Level Structure of ^{88}Zr Studied with the ^{90}Zr(p, t) Reaction*

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The ^{90}Zr(p, t) reaction has been used to investigate the level structure of ^{88}Zr. The experiment was performed with 31-MeV protons from the Oak Ridge Isochronous Cyclotron. The tritons were analyzed with a broad-range magnetic spectrograph, and the over-all energy resolution was of the order of 20 keV. Angular distributions were obtained and spin-parity assignments were made on the basis of comparison with distorted-wave calculations. Levels in ^{88}Zr up to about 3.5 MeV in excitation have been analyzed. Comparisons are made with previously reported γ-ray energies. Spectroscopic factors extracted from the distorted-wave analysis have been obtained, and provide information on the shell-model structure of the observed levels.

I. INTRODUCTION

NUCLEI in the zirconium region have been treated quite extensively on the basis of a fairly simple shell-model picture.[1–5] Most of the calculations have been performed for nuclei with neutron number $N \geq 50$ and with the assumption that the major neutron shell closure at $N=50$ can be treated as an inert core. Such calculations have been quite successful in accounting for the gross features of these nuclei and have served as a useful guide for further experimental investigations.

Relatively little work has been done in calculating nuclear properties for $N<50$, i.e., for nuclei with spectra arising from holes in the $N=50$ core. Two reasons for this are: first, the data for these nuclei are considerably more scarce than for nuclei with $N \geq 50$ and second, the shell-model calculations are more difficult since the $1g_{9/2}$ level will participate for both protons and neutrons. This latter point is fairly critical since the subsequent increase in the "vector space" of the shell-model calculation caused by the participation of two $j=\frac{9}{2}$ orbitals make most calculations in this region feasible only because of the availability of extended shell-model programs.[6] One rather simple nucleus for which to attempt such calculations is ^{88}Zr. On the basis of a ^{88}Sr core, the levels in ^{88}Zr can be described as arising from the possible couplings of two protons with two neutron holes.

A recent paper[7] has reported the observation of a number of γ rays following the $\beta^+ +$(EC)-decay of ^{88}Nb. These transitions were placed in a tentative level scheme for ^{88}Zr constructed by analogy with nearby even-even nuclei.

To provide more quantitative information on the positions and character of the levels in ^{88}Zr, as well as to locate levels not populated by radioactive decay, we have studied the ^{90}Zr(p, t) reaction. This paper reports the energy levels observed, the distorted-wave analysis of their angular distributions, and the deduced spin-parity assignments.

II. EXPERIMENTAL DETAILS

This experiment was performed with 31-MeV protons from the Oak Ridge Isochronous Cyclotron. This energy was chosen because of the availability of good optical model parameters for both entrance and exit channels. The proton parameters are well defined at this energy and the very negative ground-state Q value (~ -12.6 MeV) makes the observed tritons fall in the energy range covered by existing triton elastic scattering data.

The tritons were observed with the broad-range spectrograph facility[8] and recorded with 50μ Kodak NTB emulsions. A spectrograph entrance angle of 4.0° and a scanning zone of 3 cm gave a solid angle of about 0.6 msr for the system.

The target was a rolled self-supporting foil, of thickness 0.25 mg/cm^2, enriched to 97.8% in ^{90}Zr. Absolute cross sections were obtained using the charge collected in a Faraday cup and the measured target thickness. A further check on the cross sections was made by comparing several of the deuteron groups with earlier ^{90}Zr(p, d)^{89}Zr measurements.[9] Very good agreement was obtained and would indicate an uncertainty in the (p, t) cross sections of about $\pm 10\%$ due to uncertainties in the current integration and target thickness.

