Coupled-Channel Calculations of the Energy Dependence of the (p, n) Charge-Exchange Reaction*

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Excitation functions of the $(p,n\tilde{p})$ reaction on ^{91}Zr, ^{119}Sn, ^{208}Pb, and ^{209}Bi are compared with the predictions of exact solutions of the coupled Lane equations, and it is found that the distorted-wave Born-approximation and coupled-channel predictions have essentially the same overall shape if the same optical and symmetry potentials are used. A linear energy dependence of the complex symmetry potential, suggested earlier from distorted-wave Born-approximation analyses, as well as modification of the neutron optical potential are required to describe the available data from threshold to ~45 MeV if global optical parameters are used.

Excitation functions of the $(p,n\tilde{p})$ reaction [a (p,n) charge-exchange reaction followed by proton $(\tilde{p})$ emission] for a wide range of target masses from threshold to 45 MeV have been reported[1] to show a characteristic energy dependence that cannot be described with conventional distorted-wave Born-approximation (DWBA) calculations unless the symmetry potential itself is given a complicated energy dependence. That is, it was found necessary, if the global optical-model parameters of Becchetti and Greenlees[2] (BG) were used to describe elastic scattering in proton and neutron channels, to adopt an energy dependence for the symmetry potential $\vec{t}\cdot\vec{T}V_1/A$ (as a function of incident proton energy E_p) of the form

$$V_1(r)\propto\{1.0+(1.0\pm0.2)\exp[(-0.25\pm0.05)|E_p-E_0|]\}[(120-E_p)f(r)+i(60-0.75E_p)g(r)]\ \text{MeV}, \quad (1)$$

where $f(r)$ is a Woods-Saxon form factor with the same geometry as the real part of the proton optical potential, and $g(r)$ is a Woods-Saxon derivative form factor with the same geometry as the surface imaginary part of the proton optical potential. The quantity E_0 is given by $E_0\simeq E_{th}+1.5$ MeV, where E_{th} is the (p,n) charge-exchange threshold energy.

In the energy region 10 MeV and greater above threshold the potential strengths of relation (1) become more realistic in that they become merely linearly dependent on the energy. From the fact that such a consistent, nucleus-independent functional form for $V_1(r)$ is required in DWBA, one might conclude that the DWBA is failing to account for a general energy dependence characteristic of the $(p,n\tilde{p})$ reaction mechanism, particularly near threshold, where there occurs a relatively rapid buildup of flux in the neutron channel. These observations suggest that exact solutions of the coupled Lane equations might be necessary to account satisfactorily for the observed $(p,n\tilde{p})$ excitation functions near threshold.

In this Letter we report the results of such coupled-channel (CC) calculations. We have found that DWBA and CC methods predict essentially the same overall shapes for the $(p,n\tilde{p})$ excitation functions when the same optical and symmetry potentials are used. Further, if one has confidence in the BG[2] neutron optical potential for $E_n>10$ MeV, one again concludes that the complex symmetry potential does have an energy dependence given roughly by the asymptotic form of Eq. (1):

$$V_1(r)\propto(120-E_p)f(r)+i(60-0.75E_p)g(r)\ \text{MeV}, \quad (2)$$

where $f(r)$ and $g(r)$ have been previously defined. It is also found that a neutron surface imaginary potential given (in the notation of BG) by $W_{SF}{}^n=3.1+0.575E_n-(60-0.75E_p)(N-Z)/4A$ MeV, for $E_n<12$ MeV, rather than that obtained from the BG analysis, can account satisfactorily for the detailed shape of the $(p,n\tilde{p})$ excitation function when the energy-dependent potentials of Eq. (2) are used as well.

