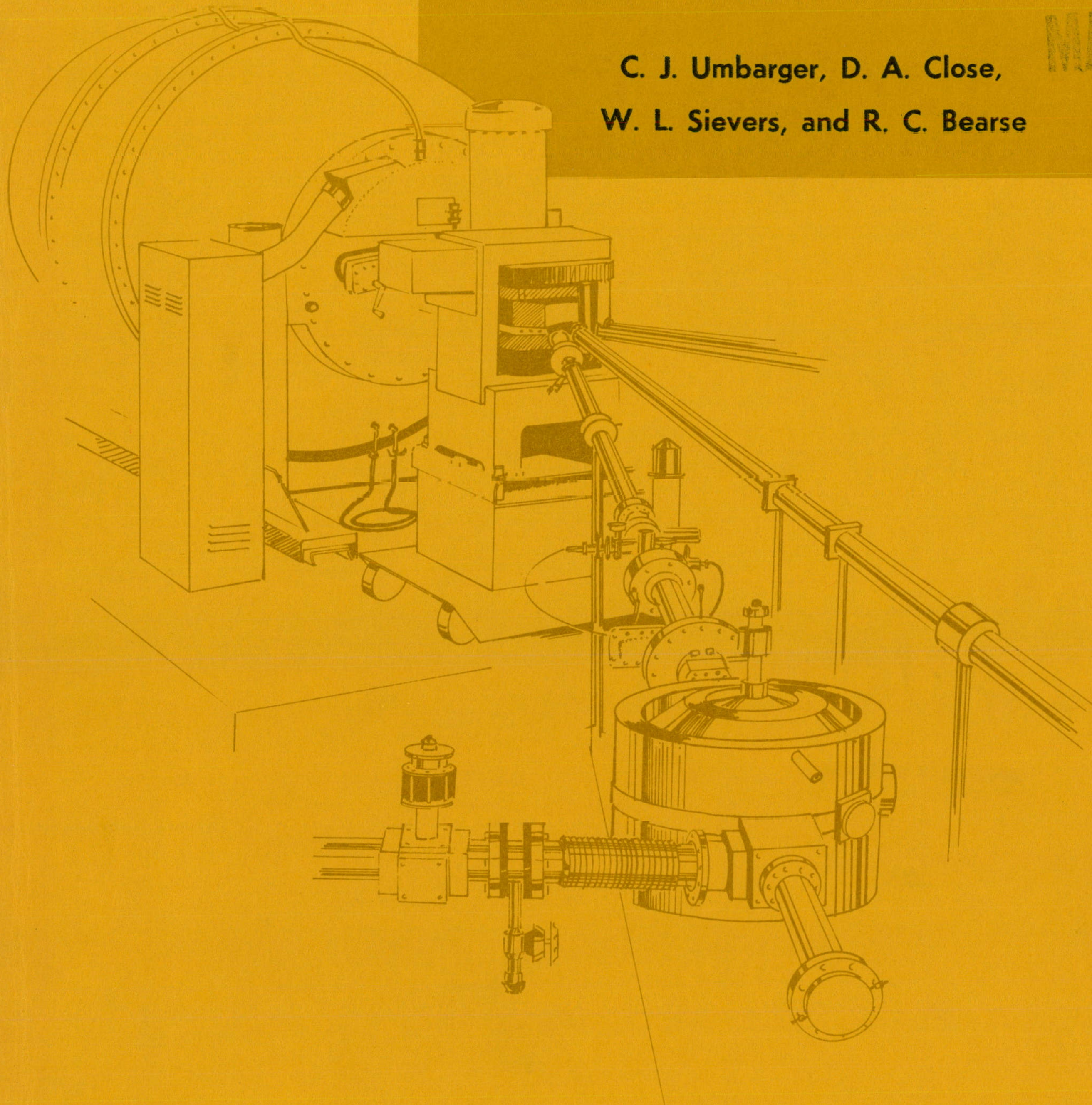
COO-1120-119

STUDY OF $^{88}Sr(p,\gamma)^{89}Y$ and $^{89}Y(p,\gamma)^{90}Zr$ FROM E_p = 2.3 to 3.0 MeV

MASTER

C. J. Umbarger, D. A. Close,

W. L. Sievers, and R. C. Bearse



NUCLEAR STRUCTURE LABORATORY
UNIVERSITY OF KANSAS, LAWRENCE

AEC CONTRACT AT (11-1) 1120

Study of $^{88}Sr(p,\gamma)^{89}Y$ and $^{89}Y(p,\gamma)^{90}Zr$ from E_p = 2.3 to 3.0 MeV*

C. J. Umbarger, D. A. Close, W. L. Sievers, and R. C. Bearse

Department of Physics, University of Kansas

Lawrence, Kansas 66044

ABSTRACT

The $^{88}Sr(p,\gamma)^{89}Y$ and $^{89}Y(p,\gamma)^{90}Zr$ reactions have been investigated in the energy range E_p=2.3 to 3.0 MeV. Excitation functions for the transition to the ground state, with a total resolution of 2 keV, were determined for each reaction over this energy region. Using thick targets and both a single Ge(Li) detector and a Ge(Li) detector incorporated into a pair spectrometer, total summed spectra for the 700-keV region were obtained. The average total cross section of $^{88}Sr(p,\gamma_o)^{89}Y$ and $^{89}Y(p,\gamma_o)^{90}Zr$ was 12 ± 5μb and 17 ± 7μb, respectively. These total summed spectra, which represent the total gamma-ray yield in this region, have been examined for a possible dependence of the intensity on the J^{π} of the final state. The data suggest such a J-dependence hypothesis, but detailed theoretical analysis of the $^{88}Sr(p,\gamma)^{89}Y$ reaction does not completely agree with experiment. A spectrum from a Ge(Li) detector in coincidence with a NaI(Tℓ) detector was accumulated for the $^{88}Sr(p,\gamma)^{89}Y$ reaction. The decay scheme of the states of ^{89}Y up to an excitation energy of 3.621 MeV was determined and the implications about spins and parities are consistent with accepted assignments.

---

*Work supported in part by the U.S. Atomic Energy Commission and the University of Kansas General Research Fund.

1. INTRODUCTION

It does not appear to be generally realized that it is possible to excite nuclei of $A\sim 90$ with protons of $E_p<3$ MeV with sufficient cross sections to allow spectroscopic studies by radiative capture reactions. It can be shown that unless the proton width is smaller than $\sim$1 eV, the inhibition due to the coulomb barrier ($\sim$8 MeV) should not matter so long as only the proton and gamma-ray channels are open. If the neutron channel is closed, the only contribution to Γ_T can come from Γ_p and Γ_γ since other channels are either energetically forbidden or more severely inhibited by the coulomb barrier than the protons. The Weisskopf single-particle estimate of Γ_γ[1] for a 10 MeV E1 transition in ^{90}Zr, for instance, is $\sim$1 keV. Such a transition corresponds to gamma-ray decay to the ground state following capture of 2.5 MeV protons by ^{89}Y. The Wigner limit[2] for the proton reduced width is $\sim$1 MeV and, since the s-wave penetrability is about 10^{-3}[3], Γ_p would also be $\sim$1 keV for single-particle states. If we assume that the states populated will have widths of 10^{-3} single-particle units, Γ_T is $\sim$1 eV. On this premise, the resonance states should be narrow compared to any reasonable target thickness and the thick-target yield equation[4] will apply:

$$Y = \frac{2\pi^2 \lambda\!\!\!^{-}{}^2}{\varepsilon} \frac{(2J_R+1)}{(2J_T+1)(2J_p+1)} \frac{\Gamma_{p0}\Gamma_\gamma}{\Gamma_T} \qquad (1)$$

This means that since Γ_p, Γ_γ and Γ_T can all be as large as 1 eV, the (2J+1) $\Gamma_p\Gamma_\gamma/\Gamma_T$ portion of **Eq.** (1) can also be as large as 1 eV. For comparison, (2J+1) $\Gamma_p\Gamma_\gamma/\Gamma_T$ = 40 eV[5] for the strong resonance at E_p = 0.992 MeV in the $^{27}Al(p,\gamma)^{28}Si$ reaction. The possibility that yields as large as 1/40 of the Al yield might be realized indicates that experiments on A∿90 nuclei with E_p<3 MeV should be feasible. It is not readily possible to resolve individual resonances, however, because the expected average level spacing in ^{90}Zr at 10 MeV excitation is ∿100 eV.[6] The usual techniques of resonance spectroscopy cannot be used, therefore, to determine the spins and parities of the states of the residual nucleus.

