Excited States of ^{88}Y Studied by the ^{88}Sr(p, n)^{88}Y Reaction*

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Excitation functions and angular distributions have been measured for two neutron groups in the ^{88}Sr(p, n)^{88}Y reaction, leaving ^{88}Y in the excited states at 706 and 773 keV, respectively. The spins and parities of these two states are deduced from comparison with computations based on the statistical theory of nuclear reactions.

INTRODUCTION

PREVIOUS work on the low-lying excited states of ^{88}Y has indicated states at 240 keV, 390 keV, 750 keV, 1.280 MeV, and 1.620 MeV, in the (p, d) study on ^{89}Y by Ludemann *et al.*[1] Lightbody *et al.*,[2] in their study of the ^{88}Sr$(p, n)^{88}$Y reaction, using a ^{3}He-filled proportional counter, observed excited states in ^{88}Y at 392 and 744 keV.

Energy spectra and angular distribution of neutrons from the (p, n) reaction on ^{88}Sr have been observed and are reported here. The investigation was undertaken particularly to study the low-lying excited states of ^{88}Y. Residual states at 706 and 773 keV were observed, and the experimental results have been analyzed assuming a statistical formation and decay of a compound nucleus as the reaction mechanism. Kim and Robinson[3] have shown that for the case of states in ^{89}Zr, this picture is a valid one and application of this method to other cases is of general interest.

EXPERIMENTAL RESULTS

In the present work, the ^{88}Sr$(p, n)^{88}$Y reaction was studied using time-of-flight techniques. Targets of ^{88}SrO (enriched to 99% in ^{88}Sr), evaporated on 0.005-in.-thick gold backings, were bombarded by a terminal pulsed beam of protons, accelerated in the University of Kentucky Van de Graaff accelerator. The target thickness used was about 6 keV at a proton energy of 5 MeV. The neutrons were detected by an NE[3a] 213 liquid scintillator biased at an energy equivalent of 50-keV protons. Using a flight path of 1.5 m and a time resolution of 10 nsec, it was possible to separate the different neutron groups. Figure 1 shows a time spectrum taken at a proton energy of 5.4 MeV. The background time spectrum, obtained by bombarding the gold backing with protons, is also shown in Fig. 1. Four neutron peaks corresponding to states in ^{88}Y at 0.0 MeV (n_0 group), 394±10 keV (n_1 group), 706±15 keV (n_2 group), and 773±20 keV (n_3 group) were observed in the time spectrum. The ground-state Q value assumed in calculating the energies of excitation in ^{88}Y was −4.404 MeV.[4]

The state at 240 keV reported by Ludemann *et al.*[1] is not seen in the ^{88}Sr(p, n) study. The state at 394 keV is known to have a spin and parity of 1^+.[5] The states at 750 keV reported by Ludemann *et al.*[1] and at 744 keV observed by Lightbody *et al.*[2] may be the two states at 706 and 773 keV, observed here, but unresolved in their work.

Figure 2 shows the excitation functions of the n_2 and n_3 neutron groups for incident proton energies below 5.54 MeV. Figures 3 and 4 show the angular distributions of the n_0, n_1, n_2, and n_3 neutron groups. The relative error and the absolute error in the cross section are estimated to be ±8 and ±20%, respectively. The excitation functions show reasonably smooth variation with energy and the angular distributions are symmetric about 90°, within the experimental error, which are consistent with the statistical theory of nuclear reactions.[3,6]

DISCUSSION

In the statistical theory of nuclear reactions, the partial cross section for a reaction proceeding from channel i to channel f, through the formation of a compound nucleus specified by unique values of J, l_i, l_f, j_i, and j_f, is proportional to $T(Jl_ij_i)T(Jl_fj_f)$, where $T(Jlj)$ is the transmission coefficient for formation of a compound nucleus state of spin J, l is the orbital angular momentum, and $j=l\pm\frac{1}{2}$ for nucleons. The expression for the differential cross section is given explicitly in Ref. 3.

In the present work, the transmission coefficients were calculated using an optical-model potential. Using this formulation of the statistical model with the optical-model transmission coefficients, the angular distributions of the neutrons from the ^{88}Sr$(p, n)^{88}$Y reaction were calculated for neutron groups leaving ^{88}Y in the ground and first three excited states. The object of the analysis was to determine the J^π for the 706- and 773-keV excited states in ^{88}Y.

