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TOWARD A GLOBAL EXCITON MODEL FOR LIGHT PARTICLE REACTIONS[1]

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A version of the exciton model is being developed to allow the *a priori* calculation of double differential and angle integrated cross sections for light particle induced reactions at incident energies of 14 to 200 MeV. It includes shell structure, pairing, isospin conservation, and surface effects as well as multiple particle emission during equilibration. A preliminary set of model input for *(N,N)* reactions developed for systems in the $A = 90 - 100$ mass region at incident energies of 18 to 25 MeV is now being refined by comparisons with data from other mass/energy domains. So far other mass regions at 18 to 25 MeV and data for a range of masses at 90 MeV have been studied, and the basic set of input appears to be remarkably stable.

1. Introduction

For nearly thirty years the exciton model has been developed through the inclusion of additional physics, and it has shown itself to be remarkably successful at describing experimental results with a small number of model parameters. Thus, because of its simplicity, its physical transparency, its utility, and its adaptability, it continues to be used in spite of the development of more microscopic, quantum mechanical models such as the Feshbach-Kerman-Koonin (FKK) approach.

The long-range goal of the preequilibrium phenomenology program at T.U.N.L. is to develop the exciton model code PRECO-E with an associated set of global input to provide a fairly accurate tool for performing calculations of energy spectra and angular distributions for unmeasured or unmeasureable light particle reactions. Incident energies of 14 to 200 MeV on a full range of targets are being considered. This code system should be useful in the design of facilities for radioactive ion beam studies as well as accelerator driven transmutation projects for waste processing and/or tritium production. In addition, its development requires that areas of interesting physics be studied, described, and resolved. A number of physical phenomena are already included

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in the model, and their importantance in different mass/energy domains can now be determined. Ultimately, for maximum utility, the code PRECO-E is designed to be included in larger Hauser-Feshbach model codes such as GNASH at Los Alamos. Current work is focussed on *(nucleon,nucleon)* or (N,N) reactions, and this paper will describe recent progress in developing and testing both the model and its input.

2. Summary of the model in PRECO-E

Work on the exciton model and the code PRECO-E has aimed at improving their accuracy and range of validity while retaining as much as possible of the simplicity and transparency of the original model proposed by Jim Griffin in 1966 [1]. Additional physics has been included as needed to describe particular classes of data. As much input as possible, particularly for the description of the additional physics, is taken from independent sources, while appeals to available data have guided choices between alternative formulations and provided values for key model parameters.

In order to minimize the effects of possible experimental errors, an effort has been made to use large data sets containing spectra from different targets, incident energies and laboratories. Data from multiple reaction channels have been studied simultaneously to better constrain the model. In the current emphasis on (N,N) reactions, this means simultaneously reproducing the relative yields of spectra from the inelastic and exchange channels.

The exciton model code PRECO-E uses the two-component version of the model in which proton and neutron degrees of freedom are treated separately. This is important for the accurate treatment of effects such as shell structure. Since much of the physics related to these effects is contained in the particle-hole state densities, their development has been the goal of a great deal of work over the years.

The basic particle-hole state density is given by the two-component equi-spacing model (ESM) formula [2]. Corrections to this formula for collective pairing, shell structure, finite well depth effects (including surface peaking of the initial target-projectile interaction) and isospin as a quantum number have all been derived. Then similar corrections were applied to the transition state densities for the residual interactions causing nuclear energy equilibration. Now, at last, the pieces of the puzzle are coming together so that coherent calculations including all of these effects are possible. A recent paper [3] describes how the effects have been combined and gives the independent sources for the shell and pairing gaps and the isospin symmetry energies. Angular distributions and the effective well depth for the first target-projectile interaction are handled completely phenomenologically.

Other features which are not yet considered are (i) the angular momentum quantum number (important for calculating the relative yields of ground and isomeric states), (ii) linear momentum as a state descriptor (useful in a more rigorous treatment of angular distributions), (iii) collective excitations (important for the upper few MeV of inelastic spectra), (iv) gamma channels, and (v) emission of more than two particles from the system (included in Hauser-Feshbach codes).