The purpose of the present investigation is twofold: 1) to establish whether or not yields are sufficient to allow studies of these nuclei, and if so, 2) to discover what techniques can be applied to determine spins and parities. Recently, Mason et al.[7] published some studies of $^{89}Y(p,\gamma)^{90}Zr$ for E_p = 2.6 to 19.0 MeV which show peak cross sections of ∿100μb in the region below 3.0 MeV. Their interest, however, was in the details of the giant dipole resonance in ^{90}Zr, rather than in the spectroscopy of the low-lying states of that nucleus.

Both the $^{88}Sr(p,\gamma)^{89}Y$ and $^{89}Y(p,\gamma)^{90}Zr$ reactions are aptly suited for this investigation: they have (p,n) thresholds above 3 MeV; both have (p,γ) Q-values sufficiently high to produce gamma transitions with energies higher than the contaminant $^{19}F(p,\alpha\gamma)^{16}O$ gamma rays; and both targets are easily produced. The natural abundance of ^{88}Sr is 83%; it has the largest Q-value for proton capture of all the Sr isotopes. The only naturally occuring isotope of Yttrium is ^{89}Y. Further, the properties of the low-lying states of both ^{89}Y and ^{90}Zr are well established. Accurate energies and reliable spin assignments are available for many of these states, thus allowing a check on the techniques used here. The presently accepted level scheme for each nucleus[8,9] is displayed in Fig. 1.

Thin target and thick target excitation functions were measured for both reactions, the former to study the details of the excitation functions and the latter to obtain spectra summed (or "averaged") over a wide energy region to remove local fluctuations in the yield. These "average" spectra were obtained in the hope that the methods of Bollinger and Thomas[10] for treating average (n,γ) spectra might be applicable to (p,γ) spectra. A γ-γ coincidence spectrum was obtained for the $^{88}Sr(p,\gamma)^{89}Y$ reaction.

2. TARGETS

The ^{88}Sr targets were prepared by decomposing natural $SrCO_3$ (83% ^{88}Sr) in vacuum and depositing a thin layer of metallic Sr onto 0.013 cm thick gold discs. A thin gold overlay was then evaporated over the Sr layer before removing it from the vacuum system. This overlay prevented oxidation of the Sr and reduced buildup of fluorine compounds during bombardment as well as improving heat conduction away from the beam spot. In like manner, ^{89}Y targets were prepared from metallic Y (100% ^{89}Y). Each target was placed onto a tantalum lined aluminum tube with the gold backing of the target serving as the vacuum seal. A stream of water was directed at the backing to prevent the target from being melted by beam currents of 8-15μa. Using this technique, targets were able to withstand ∿20μa of beam without significant deterioration.

Target thicknesses were determined by evaporating Sr (or Y) onto a thin Al target simultaneously with the preparation of the Sr (or Y) target and then measuring the shift in energy of the $^{27}Al(p,\gamma)^{28}Si$ resonance at $E_p = 0.992$ MeV[5]. The thickness of the gold overlay was obtained from another Al target that was masked during the evaporation of the Sr (or Y) and uncovered prior to evaporation of the gold overlay. The overlays were always $\sim$1 keV thick. Using standard range-energy tables[11] the target thicknesses were determined to within 10%.

3. EXCITATION FUNCTIONS

Excitation functions at 0^o were determined for $^{88}Sr(p,\gamma_o)^{89}Y$ and $^{89}Y(p,\gamma_o)^{90}Zr$ from $E_p = 2.3$ to 3.0 MeV, with an overall energy resolution of 2 keV. Over small regions of energy the excitation functions were repeated several times, resulting in a reproduction of the original data points to within acceptable statistical deviation. A 23 by 10-cm NaI(Tℓ) detector in conjunction with a single-channel analyzer was employed for the $^{88}Sr(p,\gamma_o)^{89}Y$ measurements. The $^{89}Y(p,\gamma_o)^{90}Zr$ excitation function was measured with a 15 cm^3-coaxial-Ge(Li) detector and single-channel analyzer.

The two (p,γ_o) excitation functions are shown in Fig. 2. The data in each case are very similar. The onset of violent fluctuations in the yield occurs at about the same energy in both cases ($\sim$2.4 MeV) and continues to the highest energies studied here. A comparison of our results for $^{89}Y(p,\gamma_o)^{90}Zr$ with those of Mason _et al._[7] in the energy range $E_p = 2.67$ to 2.74 MeV results in excellent agreement. Outside this region detailed comparison is not useful because the present resolution is considerably higher than that (25 keV) used by Mason _et al._

In this energy region the intensity of gamma rays to the 1.507-MeV second-excited state and the 1.745-MeV third-excited state in ^{89}Y were measured using the 15-cm^3 Ge(Li) detector for comparison to the ground-state yield. Over this region, the excitation functions showed no correlation in proton energy with each other, which is consistent with the assumption that the peaks in the cross-section are not due to isolated resonances.

The number of fluctuations in the excitation function appear to increase with energy. This implies that the states being excited are not strongly overlapping because strongly overlapping resonances give rise to fluctuations (Ericson fluctuations) whose average spacing does not change with excitation energy. Since, in addition, the states have $\sim$1 eV widths, an autocorrelation analysis of the excitation functions should reveal the overall resolution (target thickness and beam spread) of the experiment. Such an analysis indicated that the overall energy resolution was $\sim$1.5 keV for the ^{88}Sr$(p,\gamma_0)^{89}$Y data and $\sim$3 keV for the ^{89}Y$(p,\gamma_0)^{90}$Zr data.

4. COINCIDENCE SPECTRUM

Because of a discrepancy between the observed and predicted average yield to the $5/2^+$ state at 2.221 MeV in ^{89}Y (see Sec. 5), a coincidence spectrum was obtained for the ^{88}Sr$(p,\gamma)^{89}$Y reaction to verify that spin assignment. The Ge(Li) detector and the NaI(Tℓ) detector mentioned in Sec. 3 were placed at 0° and 90°, respectively. Pulses from the Ge(Li) detector were stored in a 1024 channel analyzer when such pulses were in coincidence (50 ns resolving time) with pulses from the NaI(Tℓ) detector which corresponded to $E_\gamma \gtrsim 6$ MeV. A lead absorber of 3.6 g/cm^2 was placed in front of the Ge(Li) detector. The absorber served to attenuate the extremely high flux of low-energy gamma rays and x-rays which otherwise would have swamped the detectors. The target was ∿70 keV thick to 3-MeV protons and consisted of three alternating layers of Sr and Au. It showed no deterioration after 66 hours of bombardment with 12.5μa of 3-MeV protons.

The coincidence spectrum produced by 2.3 coul of 3.0-MeV protons is shown in Fig. 3 and the decay scheme obtained from the data is shown in Fig. 4. The energy calibration for the spectrum was obtained by a linear least-squares fit to the positions and energies of the three most prominent lines; the 0.511-MeV annihilation radiation, and the 1.507-MeV 2-0 transition and 1.745-MeV 3-0 transition in ^{89}Y. The energies of the excited states of ^{89}Y inferred from the energies of the observed transitions are shown in Table 1 along with the accepted energies and expected J^{π} of the states. The energies are in excellent agreement with those given by the "midstream" analysis of Van Patter[8]. Transitions from several of the states listed by Van Patter, however, were not observed in this measurement. The half life of the $9/2^{+}$ first-excited state in ^{89}Y is 16 sec.[13]. Accordingly, no transition from this state would be observed in a coincidence measurement of this type. We also fail to observe transitions from three states accepted to have energies of 2.566 MeV, 2.622 MeV, and 2.871 MeV, but since these states all have $J>7/2$, this is not surprising in light of the conclusions of Sec. 5.

The second excited state at 1.507 MeV shows no branch to the $9/2^{+}$ state, which is consistent with the accepted $3/2^{-}$ assignment for this level. The 1.745 MeV state shows a decay only to the ground state, whereas the Weisskopf estimate would predict a 50% branch to the 1.507 MeV state. Because of the absorber in front of the Ge(Li) detector, the detection efficiency of the system is very low at this energy (0.240 MeV) and we would not expect to see such a transition. Hence, our data is not inconsistent with a $5/2^-$ assignment.