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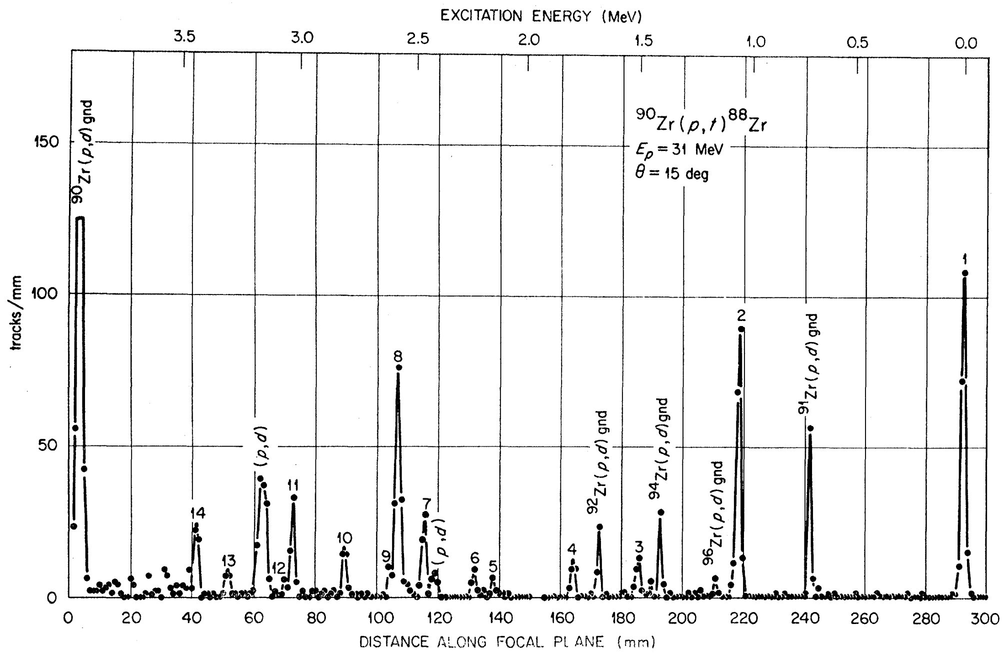

FIG. 1. Triton spectrum from the ^{90}Zr(p, t) ^{88}Zr reaction, obtained with a broad-range magnetic spectrograph. Also evident are several deuteron groups from (p, d) reactions on isotopic impurities in the target.

A spectrum from this reaction is shown in Fig. 1. The over-all resolution obtained for the triton groups was about 20 keV. Although the isotopic impurities in the target are less than 1% for each of the stable zirconuim isotopes, deuteron groups from (p, d) reactions are observed for all isotopes. In general, these deuteron impurities did not cause serious difficulties and were easily identified by their kinematic shift with change in scattering angle.

Angular distributions of the triton groups were obtained from 5 deg to 65 deg for comparison with distorted wave calculations.

III. DISTORTED-WAVE ANALYSIS

The distorted-wave Born-approximation (DWBA) calculations for the ^{90}Zr$(p, t)^{88}$Zr reaction were made with the code JULIE.[10] The formalism for the two-nucleon transfer calculation has been discussed in detail in the literature.[11] Since wave functions for ^{88}Zr were not available, the calculations were made assuming that the states of ^{88}Zr can be represented by two neutron holes in a closed $N=50$ neutron shell coupled to the ^{90}Zr ground state.

The calculations were made, using single-particle wave functions calculated in a Woods-Saxon well, by means of an oscillator wave-function expansion.[12] The parameters for the neutron bound-state well were radius $r_0=1.20$ F, diffuseness $a=0.65$ F, and a spin orbit strength of 25 times the Thomas term. The neutron binding energy was taken to be one-half the two-neutron separation energy for each of the transferred neutrons.

The proton optical model parameters used in the calculations are the "average" parameters of Satchler[13]

TABLE I. Optical model parameters used in the DWBA calculations. The notation for the parameters is the same as that of Satchler.[a]

	Proton	Triton($T1$)	Triton($T2$)
V (MeV)	51.4	170.1	150.4
r_0 (F)	1.17	1.15	1.24
a (F)	0.73	0.74	0.67
W (MeV)	2.59	19.0	20.5
W_D (MeV)	7.50	0.0	0.0
r_0' (F)	1.31	1.52	1.46
a' (F)	0.65	0.76	0.79
r_c (F)	1.20	1.40	1.40
V_s (MeV)	6.12	0.0	0.0
r_s (F)	1.17	1.15	1.24
a_s (F)	0.73	0.74	0.67