The $(p,n\tilde{p})$ excitation function data, from threshold to about 45 MeV, for target nuclei ^{91}Zr, ^{119}Sn, ^{208}Pb, and ^{209}Bi are shown in the Fig. 1. The coupled-channel program JUPITOR II,[3] which provides the exact solution of the coupled Lane equations, was modified to allow for differing neutron and proton optical parameters and a complex symmetry potential. The initial coupled-channel calculations, like the DWBA calculations pre-

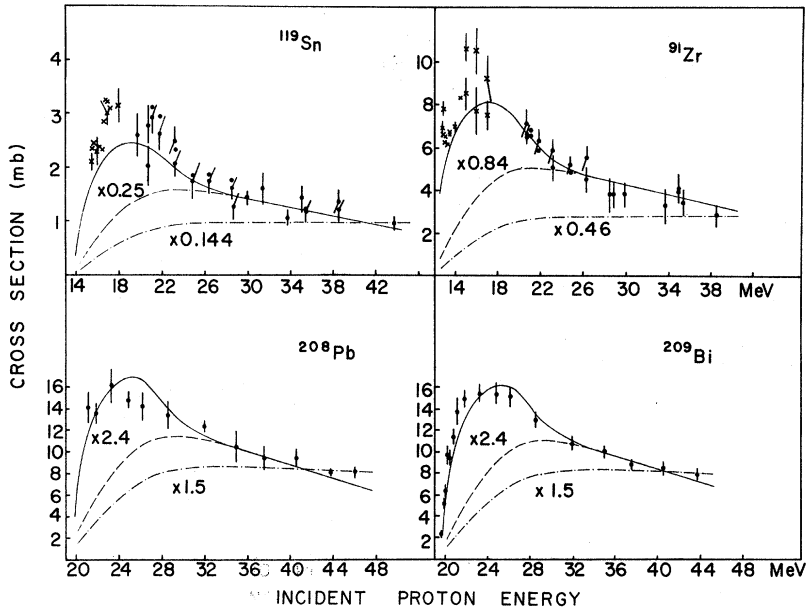

FIG. 1. $(p,n\tilde{p})$ excitation functions of ^{91}Zr, ^{119}Sn, ^{208}Pb, and ^{209}Bi. Solid circles, from Ref. 1; crosses, from Ref. 7. Dot-dashed curves, CC predictions using the BG optical-model potential with complex symmetry potential strengths 96 MeV (real volume) and 48 MeV (surface imaginary). Dashed lines, CC predictions using the linearly energy-dependent complex symmetry potential of Eq. (2), but keeping the isospin-independent BG parameters unchanged. Solid lines, CC predictions using the linearly energy-dependent complex symmetry potential of Eq. (2) and replacing the BG value of $W_{SF}{}^{n}=13.0-0.25E_n-12(N-Z)/A$ with a neutron imaginary surface strength $W_{SF}{}^{n}=3.1+0.57E_n-(15-0.19E_p)(N-Z)/A$ for $E_n<12$ MeV. The predictions are normalized to the data by the factors indicated in the figure. The upper factors apply to the solid and dashed curves, while the lower factors apply to the dot-dashed curves.

viously reported,[1] were performed using the BG neutron and proton optical parameters and the complex symmetry strengths 96 MeV (real volume) and 48 MeV (imaginary surface). The BG neutron and proton potentials differ slightly other than through the symmetry terms, and thus are not strictly in the spirit of the Lane equations. However, (1) the BG parameters are the only global set of parameters, known to the authors, adequate for the wide range of nuclei and energies under investigation; (2) all recent surveys[4,5] of (p,n) charge-exchange reactions, whether they employ DWBA or CC analyses, have in fact used these parameters and obtained good overall fits to the shapes of the (p,n) angular distributions; (3) no completely charge-independent nuclear potential parameters are available; and (4) we wish to make a comparison with previous DWBA calculations,[1] which used the BG parameters.