The 2.221-MeV state shows a decay to the $9/2^+$ state but a branch that would be expected to the $3/2^-$-1.507-MeV state is obscured by the double-escape peak produced by the transition from the 1.745-MeV state to the ground state. This decay to the $9/2^+$ state is consistent only with $J \gtrsim 5/2$ for the 2.221-MeV state. Furthermore, a $5/2^-$ assignment is ruled out since such an assignment would imply that decay to the $9/2^+$ state is via M2 radiation in preference to an E2 decay or M1 decay to the ground state or second-excited state, respectively.

The state at 2.530 MeV shows a decay to the $5/2^-$-1.745-MeV state but there is no evidence for any other transition. The accepted assignment for this state is $J^\pi = 7/2^+$ and hence a decay to the 0.909-MeV $9/2^+$ state might be expected. The Weisskopf estimate gives, however, 10^{-3} for the expected branch, consistent with our findings.

Only one transition is seen from the 2.871-MeV, 2.882-MeV doublet and that is to the ground state. This is the de-excitation of the 2.882-MeV state as the 2.871-MeV state has $J^\pi = (7/2)^+$ and would not decay to the ground state, and furthermore, we do not expect the $(7/2)^+$ state to be strongly fed (Sec. 5). The 3/2 state, however, would be expected to have additional transitions to the $3/2^-$ and $5/2^-$ states, but since the ground state transition has twice the energy or more than the other transitions they should be too weak to be seen here even if the transition matrix elements involved are equal. The same argument also applies to the 3/2 state at 3.068 MeV.

Decays to the ground state are also seen from the 3.106-MeV and 3.138-MeV states with no other branches observed. Since these are both $5/2^-$ states, the ground state decay is E2 in character and reasonable competition might be expected by E1 decay to the $5/2^+$ state at 2.221 MeV, but no such transitions are observed nor do we see M1 transitions to the 1.507-MeV or 1.745-MeV states.

The state observed by us at 3.520 MeV is above the energy region considered in the "midstream" analysis of Van Patter. It decays only to the ground state and hence it must have $J \leq 5/2$ and cannot be $5/2^+$. Picard and Bassani[15] observed a state at 3.49 MeV populated by $\ell = 1$ transfer in the $^{88}Sr(^3He,d)^{89}Y$ reaction. If this state is the same one observed in this experiment, then the 3.520-MeV state is either $1/2^-$ or $3/2^-$. We also observe a gamma-ray of 3.612 MeV that probably corresponds to a transition between the ground state and the state at 3.61 MeV observed in inelastic proton scattering by Scott _et al._[16]. It probably has $J \leq 5/2$ and it is unlikely that it is $5/2^+$.

5. THICK-TARGET DATA

Figs. 5 and 6 display typical individual spectra obtained using a Ge(Li) detector at 0^o, with thick targets (∿24 keV) of Sr and Y, respectively, and a proton beam energy of 3.0 MeV. For each thick target, three separate sets of excitation functions were measured in energy increments of 20-30 keV, or approximately 25 separate spectra for each excitation function. In each case, the target thickness was determined as discussed in Sec. 2 and the energy step-size chosen so that no continuum state would be excited in two different data points. Two of these excitation functions were measured using the 15-cm^3 Ge(Li) detector and a third with a 23-cm^3 Ge(Li) detector incorporated as the central crystal in a pair-spectrometer. The detector efficiency was determined using standard sources and the $^{27}Al(p,\gamma)^{28}Si$ reaction[5] at the 0.992 MeV resonance. The average total cross-sections thus obtained for the $^{88}Sr(p,\gamma_o)^{89}Y$ and $^{89}Y(p,\gamma_o)^{90}Zr$ reactions were 12 ± 5μb and 17 ± 7μb, respectively.

The intensities of transitions to the other bound states averaged over the energy region E_p = 2.3 to 3.0 MeV were also determined from these sets of data and the results, normalized to the ground state intensity, are shown in Table 2. The intensities of eight of the transitions could not be extracted at some bombarding energies because of interference with the $^{19}F(p,\alpha\gamma)^{16}O$ reaction. Because of this interference the results obtained for these eight states are due to only a portion of the pair-spectrometer data and have been normalized to the whole. The data from the single Ge(Li) detector was only useful in determining intensities for transitions to the first few states in each nucleus. The intensities obtained from each set agree with those from the other sets to within the accuracy of the experiment. No corrections have been made for angular distributions as these are not known. The errors indicated on the intensities in Table 2 contain contributions from counting errors, Ge(Li) detector efficiency errors, and Porter-Thomas fluctuations in the proton widths and the radiation widths of the states excited in the compound nucleus.

To determine the size of the Porter-Thomas[17] fluctuations, a statistical analysis was performed on each excitation function. The relative standard deviation was ∿10% in all cases. If we assume that all contributions to the standard deviation are small compared to the Porter-Thomas fluctuations (the counting statistics, for instance, for the low-lying states were only 2%), then an estimate can be made of the density of those states in the compound nucleus that contribute to the yield. For Porter-Thomas fluctuations[17],

$$\langle \Delta\Gamma/\Gamma \rangle = (2/n)^{1/2} \qquad (2)$$

where n is the number of states excited in the energy interval considered. To obtain an estimate of n from our data we replace $\Delta\Gamma/\Gamma$ by the relative standard deviation of the yield. This will allow an order-of-magnitude estimate of the density of states, and we find $n \sim 10^3$/MeV. The theoretical density, calculated from the formalism of Gilbert and Cameron[6], is $\sim 10^4$/MeV for these nuclei, but it is well known[18] that such theories suggest densities that are much too high for nuclei near closed shells.

J-Dependence

Recently, Bollinger and Thomas[10] have reported that the gamma-ray intensities, divided by E_γ^5, of primary transitions following low-energy neutron capture, averaged over many resonances, are determined by the spin and parity of the final state. This comes about because the predominantly s-wave neutron capture can lead to only those states in the compound nucleus which have the same parity as the target ground state and a spin 1/2 unit larger or smaller than the target spin. If it is assumed that the average gamma-ray transition rate for a decay is only governed by its multi-polarity, then summing over the various possible paths to final states of a particular J^π will lead to variations in the intensity of transitions to final states of different J^π. The process of summing over many resonances tends to damp out variations in the intensity of transitions due to nuclear structure effects, leaving the variations as a function of multi-polarity alone. The description of this process is very similar to a Hauser-Feshbach analysis.

In the present case, the sharp cutoff of partial waves with ℓ>o does not occur, but calculations using the optical model code ANSPEC[3] indicate that the decrease of the penetrability is quite rapid; about a factor of three for each unit of angular momentum increase. Hauser-Feshbach calculations indicate (see below and table 3.) that a J-dependence should also occur in (p,γ) reactions of the type studied here. The conditions are that the neutron channel be closed and all other channels, except p_o and γ be weak. Since a J-dependence was expected, we examined our data for a dependence of intensity on final state J^{π}.

This J-dependence effect in (n,γ) reactions is only apparent when the intensities are reduced (divided by some power of E_{γ}) to remove the energy dependence of the radiation widths. Bollinger and Thomas found that the J-dependence was most apparent when the gamma-ray intensities were reduced by E_{γ}^5. This E_{γ}^5 dependence presumably arises (at least for El radiation) because of the influence of the tail of the giant-dipole resonance in the region of gamma-ray energies considered[19]. Since the single-particle model would predict an E_γ^3 dependence[1] for the E1 width, we cannot, *a priori*, exclude reduction by E_γ^3. It should be noted that we assume only E1 radiation need be considered and that contributions arising from other multipolarities are insignificant in comparison. Unfortunately, the only justification for this assumption is the extreme-single-particle model.