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from an analysis of 30-MeV proton elastic scattering. They are listed in Table I. One other set of proton parameters was tried. Although the calculations showed some sensitivity to the choice of proton parameters, a much stronger sensitivity is exhibited for the choice of the triton optical model parameters. This is consistent with the results of extensive investigations of the inverse (t, p) reaction at similar energies on various zirconium isotopes.[14] Previously a remarkable sensitivity to the choice of the ^{3}He potential from the Vr^n continuous ambiguity was seen in the $^{40}Ca(^3He, p)^{42}Sc$ reaction.[15] As a result of the observed sensitivity to the mass-3 parameters we investigated this ambiguity for our (p, t) results.

The triton optical-model parameters were taken from an analysis of 20-MeV triton elastic scattering on ^{90}Zr by Drisko, *et al.*[16] Calculations for the (p, t) transition to the 0+ ground state of ^{88}Zr are shown in Fig. 2. These calculations were done for the pickup of $(\nu g_{9/2})^2{}_0$, but calculations for $(\nu p_{3/2})^2{}_0$, $(\nu p_{1/2})^2{}_0$, $(\nu f_{5/2})^2{}_0$ results in essentially identical angular distributions (except for magnitude). The two calculations shown differ only in the choice of the triton optical potential from the continuous ambiguity, each potential giving equivalent fits to the elastic-scattering data. The two potentials are listed in Table I. The data show a distinct preference for the smaller triton radius (full curve). The larger radius (dashed curve) predicts a maximum in

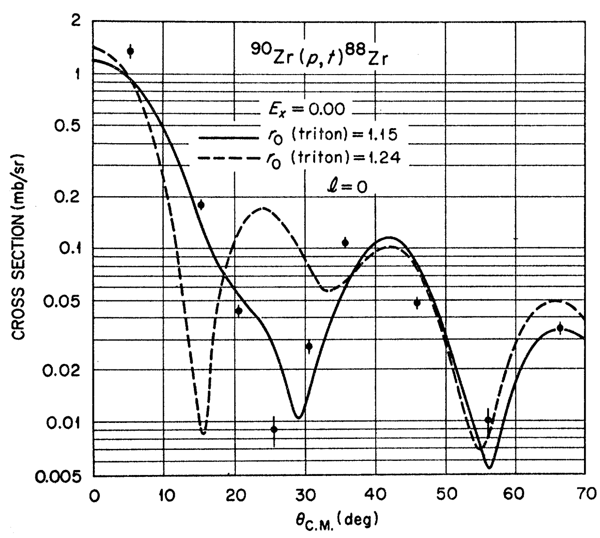

FIG. 2. Comparison of the experimental data for the $^{90}Zr(p, t)^{88}Zr$ (ground state) with distorted-wave predictions obtained using two different values for the radius in the triton optical potential.