The results of the CC calculations using the unmodified BG parameters are shown as the dot-dashed lines in the figure. Note that the predictions are for the (p,n) charge-exchange cross sections, not the $(p,n\tilde{p})$ cross sections. However, these two excitation functions, both theoretically and experimentally, have the same *shapes*, since the proton decay $(\tilde{p})$ of the isobaric analog state (IAS) populated by the (p,n) reaction is independent of the incident proton energy. The magnitude difference between the two excitation functions is then presumably accounted for by the fact that the $(p,n\tilde{p})$ cross sections are reduced by the factor R_p, where R_p is the probability of proton $(\tilde{p})$ decay of the IAS. Since here we are mainly interested in the shapes of these excitation functions, the predictions are arbitrarily normalized to the data. The normalization factors are shown in the figure. It is by no means clear that the factors are closely related to R_p, since for ^{208}Pb and ^{209}Bi, these factors are greater than 1. However, one must not exclude the possibility that the rather wide $\tilde{p}$ peaks observed for ^{208}Pb and ^{209}Bi may themselves sit on structures of comparable widths. Hence, background subtraction could overestimate the area under the $\tilde{p}$ peaks for ^{208}Pb and ^{209}Bi by a factor of 1.5 to 2.0. This would not affect the conclusions of

the present study.

The next set of CC calculations considered were those for the asymptotic, linearly energy-dependent complex symmetry potential given by Eq. (2). The BG neutron and proton optical potentials were used, except that the BG symmetry potentials were replaced by those derived from Eq. (2). These predictions are shown as the dashed lines in the figure. As was the case for the DWBA, the energy dependence of the $(p,n\tilde{p})$ excitation functions is well reproduced for energies 10 MeV and greater above threshold. The DWBA predictions are not shown because they are essentially identical to the CC results. The cross sections were normalized to fit the data; the factors used are shown in the figure. The rapid rise and broad maximum near threshold is no better reproduced with these CC calculations than with DWBA, which suggests that charge exchange coupling is not responsible for the discrepancy.

There are a number of experiments, including measurements of the neutron strength function,[6] as well as earlier $(p,n\tilde{p})$ studies rather near threshold,[7] which suggest that near zero neutron energy an imaginary surface strength $W_{SF}{}^{n}$ of between 3 and 5 MeV and an imaginary volume strength $W_{V}{}^{n}$ of 0 are needed to describe the available strength function and total neutron cross-section data. However, the BG neutron parameters give $W_{SF}{}^{n} \simeq 10-12$ MeV at $E_n = 0$ over the same mass range. Clearly, the smaller strength for $W_{SF}{}^{n}$ would cause a much more rapid rise at threshold for the predictions for the (p,n) charge-exchange reaction, since the total cross section is roughly proportional to $1/W_{SF}{}^{n}$. Although the BG proton optical parameters may be very reliable, the neutron parameters were derived from data substantially inferior to the proton data. Further, at neutron energies below 10 MeV, important compound elastic corrections of considerable ambiguity had to be included in the BG analysis. Hence, it is now entirely unexpected that the *neutron* parameters below $E_n = 10$ MeV may require modification. By extrapolating the neutron imaginary surface strength between values of 3–4 MeV for $E_n = 0$ and the BG value for $E_n > 10$ MeV, fits for the $(p,n\tilde{p})$ excitation function data were obtained, using the BG optical potentials, except that $W_{SF}{}^{n} = 3.1 + 0.575E_n - (60 - 0.75E_p)(N-Z)/4A$ for $E_n < 12$ MeV, when the energy-dependent complex symmetry potential of Eq. (2) was used as well. The results of these CC calculations are shown as the solid lines in the figure. It is seen for all four nuclei that the predictions reproduce the shape of the experimental $(p,n\tilde{p})$ excitation functions.

In conclusion we submit that, if the BG optical-model parameters are adequate for $E_n > 12$ MeV, the experimental data for the $(p,n\tilde{p})$ excitation functions for a variety of nuclei from threshold to 45 MeV strongly support a linearly energy-dependent complex symmetry potential, as in Eq. (2). Our analysis also suggests that for $E_n < 12$ MeV the BG neutron optical potentials require modification and that a new study of the neutron parameters in this energy region needs to be considered.

Since this paper was written, results of a very extensive analysis of cross sections for neutron-induced reactions and scattering on lead isotopes have become available.[8] In their detailed analysis of the data, Fu and Perey[8] obtain an optical potential almost identical, except for choice of geometry, to that used here. Their potential fits neutron data from threshold to 14 MeV.

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