Table 2 lists the intensities extracted from the data and these intensities reduced by E_γ^3 and by E_γ^5. A J-dependence is observed in both cases, but especially in ^{90}Zr, the effect is most easily discerned when the data are reduced by E_γ^5. Further discussion will be limited to the data reduced by E_γ^5. Starting with ^{90}Zr, the reduced intensity to the two 0^+ states is the same and significantly smaller than the reduced intensity to the two 2^+ states which are in turn equal to each other. It is to be expected that the reduced intensity to the 2^+ states should be larger because (assuming E1 transitions) the 2^+ states may be fed from 1^-, 2^-, and 3^- states in the compound nucleus, whereas only the 1^- states can contribute to the transitions to the 0^+ states. Although there are no other low-lying pairs of states in ^{90}Zr with the same spin and parity, the reduced intensities to states of $J>2$ are smaller than the yields to 0^+ and 2^+ states assuming that neither the 3^- state nor the 4^- state is receiving most of the strength to the 2.74 MeV doublet. This would be expected since exciting the relative E1 states would require higher ℓ-values for the incoming proton, and this, of course, would mean a reduced penetrability, and, in turn, a reduced contribution from these states. The situation in ^{89}Y is not as clear, because there are no pairs of states of the same known J^{π} that we can resolve. Assuming that the gamma-ray strength function does not change significantly between ^{87}Y and ^{89}Y, the reduced yields to the respective ground states can be compared and they are the same. The reduced intensity to the $3/2^-$ state at 1.507 MeV is not significantly greater than that to the $1/2^-$-ground state and this is reasonable since the difference can only result from E1 contributions from $5/2^+$ states in the compound nucleus. These are not excited strongly because d-wave proton penetrability is small compared to s-wave. The reduced intensity to the $5/2^-$ state at 1.745 MeV is smaller than those mentioned previously and this can be explained because here the $1/2^+$ states, which are formed by s-wave protons, are not contributing to the yield. If the yield to $9/2^+$ states is primiarly due to E1 radiation following capture of f-wave protons, it should be small, as is the case for the intensity to the 0.909-MeV state. The yields to the states at 2.530 2.566 and 2.622 MeV are very suspect. These transition energies occur in a region where $^{19}F(p,\alpha\gamma)^{16}O$ contributions are present. If the yield to the unresolved states at 2.871 and 2.882 MeV is due solely to the 3/2 state, and if we assume it has negative parity, its reduced yield should equal the reduced yield to the 1.507-MeV-$3/2^-$ state, which is the case. If the 3.068-MeV state is assumed to have negative parity, then the expected reduced yield to the triplet at 3.068 MeV, 3.106 MeV, and 3.138 MeV should be 2463, in excellent agreement with the observed reduced yield. It should be noted that we are making no claim of negative parity for the two 3/2 states mentioned above. Since there are no known $3/2^+$ states for comparison, the reduced yield expected to $3/2^+$ states is unknown. It is true that the theory discussed immediately following suggests a negative parity assignment for these 3/2 states, but since the theory fails to explain the yield to the $5/2^+$ state at 2.221 MeV, it cannot be considered reliable.

The thick target data for $^{88}Sr(p,\gamma)^{89}Y$ was compared to the theory of Hauser and Feshbach[20] over the energy range E_p = 2.3 to 3.0 MeV. The proton transmission coefficients were calculated using the program ANSPEC[3] adapted for the University of Kansas GE 635 computer. The gamma-ray transmission coefficients were assumed to be given by[21]

$$T_\gamma = cE^m \tag{3}$$

where c was a constant and m was chosen to be either 3 or 5. Searches for a best fit were made for both values of m by varying the energy-dependent optical-model parameters of Perey[22] and the constant c in Eq. (3) and comparing the Hauser-Feshbach results to the measured intensity ratios. Reasonable fits could be obtained for some value of c for every set of potentials used and for gamma-ray strength depending on either E_γ^3 or E_γ^5. The major difference between acceptable fits was theoretical cross sections differing by as much as a factor of two.

Table 3 shows a particular set of these predicted intensity ratios compared to the measured values. These theoretical results were obtained using proton transmission coefficients calculated with the optical-model parameters given by Perey[22] and gamma-ray transmission coefficients calculated from the expression given by Bollinger[23]. His expression is

$$T_\gamma = 2 \times 10^{-14} A^{8/3} E_\gamma^5 \tag{4}$$

where A is the atomic mass of the nucleus. The results obtained from the Hauser-Feshbach formalism using these particular transmission coefficients were quite similar to those calculated from other parameters. Note that agreement is quite acceptable for the $3/2^-$ state at 1.507 MeV and for the $5/2^-$ state at 1.745 MeV. The theory also predicts a small yield to the $9/2^+$ state at 0.909 MeV as observed. The most disappointing feature is the lack of agreement with the yield to the $5/2^+$ state at 2.221 MeV. The yield of this state is difficult to extract from the data because of the presence of gamma rays from the $^{19}F(p,\alpha\gamma)^{16}O$ reaction. The extracted yield, however, is several times <u>smaller</u> than that which the formalism predicts. The fact that only 14% of the data is used to evaluate the experimental ratio may mean that the discrepancy is a local fluctuation and an average over a larger range of proton energy would improve agreement with the theory.

It is also possible to predict the shapes of the excitation functions using this formalism. The excitation functions generated by the theory do fit the data, but the fluctuations of the individual experimental points are large and this agreement is probably not significant.

The absolute cross section for $^{88}Sr(p,\gamma_o)^{89}Y$ was also calculated. The theoretical average value is 138μb to be compared with the experimental average value of 12 ± 5μb. It is known[24] that failure to account for width fluctuations in Hauser-Feshbach theory will lead to cross sections that are too high.

6. SUMMARY

The possibility of investigating nuclei of A∿90 via (p,γ) reactions, with protons of energy less than 3 MeV, is not only possible, but relatively easy. Each thick-target excitation function was obtained in about 18 hours; the coincidence spectrum in 66 hours. Although large yields can only be expected when the neutron channel is closed, there are ∿25 nuclei in the mass region A∿100 that meet this requirement and for most of them very little data are presently available.

The data are consistent with an E_γ^5 dependence on the gamma-ray strength-function but dependence on other powers is not completely ruled out. There is every indication in the reduced yields that a J-dependence effect is operating, but until data is available for which it is certain that Porter-Thomas fluctuations are small, it will not be possible to adequately test the validity of the Hauser-Feshbach theory for (p,γ) reactions in this mass region.

ACKNOWLEDGMENTS

We wish to thank Dr. L. M. Bollinger, Dr. W. J. Thompson, Dr. J. P. Davidson, and Dr. R. W. Krone for helpful discussions. We are further indebted to the latter two for a critical reading of the manuscript. We are grateful to Dr. S. Fiarman for help in determining the transmission coefficients used in the Hauser-Feshbach analysis.

TABLE 1. The energies of the excited states of ^{89}Y as observed in the coincidence spectrum compared to the accepted energies.

STATE	J^{π}	ACCEPTED ENERGY[a] (MeV)	OBSERVED ENERGY (MeV)
GND	$1/2^-$	0	0
1	$9/2^+$	0.909	--
2	$3/2^-$	1.507	1.507[b]
3	$5/2^-$	1.745	1.745[b]
4	$5/2^+$	2.221	2.222 ± 0.002[c]
5	$7/2^+$	2.530	2.537 ± .004
6	$11/2^{(+)}$	2.566	--
7	$(9/2^+)$	2.622	--
8	$(7/2)^+$	2.871	--
9	3/2	2.882	2.889 ± .005
10	3/2	3.068	3.070 ± .006
11	$5/2^-$	3.106	3.108 ± .006
12	$5/2^-$	3.138	3.138 ± .006
		3.49[d]	3.520 ± .005
		3.61[e]	3.612 ± .004

a) Ref. 8.

b) Accepted energy used as energy calibration standard.

c) Accepted energy of first-excited state used in arriving at this value.

d) Observed in $^{88}Sr(^{3}He,d)^{89}Y$, Ref. 15.

e) Observed in $^{89}Y(p,p')^{89}Y$, Ref. 16.

TABLE 2. Intensities from average spectra. The yields are, in each case, normalized to the ground state yield except for $^{86}Sr(p,\gamma_o)^{87}Y$ which is normalized to the ^{88}Sr data.