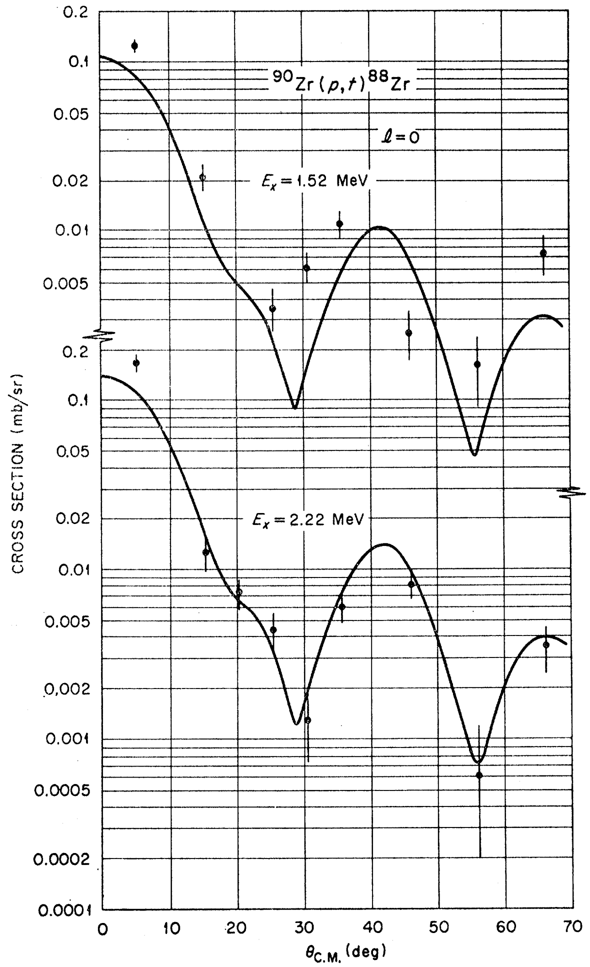

FIG. 3. Angular distributions for the 1.52- and 2.22-MeV states and their comparisons with the $l=0$ prediction.

the angular distribution where there is an experimental minimum. The calculations for the higher angular-momentum transfers ($L=2$, 4, etc.) show some sensitivity to the triton optical potential, but not nearly so pronounced as the $L=0$ transfer. Thus, the DWBA analysis of the two nucleon-transfer reactions, particularly with $L=0$ transfer, may be useful in reducing the ambiguity in the choice of triton optical potentials. It must be recognized that part of this observed sensitivity is introduced by use of the zero-range approximation and by neglect of nonlocality effects in the DWBA calculations.

Using the triton optical model parameters with $r_0=1.15$ F ($T1$), DWBA calculations were carried out for the other states observed in ^{88}Zr. Again we assumed the pickup of $(\nu g_{9/2})^2$, since the other cases resulted in the same shape but with different magnitudes. Figure 3 shows the angular distributions for the other 0+ states. In Fig. 4, the comparison between theory and experiment for 2+ and 4+ states is shown. The experimental

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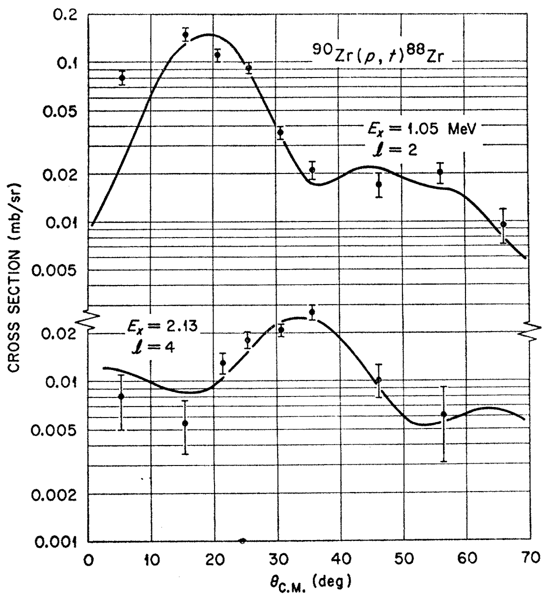

FIG. 4. Comparison of experimental and predicted $l=2$ and $l=4$ angular distributions.

angular distributions in both cases are well described by the theoretical calculations. In Fig. 5 the experimental angular distribution for a weak state at 1.82 MeV is shown. In this case no single theoretical angular distribution gave a reasonable fit to the experimental results. If we assume that this level is an unresolved doublet, the best fit to the experimental points is obtained with a combination of theoretical $l=2$ and $l=4$ angular distributions as shown in the figure. On this basis, we have tentatively assigned the observed level

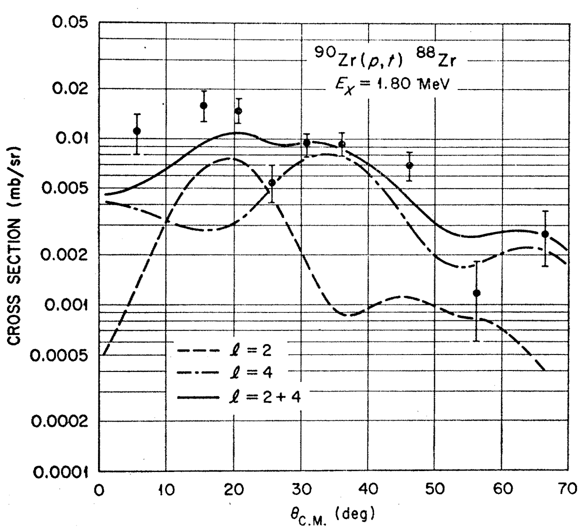

FIG. 5. Experimental angular distribution for the ^{90}Zr(p, t)^{88}Zr (1.82 MeV) reaction. As discussed in the text, this level is believed to be a doublet and the data have been decomposed into $l=2$ and $l=4$ components.

