear Mass</th>
<th>Publication</th>
<th>Institution</th>
</tr>
</thead>
</table>

1 Co-authored with G.M. Hale, LANL.
2 F. Ajzenberg-Selove, University of Pennsylvania.
3 Co-authored with S. Raman, ORNL.

1 Georgia State University, Atlanta, GA.
Table 7.2–2: Evaluations in Progress ³.

<table>
<thead>
<tr>
<th>Nuclear Mass</th>
<th>Publication</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A = 5</td>
<td>Preliminary version mailed February 1998</td>
<td>TUNL ¹</td>
</tr>
<tr>
<td>A = 6</td>
<td>Preliminary version mailed January 2000</td>
<td>TUNL ²</td>
</tr>
<tr>
<td>A = 7</td>
<td>Preliminary version mailed May 2000</td>
<td>TUNL ²</td>
</tr>
</tbody>
</table>

¹ Co-authored with G. M. Hale and C. M. Laymon.
² Co-authored with G. M. Hale and H. M. Hofmann.

7.2.2 Evaluated Nuclear Structure and Data Files - ENSDF

Along with producing evaluations of the A = 3–20 nuclei in the “Energy Levels of Light Nuclei” series that is published in Nuclear Physics A, TUNL has been charged with providing the corresponding updates to the ENSDF database that is maintained at the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory. ENSDF files are intended to contain concise nuclear structure information such as tables of adopted level energies and tables of properties for levels that have been observed in various nuclear reactions and decays. Prior to TUNL’s assumption of these responsibilities, ENSDF files for this mass range were produced by M. Martín (ORNL) and M. Bhat (BNL) in an abbreviated form which contained only adopted levels and gammas, and β-decay information. TUNL now prepares ENSDF files that contain adopted levels and gammas, as well as β-decay and reaction information.

In the mass range from A = 2–20, updated and/or revised ENSDF files that are based on the most recent “Energy Levels of Light Nuclei” have been prepared at TUNL for A = 2–13 and A = 16–20. Recently, ENSDF files for A = 11–13 have been updated to reflect the most recent reviews.

Table 7.2–3: Current publication status of ENSDF evaluations.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Content</th>
<th>Publication Center</th>
<th>ENSDF Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Levels</td>
<td>Unpublished</td>
<td>TUNL</td>
</tr>
<tr>
<td>3–5</td>
<td>Levels</td>
<td>TUNL</td>
<td>TUNL</td>
</tr>
<tr>
<td>6</td>
<td>Levels &amp; Gammas,Reactions</td>
<td>TUNL</td>
<td>TUNL</td>
</tr>
<tr>
<td>7–13</td>
<td>Levels &amp; Gammas,Reactions</td>
<td>Penn</td>
<td>TUNL</td>
</tr>
<tr>
<td>14–15</td>
<td>Levels &amp; Gammas</td>
<td>Penn</td>
<td>ORNL</td>
</tr>
<tr>
<td>16–20</td>
<td>Levels &amp; Gammas,Reactions</td>
<td>TUNL</td>
<td>TUNL</td>
</tr>
</tbody>
</table>
7.2.3 World Wide Web Services

TUNL continues to develop new WWW services for the nuclear science and applications communities. Currently, the following items are available:

- Update lists for $A = 5, 6, 7, 8, 9, 10, 11, 12$ nuclides, which provide brief descriptions of important research bearing on level information published since the last full evaluation. Lists for other nuclei are being prepared. References for the Update Lists are given for each nuclide with experimental and theoretical subdivisions for each, and include links to the NSR database. Links to the NSR database will either provide access to the full article and/or abstract usually in PDF, ASCII text, or HTML format, or access to an NSR citation page. Our intentions for the Update Lists are to provide to the nuclear community via our WWW page a continuously updated guide to important new work.

- Energy Level Diagrams in the style of Fay Ajzenberg-Selove for $A = 4-20$.

- Abridged versions of TUNL’s published evaluations for $A = 3-4$ (full), $A = 16-20$ (full), and $A = 5-7$ (preliminary) are now available online in PDF format. These PDF versions include hyperlinks for references and tables.

- An abridged version of Fay Ajzenberg-Selove’s $A = 5-15$ compilations are now available online in PDF format. These PDF versions now include hyperlinks for references and tables. Versions for $A = 5-12$ also include hyperlinks to its corresponding Update Lists. We are now in collaboration with Elsevier to provide PDF documents of all of FAS evaluations including years 1966–1987.

- A preliminary posting of our new HTML project is now online. HTML documents are provided for individual nuclides $4^n, 4^H, 4^6^H, 4^8^H, 4^{11}^H, 4^{11}^Li, 6^{10}Be, 12^{12}Be, 8^{12}B, 11^C, 13^C, 14^N, 12^O, 12^F$, and $12^Ne$. Posting of new nuclides will be continuous throughout the year. We hope to provide HTML documents for each nuclide found in the FAS and TUNL evaluations.

- Postscript ENSDAT output of the $A = 3-20$ ENSDF files.

- A short version ($A = 1–20$) of the Table of Isotopes, provided by the Berkeley Isotopes Project.

- Information about the status of the project and our publications.

- A brief but complete list that provides links to all of the available TUNL, FAS and preliminary evaluations, HTML documents, figures and Update Lists.

- Links to the National Nuclear Data Center and other useful sites, as well as to the online electronic journals we use most often are provided.
7.2.4 Evaluations of Thermonuclear Proton-Capture Reaction Rates for $^2$H, $^7$Li, $^9$Be, and $^{11}$B

J.H. Kelley, S.O. Nelson, H.R. Weller, and E.A. Wulf

In the time since the NACRE collaboration [Ang99] published their computation of hundreds of charged-particle reaction rates important in astrophysical models, the Radiative Capture group at TUNL has made several measurements of radiative proton-capture reaction cross sections and analyzing powers with proton beam energies below 100 keV. These measurements are important in extrapolating the total S factors for such reactions to the very low-energy ranges where these S factors cannot yet be directly measured. These low energies also constitute the energy range in which the bulk of stellar proton burning takes place in a real plasma.

