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Theory of the (n,p) reaction on ^{90}Zr

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A theoretical study of the ^{90}Zr(n,p) reaction is performed at an incident energy of 200 MeV. The forward angle ^{90}Zr(n,p) spectra are calculated within a microscopic model using random phase approximation transition densities for the description of the nuclear excited states. The calculated spectra are compared to those published previously by Klein, Love, and Auerbach.

The (n,p) reaction at intermediate energies is one of the best probes for studying the spin-isospin degrees of freedom of the nucleus in the τ_+ channel. Recently a new (n,p) facility was installed at TRIUMF,[1] and preliminary (n,p) experiments have been reported.[1,2] One of the major aims of these experiments is to solve the problem of the "missing" Gamow-Teller (GT) strength observed in (p,n) reactions.[3] In this connection the ^{90}Zr(n,p) reaction is of great interest for several reasons. Firstly, detailed experimental results are already available for the ^{90}Zr(p,n) reaction. Secondly, the measured ^{90}Zr(p,n) data at $E=200$ MeV have been thoroughly analyzed within microscopic models by several groups.[4,5] These analyses indicate that a large fraction of the so-called "missing" GT strength might be hidden in the background below and beyond the giant GT states. In this situation the ^{90}Zr(n,p) measurements are of great importance since they might help to solve this question of the "missing" GT strength in the following sense. By measuring both the zero-degree (p,n) and (n,p) spectra at the same incident energy, i.e., with the same hadronic transition operator, one can subtract the (n,p) from the (p,n) data. The remaining cross section should then be proportional to $3(N-Z)$ if the Ikeda-Fujii sum rule[6] for GT transitions is valid. This subtraction method has, of course, some uncertainties because the 0° spectra contain not only the GT cross section but also a background component. The latter is different for (p,n) and (n,p) in cases when the target nucleus possesses a neutron excess. Therefore one needs microscopic cross section calculations for the (p,n) and (n,p) spectra to assess the accuracy of this subtraction method.

In this paper we present such microscopic calculations for the ^{90}Zr(n,p) reaction at $E=200$ MeV. This reaction is presently being studied experimentally at TRIUMF.[2]

The (n,p) cross section calculations reported here were performed in a similar way as those published earlier for the ^{90}Zr(p,n) (Ref. 5) and the ^{90}Zr($\vec{p},\vec{p}\,'$) (Ref. 7) reactions. The ^{90}Zr(n,p) spectra were calculated within the antisymmetrized distorted wave impulse approximation (DWIA) using the free nucleon-nucleon t matrix in the parametrization of Franey and Love[8] for the effective projectile-target nucleon interaction. The energy-dependent optical potential of Schwandt *et al.*[9] was employed for the evaluation of the distorted waves in the incident and exit channels. The wave functions for the nuclear excited states were generated from microscopic random phase approximation (RPA) calculations.[5] The RPA model space included all $\leq 4\hbar\omega$ excitations. The residual interaction was taken from Ref. 5.

For all the RPA discrete final nucleus states n we first calculated the differential cross sections $d\sigma_n/d\Omega$. All states with multipolarities $J^\pi \leq 3^+$ were considered. From the discrete cross sections we generated continuous spectra by folding them into an asymmetric Breit-Wigner function as described in detail in Ref. 10. The widths used in the folding procedure were either derived from the imaginary part of the empirical nucleon-nucleus optical potential[11] or taken as free parameters.

In Fig. 1 we show the calculated ^{90}Zr(n,p) spectra at three different scattering angles θ. For each angle two different curves are shown which differ by the choice of widths used in spreading the discrete cross sections. The dashed curves were obtained with widths derived from the

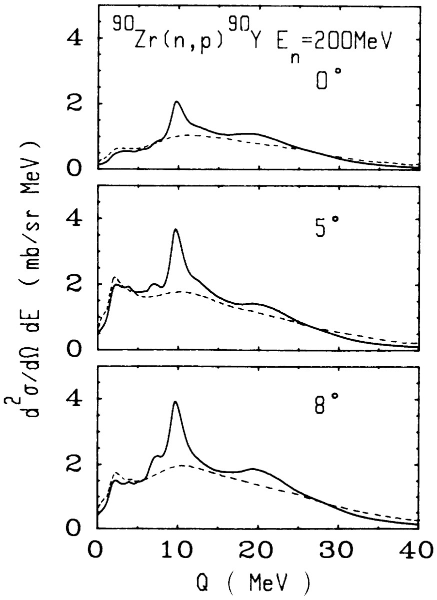

FIG. 1. Calculated ^{90}Zr(n,p) spectra at different angles θ. The dashed lines show the results of our model with the widths derived from the imaginary part of the empirical optical potential (Ref. 11) (see the text). The solid lines show the results obtained by using smaller widths than those of the dashed lines.

energy-dependent empirical optical potential of Rapaport *et al.*[11] The widths varied between 1 and 15 MeV depending on the excitation energies of the particular states under consideration. The full curves were obtained by using smaller widths which were nearly half (1–8 MeV) of that mentioned above. It can be noticed that the spectra differ from each other mainly in the 10 MeV excitation energy region. Here the full curves show a prominent peak which is due to a collective $J^\pi=2^-$ state. This peak does not appear in the dashed curves since the width used for the spreading of the 2^- strength in this case is much larger (8 MeV) than that used in creating the full curves (2 MeV). We mention that the calculated spectra obtained with the small spreading widths (full curves) are very similar to those calculated by Klein, Love, and Auerbach.[12] They performed continuum RPA (Ref. 13) calculations for the nuclear excited states and calculated the (n,p) cross sections in a similar manner as ours.

In Table I we compare our calculated energy integrated cross sections (integration interval $0 \geq Q \geq -40$ MeV) with those obtained by Klein *et al.*[12] It can be noticed that the results are very similar, although the cross sections of Klein *et al.* are always slightly larger than ours. This is due to the fact that the authors of Ref. 12 include more states than we do. They consider all states with spin-parity $J^\pi \leq 5^+, 5^-$ while we only include the states with $J^\pi \leq 3^+$.

We want to point out that both calculations predict a dropoff of the (n,p) cross section towards forward angles. This dropoff is not observed in the preliminary ^{90}Zr(n,p) data.[2] They show much larger zero-degree (n,p) cross section than is predicted by both our calculations and those of Klein *et al.*

Supposing that the preliminary ^{90}Zr(n,p) data are correct, one has to think of a mechanism which can increase the cross section at forward angles. This is in principle possible if one considers correlations in the target nucleus ground state which are not included in the RPA. The ground state correlations can produce GT transitions of the β_+ type which will lead to forward peaked ($L=0$) angular distributions.

TABLE I. Energy integrated ^{90}Zr(n,p) cross sections at 0°, 5°, and 8°. The second column shows our results while the third column shows those of Klein *et al.*

Angle (deg)	This work (mb/sr)	Klein *et al.* (mb/sr)
0	30.0	36.5
5	51.4	57.5
8	57.3	59.2

On the other hand, we would like to note that recent ^{90}Zr(d,2p) data do show an angle dependence which is similar to that obtained in our present (n,p) calculations.[14]

In conclusion, we have calculated ^{90}Zr(n,p) spectra at 200 MeV incident energy in a microscopic model. Our calculated spectra are very similar to those of Klein *et al.*,[12] although we use different nuclear structure wave functions. The shapes of the continuous spectra depend on the widths used in spreading the cross section to discrete final nuclear states. Microscopic two-particle–two-hole (2p-2h) nuclear structure calculations[15] are needed to solve this ambiguity in the choice of the spreading width.

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