as a (2+, 4+) doublet. Since we observe no broadening of the line, the splitting of such a doublet would have to be less than 4 keV. Figure 6 shows the comparison of experiment and theory for two negative-parity states with the theoretical calculations again giving good agreement with the data.

The observed levels in ^{88}Zr and the assigned spins and parities from this experiment are given in Table II. Besides spins and parities we can also derive information concerning the structure of the observed states from the transition strengths obtained by comparison with the DWBA calculations.

The experimental cross sections for a single configuration are related to the theoretical angular distributions

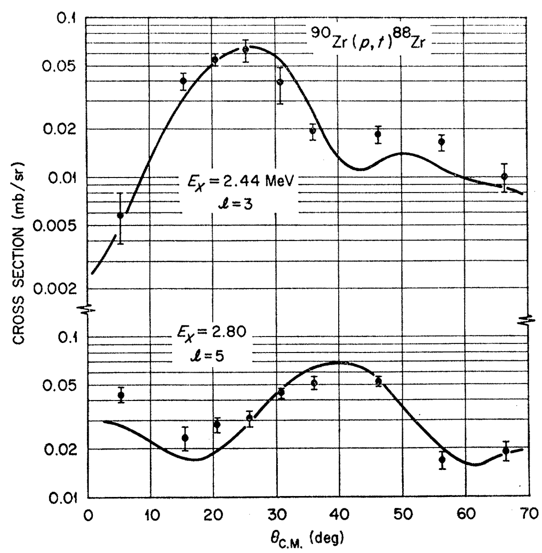

FIG. 6. Angular distributions for negative-parity states excited in the ^{90}Zr(p, t)^{88}Zr reaction. Also shown are predicted angular distributions for $l=3$ and $l=5$ pickup.

by the expression

$$\sigma_{\mathrm{exp}}(\theta)=2D_0^2C^2S\sigma_{\mathrm{JULIE}}(\theta),$$

where S is the spectroscopic factor for the removal of the two particles, C^2 is the square of the isobaric-spin coupling coefficient, and D_0^2 is the normalization constant (in units of 10^4 MeV^2 F^3) which arises in making the zero-range approximation.[17]

Results of a preliminary analysis of the Zr(t, p) reactions[14] yield a value for D_0^2 of 35. The presence of configuration mixing would decrease this number and the choice of the bound-state parameters made here would increase it. For the purposes of Table II we use a value of 37.5 for D_0^2. This value will be justified below.

[17] The two nucleon transfer option in the code JULIE has been normalized for the (^{3}He, p) reaction and the factor of 2 must be included in the (p, t) calculation in order for D_0^2 to be the same for the two reactions.

TABLE II. Summary of results obtained from the ^{90}Zr$(p,t)^{88}$Zr reaction.

Level No.	Energy (MeV)	Peak $d\sigma/d\Omega$ (mb/sr)	J,π[b]	$2D_0^2C^2S$[c]	$C^2SS/2J+1$[d]
1	0.000	1.34	0+	783	10.4
2	1.055	0.15	2+	1475	3.9
3	1.520	0.125	0+	73	0.97
4[e]	1.820	0.011, 0.006	(2+, 4+)	(105, 288)	(0.28, 0.42)
5	2.130	0.027	4+	882	1.3
6	2.225	0.17	0+	98	1.3
7	2.445	0.062	3−	98	0.19
	(2.52)	0.002	(4+)	(49)	(0.07)
8	2.57	0.116	2+	1135	3.0
9	(2.60)	0.014	(4+, 6+)	(765, 923)	(1.1, 0.9)
10	2.795	0.051	5−	506	0.61
	(2.89)	∼0.006	(4, 6, 8)	(180, 390, 680)	(0.27, 0.4, 0.5)
11	3.02	0.04, 0.018	2+, (4+)	500, (225)	1.3, (0.3)
12	3.06	0.008	(4+)	(279)	(0.4)
13	3.30	∼0.01			
14	3.43	0.041	(0+)	(70)	(0.9)