REACTION	E_x (MeV)	J^π	% Data	INTENSITIES (RELATIVE)	I/E^3 (RELATIVE)	I/E^5 (RELATIVE)
$^{88}Sr(p,\gamma)^{89}Y$	0.000	$1/2^-$	100	1000 ± 131	1000 ± 131	1000 ± 131
	0.909	$9/2^+$	100	31 ± 22	42 ± 29	50 ± 35
	1.507	$3/2^-$	100	552 ± 94	912 ± 155	1275 ± 217
	1.745	$5/2^-$	100	222 ± 49	401 ± 88	594 ± 130
	2.221	$5/2^+$	14[a]	173 ± 112	374 ± 242	627 ± 407
	2.530, 2.566	$7/2^+, 11/2^{(+)}$	14[a]	236 ± 153	579 ± 376	1057 ± 686
	2.622	$(9/2^+)$	27[a]	180 ± 99	458 ± 252	859 ± 473
	2.871, 2.882	$(7/2)^+, 3/2^-$	30[a]	256 ± 78	730 ± 219	1473 ± 443
	3.068, 3.106, 3.138	$3/2,5/2^-, 5/2^-$	55[a]	412 ± 103	1277 ± 319	2702 ± 675
$^{86}Sr(p,\gamma)^{87}Y$	0.000	$1/2^-$	100[a]	600 ± 168[b]	925 ± 259	1236 ± 346
$^{89}Y(p,\gamma)^{90}Zr$	0.000	0^+	100	1000 ± 131	1000 ± 131	1000 ± 131
	1.761	0^+	100	348 ± 80	584 ± 134	824 ± 190
	2.186	2^+	100	598 ± 144	1152 ± 277	1786 ± 427
	2.319	5^-	75[a]	86 ± 56	173 ± 113	275 ± 179
	2.738, 2.748	$4^-, 3^-$	100[a]	274 ± 66	640 ± 153	1128 ± 271
	3.077	4^+	75[a]	41 ± 41	109 ± 109	205 ± 205
	3.31	2^+	48[a]	301 ± 147	869 ± 426	1762 ± 862

a) Yields taken from 3-crystal pair spectrometer data only.

b) Corrected for relative abundance $^{86}Sr/^{88}Sr$ and normalized to $^{88}Sr(p,\gamma_o)^{89}Y$.

TABLE 3. Comparison of the experimental average intensities of gamma rays (normalized to a ground state yield of 1000) from the $^{88}Sr(p,\gamma)^{89}Y$ reaction to the predictions of Hauser-Feshbach theory.

E_x	J^{π}	Observed Yield	Predicted Yield
0.909	$9/2^+$	31 ±22	109
1.507	$3/2^-$	552 ±94	686
1.745	$5/2^-$	222 ±49	355
2.221	$5/2^+$	173 ±112	487
2.530, 2.566	$7/2^+, 11/2^{(+)}$	236 ±153	114[a]
2.622	$(9/2^+)$	180 ±99	37
2.871, 2.882	$(7/2)^+$, 3/2	256 ±78	465, 336[b]
3.068, 3.106, 3.138	$3/2, 5/2^-, 5/2^-$	412 ±103	635, 524[b]

a) The sum of the expected yields for $7/2^+$ and $11/2^{(+)}$.

b) The sum of the expected yields on the assumption of positive and negative parity, respectively, for the undetermined state.

REFERENCES

[1]V. F. Weisskopf, Phys. Rev. 83, 1073 (1951).

[2]T. Teichmann and E. P. Wigner, Phys. Rev. 87, 123 (1952).

[3]W. J. Thompson and J. L. Adams, ANSPEC-FORTRAN II Program for Analysis of Isobaric Analogue States in Proton Elastic Scattering, Technical Report No. 10, Florida State University (1967). Adapted for the GE 635 computer by S. Fiarman.

[4]W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Revs. Mod. Phys. 20, 236 (1948).

[5]P. M. Endt and C. van der Leun, Nucl. Phys. A105, 140 (1967); M. A. Meyer and N. S. Wolmarans, Nucl. Phys. A136, 663 (1969); R. E. Azuma, L. E. Carlson, A. M. Charlesworth, K. P. Jackson, N. Anyas-Weiss, and B. Lalović, Can. J. Phys. 44, 3075 (1966).

[6]A. Gilbert and A. G. W. Cameron, Can. J. Phys. 43, 1446 (1965).

[7]W. M. Mason, G. Kernel, J. L. Black, and N. W. Tanner, Nucl. Phys. A135, 193 (1969).

[8]D. M. Van Patter, Bull. Am. Phys. Soc. 15, 573 (1970).

[9]J. B. Ball, Bull. Am. Phys. Soc. 15, 574 (1970).

[10]L. M. Bollinger and G. E. Thomas, Phys. Rev. Letters 21, 233 (1968).

[11]C. F. Williamson, J. P. Boujat, and J. Picard, Tables of Range and Stopping Power of Chemical Elements for Charged Particles of Energy 0.05 to 500 MeV. (Atomic Energy Commission, Report No. 3042, France, 1966).

[12]T. Ericson and T. Mayer-Kuckuk, Ann. Rev. Nucl. Sci. 16, 183 (1966).

[13]S. M. Shafroth, P. N. Trehan, and D. M. Van Patter, Phys. Rev. 129, 704 (1963).

[14] C. D. Kavaloski, J. S. Lilley, D. C. Shreve, and N. Stein, Phys. Rev. 161, 1107 (1967).

[15] J. Picard and G. Bassani, Nucl. Phys. A131, 636 (1969).

[16] A. Scott, M. L. Whiten, and W. G. Love, Nucl. Phys. A137, 445 (1969).

[17] C. E. Porter and R. G. Thomas, Phys. Rev. 104, 483 (1956).

[18] For example, see D. J. Hughes and R. L. Zimmerman, in Nuclear Reactions, Vol. I, edited by P. M. Endt and M. Demeur (North-Holland Publishing Company, Amsterdam, 1959).

[19] P. Axel, Phys. Rev. 126, 671 (1962).

[20] W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952).

[21] L. M. Bollinger and G. E. Thomas (to be published).

[22] F. G. Perey, Phys. Rev. 131, 745 (1963).

[23] L. M. Bollinger, in Nuclear Structure (International Atomic Energy Agency, Vienna, 1968).

[24] A. M. Lane and J. E. Lynn, Proc. Phys. Soc. (London) A70, 557 (1957).

FIGURE CAPTIONS

Fig. 1. Presently accepted level schemes for ^{89}Y and ^{90}Zr taken from the data of Van Patter (Ref. 8) and Ball (Ref. 9), respectively.

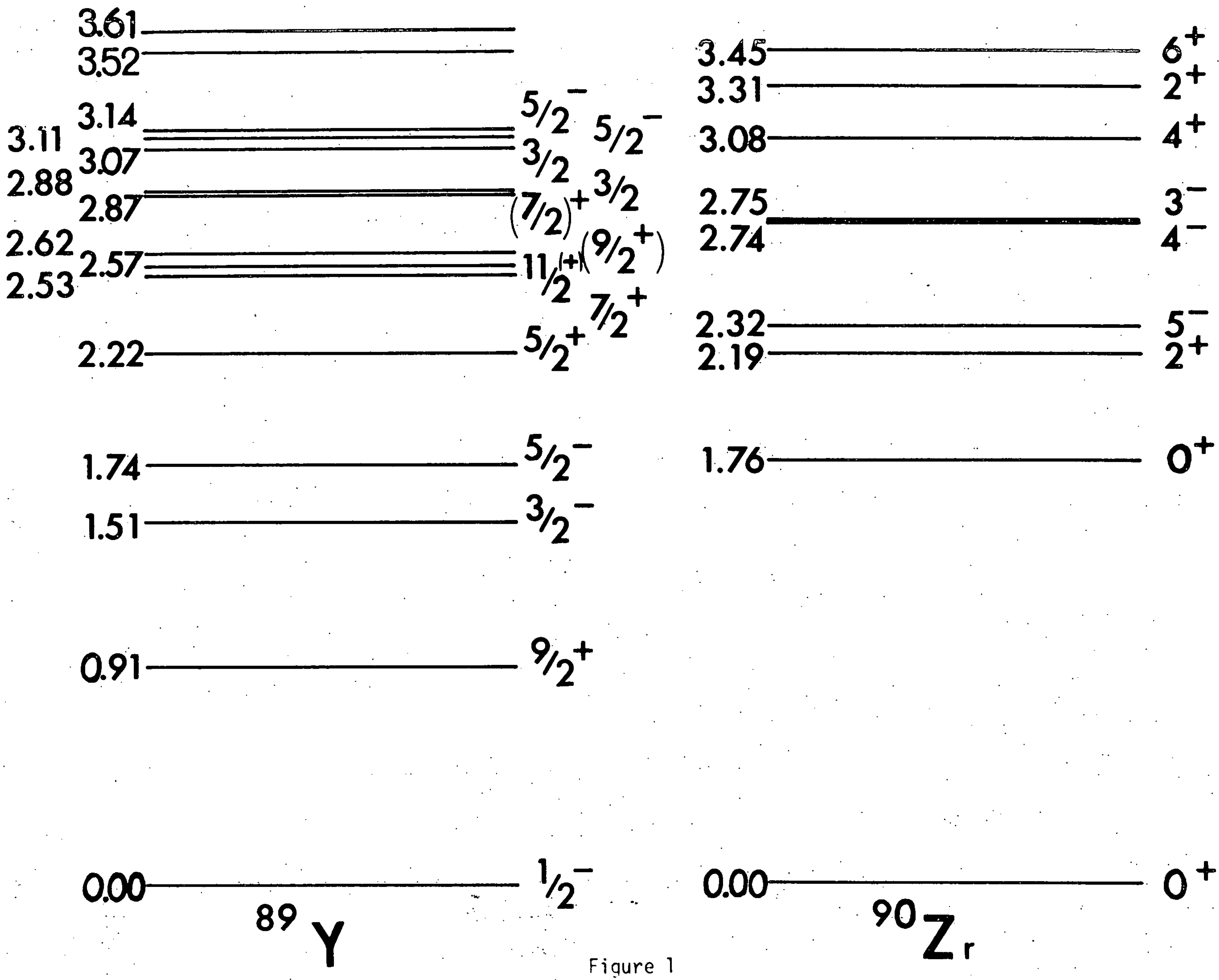
Fig. 2. Excitation functions for $^{88}Sr(p,\gamma_o)^{89}Y$ and $^{89}Y(p,\gamma_o)^{90}Zr$ over the energy region E_p = 2.3 to 3.0 MeV.