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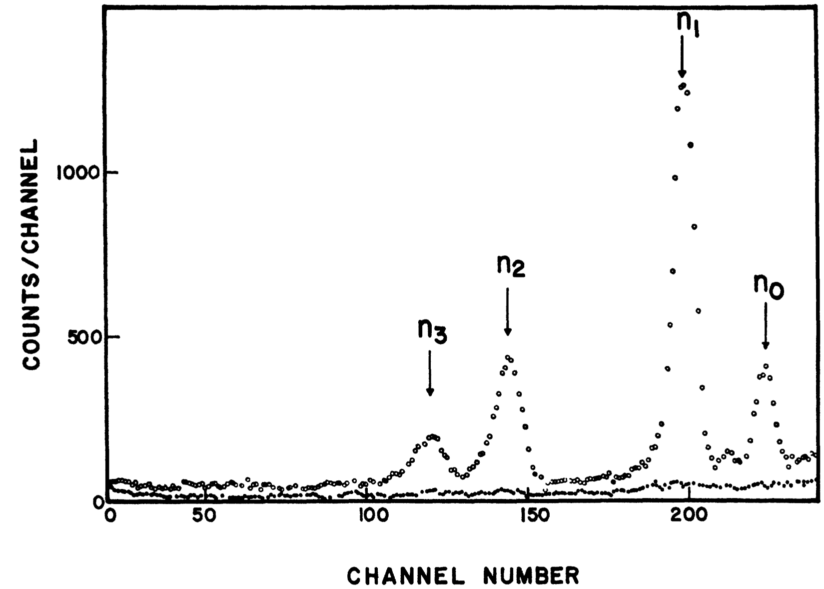

FIG. 1. Neutron time-of-flight spectrum (open circles), from the ^{88}Sr(p, n) reaction at 5.4-MeV proton energy and 1.5-m flight path. The four neutron groups are indicated by arrows. The background time spectrum is shown as closed circles.

The potential parameters of the optical model were taken from Johnson *et al.*[7] (p. 26) for the proton channels and from Moldauer[8] (Fig. 2, curve 3) for the neutron channels. These potentials were chosen because they are considered to be reasonable potentials for this mass region and, as will be seen, the transmission coefficients calculated from them produce calculated cross sections in reasonable agreement with experimental data for the angular distributions of neutrons leaving ^{88}Y in the ground state and the 394-keV state.

Among the open proton channels, the decays to the ground state ($J^\pi=0^+$), the first excited state at 1.835 MeV ($J^\pi=2^+$), and the second excited state at 2.740 MeV ($J^\pi=3^-$) of ^{88}Sr were taken into account in the calculations. All of the observed open neutron channels for decay to ^{88}Y were considered, namely, the ground state ($J^\pi=4^-$), the excited state at 394 keV ($J^\pi=1^+$), and the excited states at 706 and 773 keV. Using the above complex potential parameters,[7,8] the angular distributions of the n_0 and n_1 neutron groups were calculated for a proton energy of 5.170 MeV just below the threshold for the n_2 group. Reasonable agreement with the experimental data was observed as shown in Fig. 3. This agreement indicates that the statistical model with transmission coefficients computed in this way is a valid basis for the calculation of the angular distributions in this case.

The calculations were made for several combinations of spins and parities for the 706- and 773-keV states in ^{88}Y. The calculated angular distributions for the n_2 and n_3 neutron groups are shown as solid curves in Fig. 4 for assumed spins and parities of 2^- and 0^+ for the 706- and 773-keV states, respectively. It was found during the calculations that the shape of the experimental angular distribution for the n_2 group could be reproduced only if a spin and parity of 2^- or 4^+ was assumed for this state. Of these two possibilities 4^+ was ruled out, since the magnitude of the calculated cross section was smaller by a factor of about 3 and the calculated branching ratios for

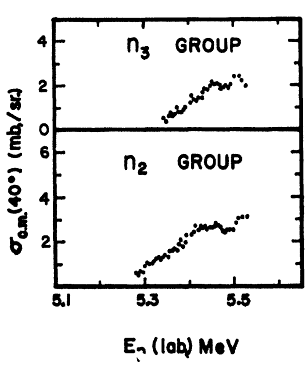

FIG. 2. Excitation functions of the neutron groups in the ^{88}Sr$(p, n)^{88}$Y reaction, leaving ^{88}Y in the 706- (n_2 group) and 773-keV (n_3 group) states, at an angle of 40°.