[a] Differential cross section at $5°(L=0)$, $15°(L=2)$, $25°(L=3)$, $35°(L=4, 5, 6, 8)$.
[b] Several values in parentheses indicate that the data are poorly described by any single prediction but the most likely values are those given here.
[c] Obtained assuming pickup of two $g_{9/2}$ neutrons for the even-parity states, and one $g_{9/2}$ plus one $p_{3/2}$ neutrons for the odd-parity states.
[d] Based on a value of $D_0^2=37.5$.
[e] Probably a doublet as discussed in Sec. III.

The strengths shown in Table II were calculated assuming that the positive-parity states are populated by the pickup of a $g_{9/2}$ neutron pair. To facilitate interpretation of these strengths it is convenient to compare these strengths with those expected from a simple shell-model picture. Since we expect $N=50$ to be a major closed shell for neutrons, it seems reasonable to consider ^{90}Zr to have the $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$, etc. neutron levels completely filled. The ^{90}Zr(p, t) reaction is thus picking up a pair of neutrons from completely filled shells. For a spin-zero target nucleus, the spectroscopic factor for removal of a pair of particles from any shell-model level with total angular momentum $I=0$, is given by

$$S_J=\mathfrak{N}G_J^2,$$

where J is the spin of the final state, $\mathfrak{N}$ is the number of particle pairs in the initial state, and G_J is the single-configuration two-particle coefficient of fractional parentage. For a completely filled level this reduces identically to

$$S_J=2J+1$$

independent of the level angular momentum j.

In the last column of Table II we have divided the observed strengths by our assumed value of $2D_0^2$ and by $2J+1$. If the assumption of pure $(g_{9/2})^2$ pickup was valid the maximum value for these "reduced strengths" would be unity.

The most obvious disagreement with such a simple interpretation is the observed factor of 10 enhancement for the transition to the ground state. Such an enhancement would seem to imply significant admixtures of $(\nu p_{1/2})^{-2}$ and $(\nu p_{3/2})^{-2}$ configurations in this state. In order to estimate the effect of such configuration mixing, calculations were performed for these two additional configurations. The results of the calculations show that although the angular distributions are essentially identical in shape, the magnitude of the cross sections for the reaction leading to pure $(\nu j)^{-2}{}_0$ states are in the ratio

$$(\nu g_{9/2})^{-2}{}_0/(\nu p_{1/2})^{-2}{}_0/(\nu p_{3/2})^{-2}{}_0=1.0{:}3.2{:}8.5.$$

Thus the preference of pickup of p particles over g particles can account for the observed enhancement. It is clear, however, that the enhancement for $p_{1/2}$ pickup is not sufficient to account for the observed strength of the ground state. Therefore, both $p_{1/2}$ and $p_{3/2}$ components must be present. As an example, the DWBA calculation for a wave function of the form

$$|\,\mathrm{Zr}^{88};\,0\rangle=0.72(g_{9/2})^{-2}{}_0+0.54(p_{1/2})^{-2}{}_0+0.44(p_{3/2})^{-1}{}_0$$

gives an enhancement of about 9, as expected from simple considerations of the above ratios. Although this is not a unique solution, the $(p_{3/2})^{-2}{}_0$ coefficient cannot be less than ~0.4 if the desired enhancement is to be obtained.

Because of the similarity in predicted angular distributions, the total strength observed for the two-neutron pickup from these three orbitals leading to 0+ final states should be, to first order, the sum of the enhancement factors (i.e., 12.7). If we assume that the first three 0+ states observed represent the bulk of this total strength, then the sum of these "reduced strengths" should be 12.7. The value of $D_0^2=37.5$ was chosen to meet this condition.