The work of [3] looked at data in the Zr-Mo mass region at incident energies of 18 to 25 MeV. It verified the treatment of shell structure effects in PRECO-E and came up with a preliminary set of model input. In particular, this work showed that the overall normalizations of two key pairs of exciton model parameters have strongly coupled values. These parameters are the densities of single particle states, $g_{\pi 0}$ and $g_{\nu 0}$, for protons and neutrons in the ESM and the normalization constants for the mean square matrix elements for the residual interactions. The data were insensitive to the ratio $g_{\pi 0}/g_{\nu 0}$, which was assumed to be Z/N. Instead, the relative yields in the inelastic and exchange channels were influenced by $(M_{\pi\nu})^2/(M_{\pi\pi})^2$, and a value of about 0.6 was indicated. Here the subscripts π and ν refer to protons and neutrons. The form used for the matrix elements was [4]

$$(M_{\pi\nu})^2 = K_{\pi\nu} A^{-3} (20.9 + E/n)^{-3} \tag{1}$$

where E is the excitation energy and n is the total number of particle and hole degrees of freedom. With this form, the values of the coupled parameters were found to be $g_{\pi 0} = Z/(15\ \mathrm{MeV})$, $g_{\nu 0} = N/(15\ \mathrm{MeV})$, $K_{\pi\nu} = 3 \times 10^6\ \mathrm{MeV}^5$ and $K_{\pi\pi} = K_{\nu\nu} = 5 \times 10^6\ \mathrm{MeV}^5$. In addition it was found that isospin appears to be conserved during the preequilibrium phase of the reaction but at least partially mixed at equilibrium. In all cases an initial configuration of $1p0h$ was assumed so that the first preequilibrium particle emission occurs from the $2p1h$ states populated in the first target-projectile interaction. The same input worked well in the Rh-Ag mass region.

3. Recent developments

While the overall agreement with experiment in [3] was quite good, the possible need to revise the mathematical form of the M^2 to give more later stage preequilibrium emission was noted. A second question raised is the sensitivity to the assumed isospin symmetry energies. Finally, the preliminary input set must be tested for other target masses and incident energies. These questions are now being investigated.

3.1 Values of the isospin symmetry energies

Isospin symmetry energies are often derived from the Q-values of (p,n) reactions. These, however, contain the effects of shell structure and the pairing interaction which are included separately in the exciton model. Thus PRECO-E uses the volume and surface (V+S) symmetry energy terms from the semi-empirical mass formula so that

$$E_{\mathrm{sym}}(T,T_z) = \left(110\ \mathrm{MeV}\ A^{-1} - 133\ \mathrm{MeV}\ A^{-4/3}\right)(T^2 - T_z^2) \tag{2}$$

Since the Q-value derived energies generally fall between the V result or first term in eq. (2) and the full V+S result, the sensitivity to the choice between these options was studied. Results for 18 MeV (p,p') spectra show that using only the volume term yields too much cross section for the neutron rich targets and destroys the previous systematic agreement with experiment. Thus eq. (2) has been retained.