Fig. 3. $^{88}Sr(p,\gamma\gamma)^{89}Y$ coincidence spectrum at E_p = 3.0 MeV. A peak that is labeled as 4-1, for example, indicates a transition from the fourth-excited state to the first-excited state. All transitions are full-energy transitions unless otherwise labeled. X-0 (p-2) is the two-escape peak of the transition from the 3.520-MeV level to the ground state, and Y-0 (p-2) is the two-escape peak of the transition from the 3.612-MeV level to the ground state. The two ^{197}Au peaks are from the target backing.

Fig. 4. Decay scheme of ^{89}Y extracted from the coincidence data shown in Fig. 3. The dashed levels are levels reported in the "midstream" analysis of Van Patter (Ref. 8) but which were unobserved in the coincidence spectrum.

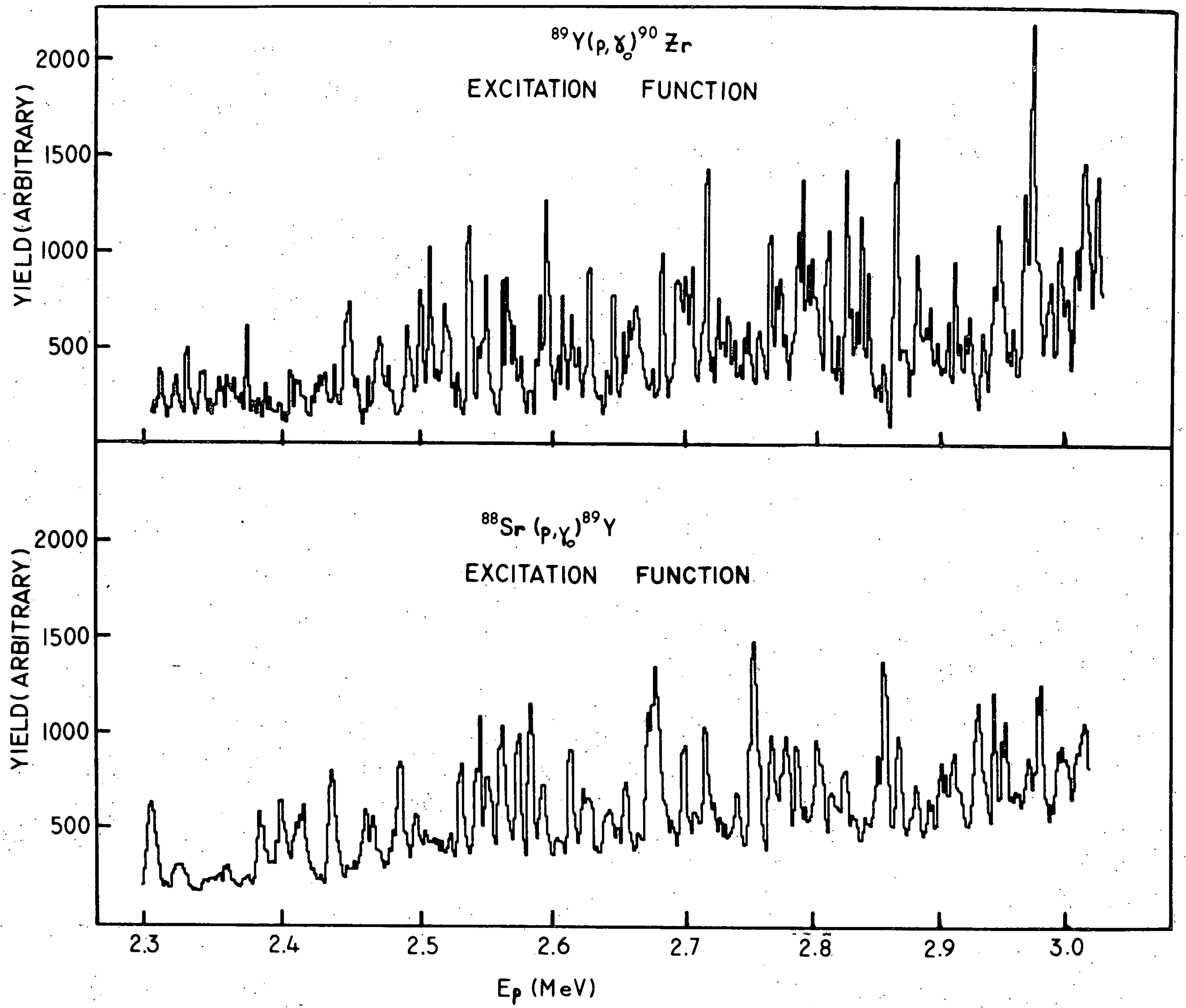
Fig. 5. $^{88}Sr(p,\gamma)^{89}Y$ spectrum for E_p = 3.0 MeV. A peak labeled, for example, as 0 (p-2) indicates the two-escape peak of the gamma-ray transition from the continuum to the ground state. The peak at approximately channel 635 is from the $^{19}F(p,\alpha\gamma)^{16}O$ reaction.

Fig. 6. $^{89}Y(p,\gamma)^{90}Zr$ spectrum for E_p = 3.0 MeV. The same labeling convention is used in this figure as is used in Fig. 5.



3.61
3.52
3.14
3.11
3.07
2.88
2.87
2.62
2.57
2.53
2.22
1.74
1.51
0.91
0.00
5/2−
5/2−
3/2
3/2
(7/2)+
(9/2+)
11/2+
7/2+
5/2+
5/2−
3/2−
9/2+
1/2−
89 Y
3.45
3.31
3.08
2.75
2.74
2.32
2.19
1.76
0.00
6+
2+
4+
3−
4−
5−
2+
0+
0+
90 Zr

Figure 1



$^{89}Y(p,\gamma_0)^{90}Zr$
EXCITATION FUNCTION
$^{88}Sr(p,\gamma_0)^{89}Y$
EXCITATION FUNCTION
YIELD (ARBITRARY)
2000
1500
1000
500
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
E_p (MeV)