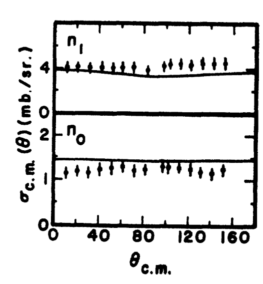

FIG. 3. Angular distributions of the n_0 and n_1 neutron groups in the ^{88}Sr$(p, n)^{88}$Y reaction at a laboratory proton energy of 5.170 MeV. The solid curves are the results of the statistical-model calculations (see text).

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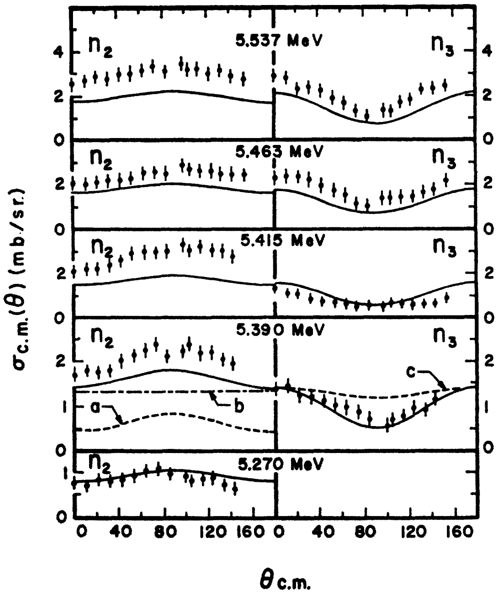

FIG. 4. Angular distributions of the n_2 and n_3 neutron groups in the ^{88}Sr$(p, n)^{88}$Y reaction at the laboratory proton energies indicated. The solid curves are the results of the statistical-model calculations (see text), assuming J^π of 2^- and 0^+ for the 706- and 773-keV states, respectively. Curve a at a proton energy of 5.390 MeV results from assuming J^π of 4^+ and 0^+ for these respective states. Curve b is obtained by assuming J^π of 2^+ and 0^+, respectively, and curve c corresponds to J^π of 2^- and (1^+ or 1^-) for the 706- and 773-keV states.

the 706- and 773-keV states were incorrect for this choice. Other possible spins, e.g., $J=1$ or 3, give computed angular distributions which are either isotropic or dip at 90°. Hence a spin and parity of 2^- is indicated for the 706-keV state in ^{88}Y. Curve b shown in Fig. 4 with n_2 at a proton energy of 5.390 MeV is the computed angular distribution assuming $J^\pi=2^+$ for the spin and parity of this final state. Although cross sections calculated from the statistical model are expected to be insensitive to parity,[9] this is a case where the computed angular distribution is sensitive to the parity of the final state. Clearly the 2^- choice gives a shape in better agreement with the data. This sensitivity to parity occurs because of relative magnitudes of the transmission coefficients for the different partial waves in the incident and exit channels. In this particular case, the $T(Jlj)$ values are larger for p-wave neutrons, by a factor of about 4, than for s-wave neutrons, and s- and p-waves are the most important incident partial waves.

Curve a shown for the 5.390-MeV angular distributions in Fig. 4 is the calculated result assuming 4^+ and 0^+ for spins and parities of the 706- and the 773-keV levels, respectively. It is seen that a spin and parity of 0^+ (solid curve) for the 773-keV state gives the best agreement to the shape of the experimental angular distributions. Thus a spin and parity of 0^+ is indicated for the 773-keV state in ^{88}Y. Other possible values of J, e.g., $J=2, 3, 4$, give computed angular distributions whose shapes agree less well with the data than does curve c, which corresponds to $J^\pi=1^+$ or 1^- for the spin and parity of the 773-MeV level (n_3). Note that the $J=1$ computation shows no sensitivity to parity.

The J^π values of 2^- and 0^+ are suggested for the 706- and 773-keV levels, respectively. Based on the calculation with these optical-model parameters which satisfactorily reproduce the experimental cross sections for the ground- and first-excited-state neutron groups, the above choices give best agreement with the experimental data. In this case, there is a clear choice among the various possibilities. Further investigation through different reactions leading to these same states would be useful to verify these results.

The work presented here also shows that there are cases when the angular distributions of the reaction products as computed from the statistical-model theory are sensitive to the parity of final state as it is for the n_2 group of this paper.

It should also be mentioned here that no attempt has been made to vary the complex potential parameters to get better fits to the absolute magnitude of the cross sections, since the experimental cross sections are accurate only to ±20% and variation in complex potential depths is not expected to change the shape of the angular distributions. For the same reasons, no corrections for level width fluctuations have been made in the calculations.

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