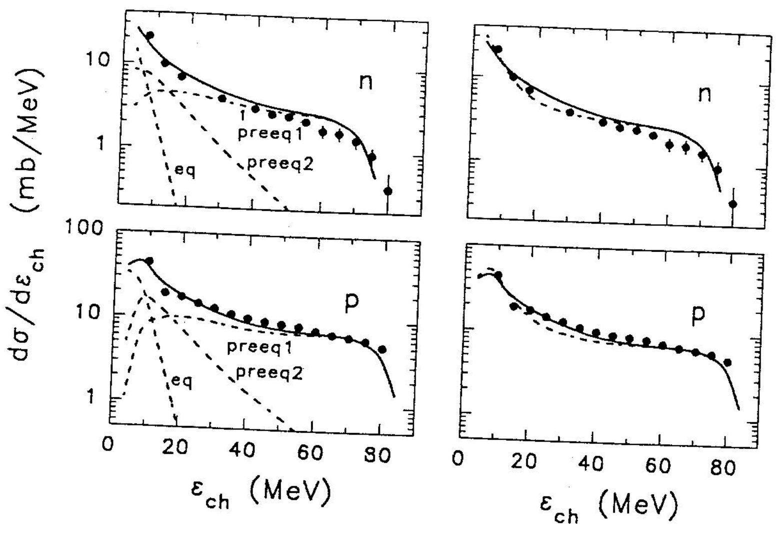

Fig. 1. Comparisons between calculation and experiment for proton induced reactions on ^{58}Ni at 90 MeV. The data are from [7, 8] and are shown as points. The solid curves are the PRECO-E results obtained with the modified matrix elements. On the left, the dashed curves show the importance of secondary preequilibrium emission while on the right they show the results with the original n-dependent mean square matrix elements.

3.2 Secondary preequilibrium particle emission

In order to extend the calculations to incident energies of 200 MeV, preequilibrium emission of more than one particle must be allowed. Fortunately, in the exciton model this is a straightforward process. All of the necessary equations and parameters are carried over directly from primary emission and all of the same physical effects are considered. Often for the hybrid model [5] and the FKK model [6] the approximation is made to consider only secondary preequilibrium emission following directly on primary emission. In the exciton model it is simple to also include secondary emission after one or more intervening two-body interactions. Currently, however, only nucleon channels are considered for secondary preequilibrium emission, even though primary emission of particles up through mass 4 is calculated. This is physically reasonable and greatly reduces calculation time. An example of the importance of multiple preequilibrium emission at 90 MeV is shown in Fig. 1.

3.3 Functional dependence of the mean-square matrix elements

Using multiple preequilibrium emission, a series of (p,xn) and (p,xp) spectra at 90 MeV were investigated to see if they, like the data in [3], indicated a need for more later stage preequilibrium emission. The same parameters were used as in [3] except that at 90 MeV isospin is assumed to be fully mixed rather than conserved during equilibration. Indeed, these calculations showed a deficit in the calculated cross sections in the intermediate portion of the spectra. To allow more later stage preequilibrium emission, the exciton number dependence in eq. (1) was eliminated by replacing n with 3, its value for the simplest emitting states. Because the interactions involved are both residual and effective, the matrix elements cannot be determined *a priori*. The original empirical dependence of M^2 involved only the quantities A and E [9], and removing the n-dependence essentially returns the matrix element to that form. It also slightly improves agreement with experiment for all of the cases studied in [3] as well as for the 90 MeV spectra. Thus the revised form was adopted. Fig. 1 shows an example of the sensitivity of the data to this change.

3.4 Exploring other mass/energy domains

Having included multiple preequilibrium emission and revised the mean square matrix elements, the next step is to explore other mass/energy domains beyond the $A = 90 - 120$ region at 18 to 25 MeV. This will test the applicability of the preliminary parameter set and show if any of these regions are sensitive to model options still left open. This is the area of continuing work. A large set of energy spectra for (N,N) reactions from the literature has been assembled. These are being converted to the center of mass system where necessary and drawn onto working plots. Calculations have so far been performed for four targets (eight spectra) at 90 MeV and for the full set of target masses at incident energies of 18 to 29 MeV. A total of about 15 additional spectra at 18 to 20 MeV and 25 spectra at 25 to 29 MeV have been studied. The agreement with experiment is comparable to that seen for the systems studied in [3].

Fig. 2 shows the level of agreement obtained for the four targets at 90 MeV when isospin is mixed. Assuming isospin conservation during equilibration raises the preequilibrium (p,n) cross section by differing amounts for the three lighter targets (the largest being a factor of 1.5 for ^{58}Ni) while leaving the (p,p') spectra almost unchanged. Thus the systematic agreement seen in Fig. 2 is destroyed. The 90 MeV results are insensitive to shell structure and pairing effects.