With the above assignment of D_0^2, the observed strengths to the 2+ states indicates the presence of p-state admixtures such as $[(p_{1/2})^{-1}(p_{3/2})^{-1}]_2$ or $(p_{3/2})^{-2}{}_2$. However, only about half of the expected total strength for these configurations is observed.

Similarly, the observed strength to the two lowest 4+ states probably indicates the participation of small components of configurations such as $[(p_{3/2})^{-1}(f_{5/2})^{-1}]_4$ and $(f_{5/2})^{-2}{}_4$ in their wave functions.

The angular distributions for the negative-parity states were calculated assuming removal of one neutron from the $1g_{9/2}$ level and the other neutron from the $2p_{3/2}$ level. The strengths extracted assuming these configurations are also shown in Table II. Experimentally, the (3−) state is about a factor of 7 smaller than expected for the simple description. This may indicate that the state is predominately a state of proton excitation or an excited neutron configuration such as $[(p_{1/2})^{-1}(d_{5/2})]_{3-}$ which would not be populated by this reaction. The 5− is also weak by a factor of 2-3. We expect that the proton configuration is important for this state.

Although the excited 0+ states are observed with a factor of ten less strength than the ground state, they are still comparable in strength to many of the other states. It is perhaps surprising that these 0+ states are seen as strongly as they are. In general, the strong similarity of the correlations in the ground-state wave functions for nuclei differing by two particles will cause essentially all of the $l=0$ strength to contribute to the ground-state transition. We thus expect that the low-lying states orthogonal to the ground state of the final nucleus will be extremely weakly populated. We would expect to populate them appreciably only if the proton configuration is changed significantly between the initial and final states. This, in fact, may be happening for this reaction since we are restricted to removing two neutrons from levels either filled or being filled for protons. This would not be the case, e.g., for the $^{92}Zr(p, t)^{90}Zr$ reaction.

Excited 0+ states arising from pickup of a neutron pair from the next major shell might be expected to be strongly excited. Although strong deuteron groups above 3.5 MeV in excitation in the triton spectra make a detailed analysis difficult, no 0+ triton states with appreciable strength were observed up to an excitation energy of 5.5 MeV. Tritons leading to states of excitation higher than 5.5 MeV were not detected in this experiment.

IV. DISCUSSION

The levels listed in Table II, up to about 3 MeV of excitation, are shown in Fig. 7. Also shown in the figure are the γ-ray energies reported by Flegenheimer[7] with appropriate reordering to compare with the energy differences from the present work.

Although the individual energy differences agree to about 5 keV, comparison of the magnet and γ-ray excitation energies suggests that a slight expansion of the magnet energies would give much closer agreement. The γ-ray energies would seem to be well established.

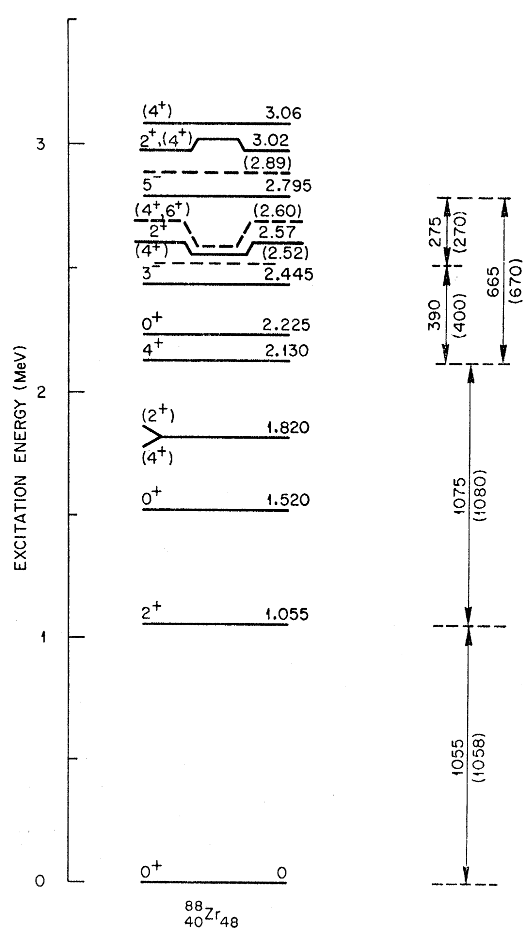

FIG. 7. Energy levels in ^{88}Zr populated in the $^{90}Zr(p, t)^{88}Zr$ reaction. These are compared on the right with the results of recent γ-ray decay studies. The energy differences are compared with the γ-ray energies given in parentheses.