Figure 2

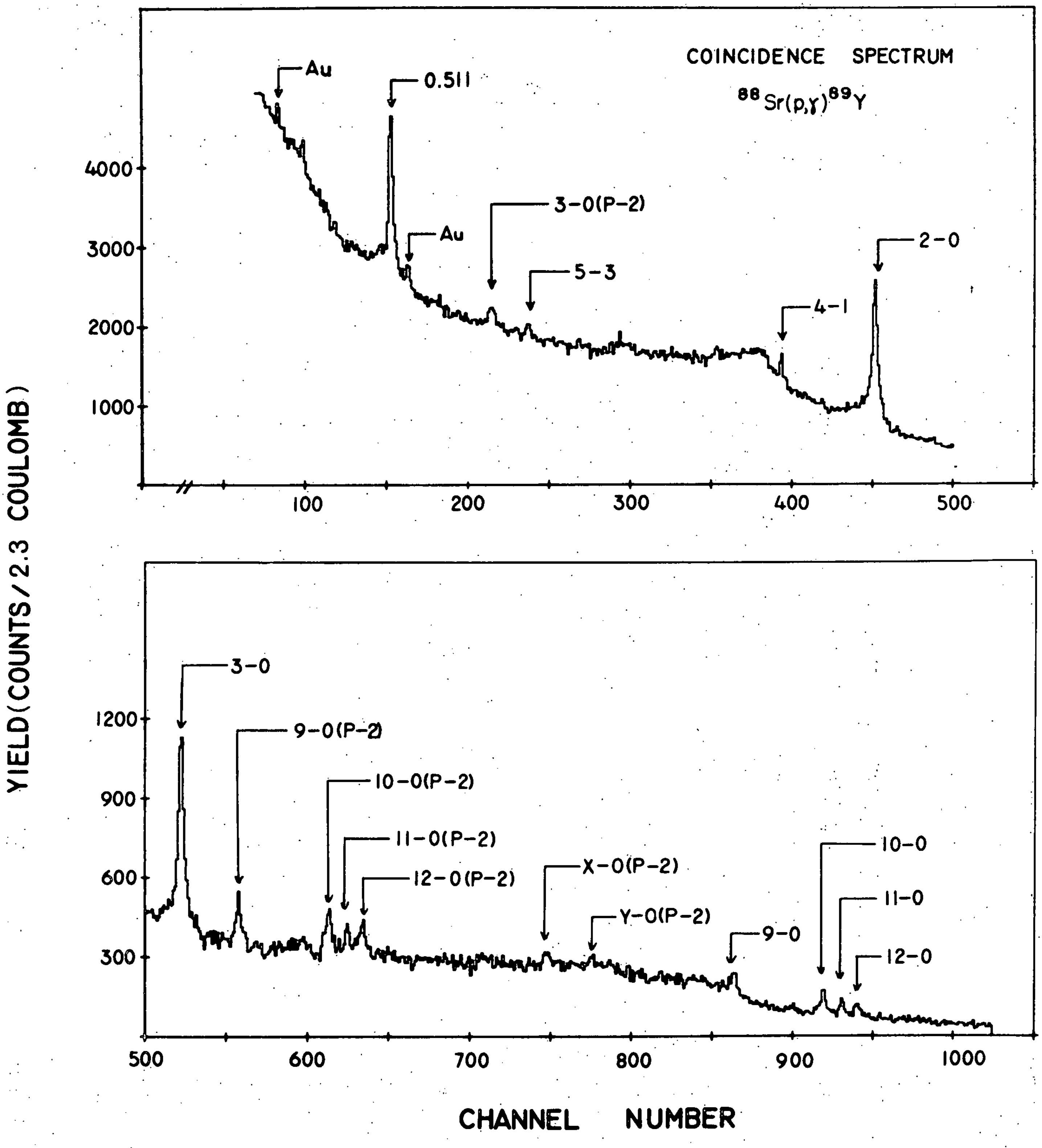

COINCIDENCE SPECTRUM
$^{88}Sr(p,\gamma)^{89}Y$
Au
0.511
Au
3-0(P-2)
5-3
4-1
2-0
4000
3000
2000
1000
100
200
300
400
500
3-0
9-0(P-2)
10-0(P-2)
11-0(P-2)
12-0(P-2)
X-0(P-2)
Y-0(P-2)
9-0
10-0
11-0
12-0
1200
900
600
300
500
600
700
800
900
1000
YIELD (COUNTS/2.3 COULOMB)
CHANNEL NUMBER