At 18 to 25 MeV, the lightest target considered was ^{27}Al, for which an (n,n') spectrum was calculated. This showed good agreement except in the region of the inelastic peak and the strong collective states.

The largest number of spectra was for the $A = 50 - 65$ region. Sample results for data from [10]-[15] are shown in Fig. 3. Spectra in this region are relatively insensitive to shell structure effects when the default degeneracies of the levels on either side of the shell gap are used, though shell structure is clearly needed for the ^{59}Co(p,n) spectrum at 25 MeV. If the default degeneracies are replaced by the corresponding shell model values, however, shell effects become much larger and the systematic agreement with experiment is destroyed. Isospin effects are relatively unimportant in this region except for the (p,n) reactions leading to $T_z = 0$ residual nuclei. There isospin conservation increases the preequilibrium yield by roughly a factor of 1.5. The ^{50}Cr spectrum is better fit when isospin is conserved while ^{54}Fe and ^{58}Ni prefer mixed isospin. However,

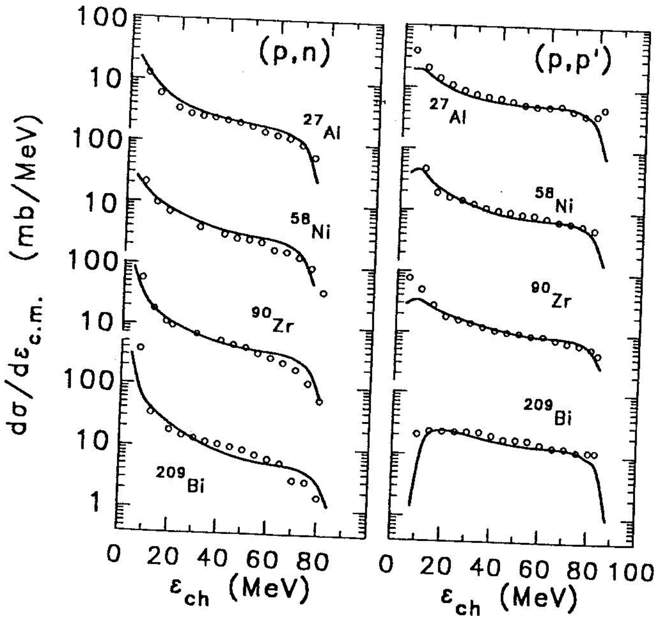

Fig. 2. Comparison between calculation and experiment for proton induced reactions at 90 MeV. The points show the data of [7, 8] for the indicated target nuclides while the curves give the PRECO-E results.

these are all weak channels. There is no real sensitivity to the choice between simple and collective pairing corrections.

For $A = 150 - 185$, between shell closures, five (p,n) spectra, five (p,p') spectra, and two (n,n') spectra have been calculated. All of the (p,n) and (p,p') spectra are well reproduced, while the (n,n') spectra tend to be underestimated by a factor of 1.5 to 2 and are discussed below.

In the lead region, only seven spectra were available. Four (p,n) spectra measured on different isotopes of lead at 25 MeV were all underestimated by about 15 to 20% in the preequilibrium region; a ^{209}Bi(n,n') spectrum at 18 MeV was underestimated by 20-25%; while ^{209}Bi(n,n') spectra at 20 and 26 MeV (taken at a different laboratory) were underestimated by about a factor of two just as in the previous mass region. Removing shell structure effects from the calculations makes agreement for the (p,n) spectra slightly worse while slightly improving agreement for the (n,n') spectra. Given the similarity of the 20 and 26 MeV (n,n') results with those in the $A = 150 - 185$ mass region, removing shell effects is not indicated. All of the lead region results were relatively insensitive to assumptions about isospin mixing.