These energies have been observed also by Hyde,[18] and by Hagenauer and Eichler.[19] Agreement in all γ measurements is obtained to about 2 keV. Previous comparisons between data taken with our spectrograph and germanium counter data have also shown agreement within 2 keV. This suggests that either there is an unknown source of magnet calibration error in this experiment, or the higher levels, particularly those above the first 4+, observed in the (p, t) reaction do not correspond to the levels participating in the γ decay.

This latter possibility is quite likely. There is also a 75-keV γ ray observed in the decay scheme study which is not placed in the figure. Since the coupling rules would predict a high spin for the ground state of ^{88}Nb, very similar to the case for ^{90}Nb and ^{92}Tc, it is expected that the β decay of ^{88}Nb will populate a high-spin state, probably 8+, in ^{88}Zr in analogy with the previously established decay schemes for ^{90}Nb and ^{92}Tc. Such a state would be expected to feed a 6+, 4+, 2+, 0+ sequence as observed in ^{90}Zr and ^{92}Mo. Flegenheimer has suggested that the 75-keV transition may lie directly above the γ transition as shown in our figure and correspond to the $8+ \rightarrow 6+$ decay. Thus the state observed in the decay scheme study at 2.808 MeV would be the 6+ state and not the 5− observed in this work at 2.795 MeV.

Recently, Jaklevic, *et al.*[20] have observed these same γ rays following the ^{86}Sr$(\alpha, 2n)^{88}$Zr reaction. They place the transitions in the same order as we have shown in Fig. 7. In addition, they are able to confirm that this sequence follows the decay of the 75-keV transition. The agreement of ordering of the 400- and 270-keV transitions suggests that at least the intermediate state may be the same in the (p, t) reaction and the γ decay.

The state at 1.820 MeV which was weakly excited, and could not be well described by a single l transfer, also presents a problem to the decay scheme observed. If there is a 4+ level at this energy, it seems likely that there should be some feeding of this state from the higher states that feed the 4+ at 2.130 MeV. It might also be expected that a 2+ level at 1.820 MeV would be fed weakly in the decay of the 2.130 MeV level. None of the possible transitions feeding a state or states at 1.820 MeV have been reported.

No clear evidence is seen in this work for states with spin greater than 5. The 6+ and 8+ states arising from the $(\nu g_{9/2})^{-2}$ couping were expected to be comparable in intensity to the 4+ states at larger angles. No evidence could be found for these states. It is possible that one of these states is included in the group near 2.5 MeV. This region contains at least three triton groups and, at some angles, one or more deuteron groups. The peak at 2.57 MeV is the only one in this region which is sufficiently intense to allow a definite spin-parity assignment to be made. The angular distribution for the state at 2.52 MeV is fit best by the $l=4$ prediction but, due to the large uncertainties, this assignment cannot be made definite. The data for the 2.60-MeV state do not agree with any of the predictions, possibly because of the presence of a deuteron contaminant.

Although the (p, t) reaction at 31 MeV did not yield positive identification of any 6+ or 8+ levels it is possible that at higher incident energies these levels could be observed. Preliminary reports of a study of this reaction at 55 MeV did not show evidence for these states but the resolution was very probably inadequate for this purpose.[21]

The levels observed in the present work can certainly account for the higher-energy γ transitions. The status of the lower-energy transitions is not clear. In addition a number of additional levels have been observed and their character established.

Detailed shell-model calculations for this nucleus are being undertaken and will hopefully serve as a guide in interpreting the two sets of experimental data for ^{88}Zr. In particular, it would be extremely helpful to know the expected position of the lowest 6+ and 8+ levels.

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