Figure 3

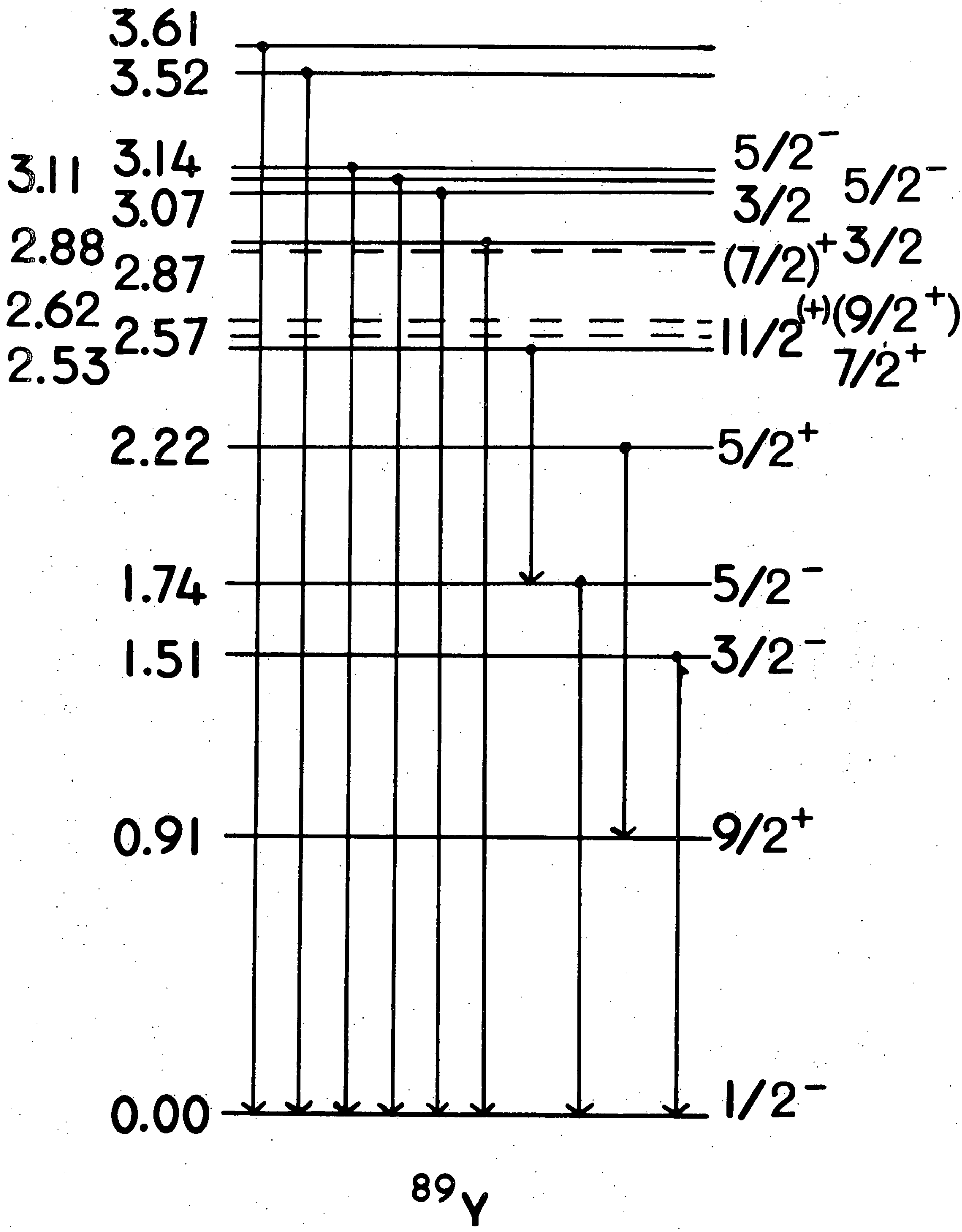
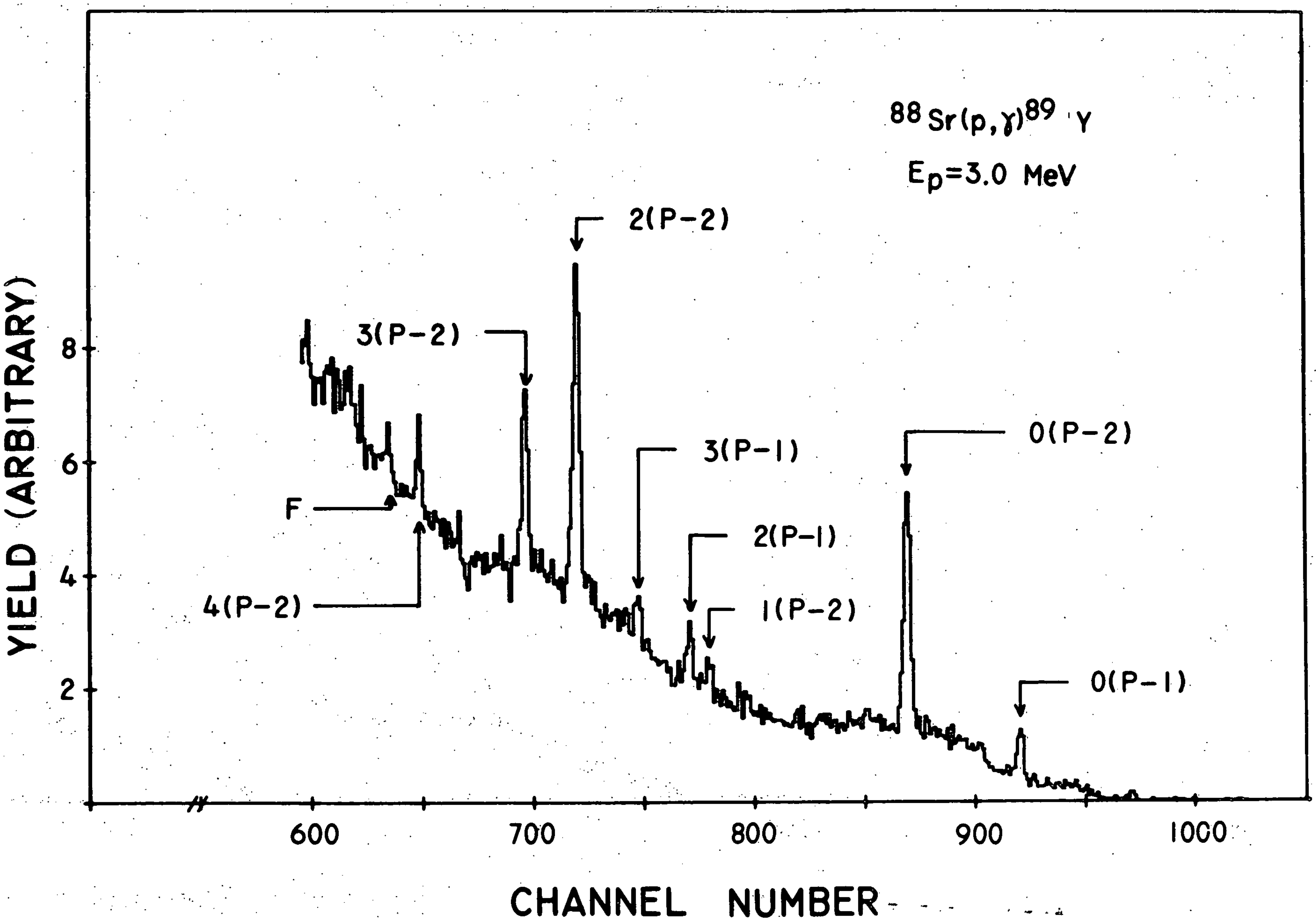
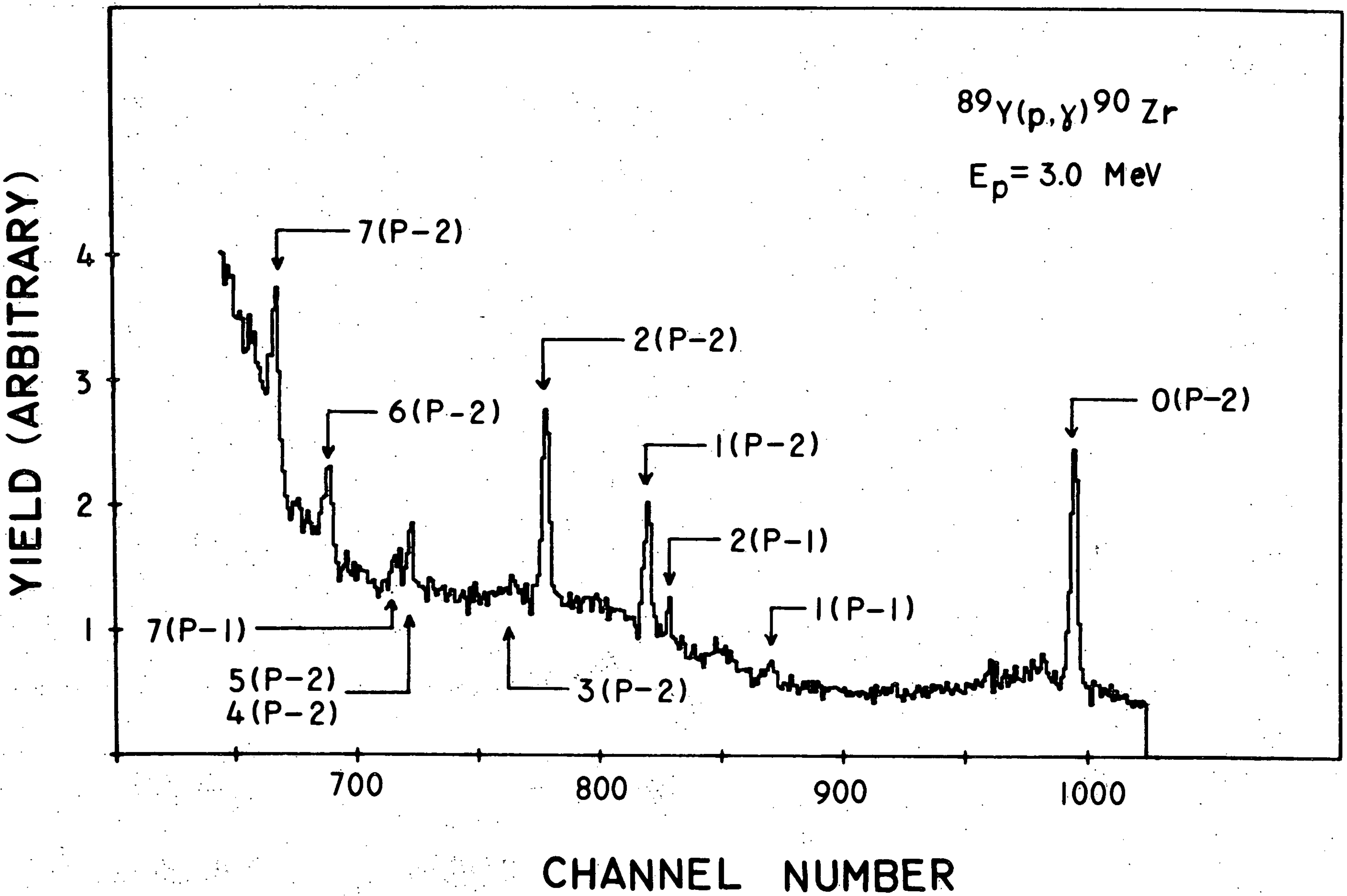

3.61
3.52
3.11
3.14
3.07
2.88
2.87
2.62
2.57
2.53
2.22
1.74
1.51
0.91
0.00
5/2⁻
5/2⁻
3/2
(7/2)⁺
3/2
11/2(+)
(9/2⁺)
7/2⁺
5/2⁺
5/2⁻
3/2⁻
9/2⁺
1/2⁻
89Y

Figure 4



$^{88}Sr(p,\gamma)^{89}Y$
E_p=3.0 MeV
2(P-2)
3(P-2)
3(P-1)
0(P-2)
2(P-1)
1(P-2)
0(P-1)
F
4(P-2)
YIELD (ARBITRARY)
8
6
4
2
600
700
800
900
1000
CHANNEL NUMBER

Figure 5



$^{89}Y(p,\gamma)^{90}Zr$
$E_p = 3.0$ MeV
YIELD (ARBITRARY)
4
3
2
1
7(P−2)
6(P−2)
2(P−2)
O(P−2)
1(P−2)
2(P−1)
1(P−1)
7(P−1)
5(P−2)
4(P−2)
3(P−2)
700
800
900
1000
CHANNEL NUMBER

Figure 6