The problem with the (n,n') spectra at 20 to 26 MeV was also noted in [3]. The spectra at those energies were taken [13, 16] at Ohio University and show an increasing discrepancy with calculation as the target mass increases. There is good agreement in the nickel region, but problems are already quite evident for ^{93}Nb. The 18 MeV spectra [15, 17] are from Tohoku University and probably show a similar but very much muted effect; agreeing with calculation up through $A = 93$ and showing a small discrepancy for ^{209}Bi. This suggests the possibility of a background problem in the data, though a problem in the calculations with increasing incident energy cannot be ruled out.

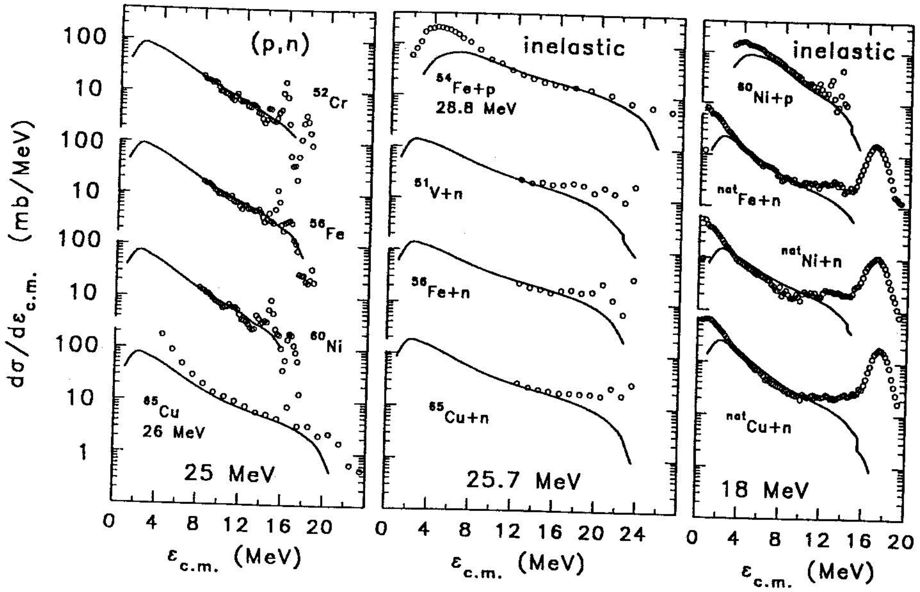

Fig. 3. Comparison between calculation and experiment for nucleons of the indicated incident energies incident on targets in the nickel mass region. The points show the data from [10]-[15] while the curves give the results of the PRECO-E calculations.

4. Conclusions and future directions

The work of [3] described exciton model calculations which include shell structure, pairing, isospin conservation, and finite well depth effects. A preliminary set of model input for (N,N) reactions was derived for the $A = 90 - 100$ region at 18-25 MeV and was shown to work well up to $A = 120$. In the present work, agreement with experiment for these systems was improved slightly by removing the exciton number dependence of the mean square matrix elements; a change which was also indicated by 90 MeV data. The same set of input has also been shown to work well in other mass regions at 18-25 MeV. With the inclusion of multiple preequilibrium emission, a range of targets at 90 MeV can also be reproduced if isospin is switched from being conserved to being mixed during equilibration. Thus the foundation has been laid for a truly global exciton model tool based on the author's code PRECO-E. The use of the default degeneracies for the levels on either side of the shell gap seems to be indicated. None of the systems studied is sensitive to the choice between simple and collective pairing corrections.

A number of open questions remain. The treatment of isospin for $T_z = 0$ nuclei needs to be reviewed, and the transition from conserved to mixed isospin as a function of incident energy should be explored. Additional (n, n') data need to be studied to decide whether there is a problem with background in the data, especially for heavy targets, or whether there is a deficiency in the calculations for these systems. Finally, the whole energy region from 90 to 200 MeV needs to be explored. A number of features of the model may change as the incident energy becomes comparable to the pion rest mass. These include the energy dependence of the mean square matrix elements, the ratio $(M_{\pi\nu})^2/(M_{\pi\pi})^2$, and, perhaps, the behavior of surface effects for the direct interaction. All of these areas are under investigation.

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