We have added the new TUNL data to existing data for the calculation of reaction rates in a real plasma for four of the reactions studied by the Radiative-Capture group: $^4$He $^3$H, $^7$Li $^8$Be $^9$Be, $^{10}$B $^9$Be, and $^{12}$C $^{11}$B [Kel, Cec92, Seg65, All64]. Following [Ang99], we have generated tables of reaction rates by numerically integrating

$$N_A <\sigma v> = N_A \frac{(8/\pi)^{1/2}}{\mu^{1/2}(k_B T)^{3/2}} \int_0^\infty \sigma E e^{-E/k_B T} dE,$$

(7.1)

where $N_A$ is the Avogadro number, $\mu$ is the reduced mass of the system, $k_B$ is the Boltzmann constant, $T$ is the temperature, $\sigma$ is the cross section at the center-of-mass energy ($E$), and $v$ is the relative velocity of the nucleus and the proton. This integral gives reaction rates in units of cm$^3$ mol$^{-1}$ s$^{-1}$.

Using partial cross sections in Eq. 7.1, we have also treated capture to the ground and first few excited states separately. This provides production rates for the various $\gamma$ rays emitted by each reaction, which can be used to calculate the $\gamma$ spectrum inside the plasma. Detailed knowledge of this spectrum may prove useful in calculations of $a(\gamma x)b$ inverse reaction rates in stellar models in the future. For completeness, we generated analytical approximations to our reaction-rate tables, which may be more useful in numerical simulations. Using a rational interpolation fit (good to 5%) to the tabulated data, we cast the approximations into a standard form of $\text{Rate} = 10^{P_1/P_2}$, where the $P_i$ are polynomials of the form $P = C_0 + C_1 X + C_2 X^2 + ...$, and $X$ is $\log_{10}(T)$, the plasma temperature in billions of Kelvin. This standard form reduces the compiled information to a short table of coefficients and should be simple to incorporate into numerical codes.

Details about the particular differences in the new data sets, the techniques used for the calculation, and the tabulated reaction rates have been collected in a paper, which has been accepted for publication in Nuclear Physics A. The abstract is given below:

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1 Naval Research Lab/National Research Council, Washington, DC.
Recent measurements and analyses of proton induced radiative-capture reactions in the vicinity of $E_p = 100$ keV performed at the Triangle Universities Nuclear Laboratory are used to calculate the thermonuclear reaction rates of relevance in astrophysical plasmas for the reactions: $D(p,\gamma)^3\text{He}$, $^7\text{Li}(p,\gamma_0,1)^8\text{Be}$, $^9\text{Be}(p,\gamma_0,1,2,3)^{10}\text{B}$, and $^{11}\text{B}(p,\gamma_0,1)^{12}\text{C}$. Higher energy data from previous measurements were included when possible. The Maxwellian-averaged reaction rates, obtained using numerical integration techniques, are presented in tabular form as a function of temperature. Capture to the ground and excited states are treated separately, thus allowing the determination of inverse reaction rates for specified target states. The high temperature cut-offs of the reaction rate calculations are discussed. The results are compared to those presented in the recent NACRE compilation, where appropriate, and new analytical approximations for the total reaction rates are presented in a standard form.


[Kel] J. Kelley et al., To be published in Phys. Rev. C.


7.2.5 Proton-Induced Thermonuclear Reaction Rates for \( A = 20\text{-}40 \) Target Nuclei

C. Iliadis

Thermonuclear reactions are the source of energy for a variety of phenomena in the Universe. At the same time, they change the composition of the nuclear fuel. Observables such as luminosity or elemental abundances represent signatures that need to be explained by appropriate astrophysical models. Therefore, accurate model calculations require, among other input information, reliable estimates of thermonuclear reaction rates. The most widely used compilation of thermonuclear reaction rates involving low-mass target nuclei (\( A = 1\text{-}30 \)) was published by Fowler and collaborators [Cau88]. An updated compilation of reaction rates involving a similar range of target nuclei (\( A = 1\text{-}28 \)) was recently presented by [Ang99].

The present work was originally motivated by our interest in various hydrogen burning scenarios covering a large range of stellar temperatures (e.g., globular cluster red giants, novae, X-ray bursts and supernovae). In particular, observations of intermediate mass elements with \( A = 20\text{-}40 \) in some of these sites could provide important constraints on the astrophysical models. Consequently, it is desirable to extend the set of compiled proton-induced reaction rates to mass \( A = 40 \). In addition, at elevated stellar temperatures a large number of short-lived target nuclei will take part in hydrogen burning nucleosynthesis. However, only a small number of reaction rates involving unstable targets have been compiled by [Cau88, Ang99]. Thus, it is also desirable to extend the set of compiled proton-induced reaction rates to short-lived nuclei.

Our goal is the presentation of evaluated and compiled proton-induced reaction rates on stable and unstable target nuclei in the mass \( A = 20\text{-}40 \) region. For stable targets, our results can be regarded as an extension of previous work to the mass \( A = 40 \) range. Moreover, present and previous compilations overlap in the mass \( A = 20\text{-}30 \) range and it is interesting to compare the results and discuss differences. For unstable targets, proton-induced reaction rates have been published previously. However, the present work represents the first systematic compilation involving unstable target nuclei in the mass range \( A = 20\text{-}40 \).

A paper describing in detail our procedures and results is in preparation.
