PHYSICAL REVIEW C VOLUME 23, NUMBER 5 MAY 1981

Enhanced primary dipole transitions in the ^{89}Y(n,γ) reaction

S. Raman, O. Shahal,* A. Z. Hussein,† G. G. Slaughter, and J. A. Harvey
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 5 November 1980)

Neutron capture γ rays from a ^{89}Y target have been studied for several resonances below 6 keV neutron energy employing a Ge(Li) detector and time-of-flight techniques. The primary $M1$ and $E1$ transitions leading to low-lying states in ^{90}Y show some enhancements. The 3.38-keV resonance (suggested previously as s wave on the basis of the smallness of the total radiation width) is definitely shown to be a p-wave resonance through neutron transmission measurements.

NUCLEAR REACTIONS ^{89}Y(n, γ), E_n =1–6 keV, measured E_γ, I_γ; ^{89}Y(n), E_n =1–10 keV, measured total $\sigma(E)$. ^{90}Y deduced resonances, resonance parameters, levels, neutron separation energy. Ge(Li) detector.

I. INTRODUCTION

The γ-ray spectra following resonance neutron capture are usually complex except near closed shells. In the case of resonance neutron capture on ^{207}Pb and ^{206}Pb, the γ-ray decay patterns from several resonances were found to be strikingly simple, being composed of less than five primary γ rays.[1] Near the N = 50 closed neutron shell we have carried out a study of the ^{89}Y(n,γ) reaction at the Oak Ridge Electron Linear Accelerator (ORELA). The γ-ray decay patterns were again sufficiently simple that we were able to deduce absolute partial radiation widths from the total radiation width and the branching ratios. The results could then be compared with empirical radiation widths for dipole transitions.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The ORELA facility was used to provide a pulsed beam (40-nsec burst at a repetition rate of 800 Hz) of neutrons for capture studies of a 200 g ^{89}Y metal target. Overlap neutrons were suppressed by a ^{10}B filter in the beam. Time-of-flight gates were set on and off the capture resonances (Fig. 1) and γ rays were detected with a 37 cm^3 Ge(Li) detector. The total running time was 2 weeks while ORELA was operated at a beam power of 36 kW. Additional experimental details follow closely those outlined in the last entry of Ref. 1. Fig. 2 shows the high-energy portions of the γ-ray spectra from several resonances. The level scheme (and the neutron separation energy) for ^{90}Y based on the present data is shown in Fig. 3. The energies (known to better than ±0.10 keV) of the bound states given in this figure were, however, obtained from the more precise thermal neutron capture γ-ray studies carried out at Los Alamos.[2] These studies also show that the secondary γ rays shown in Fig. 3 as feeding the ground state account for ≈90% of the thermal capture cross section. Therefore, it is possible to deduce the partial radiation widths shown in Table I from the known total radiation widths, the measured relative intensities of the γ rays, intensity balance at each level, and the summed intensities of γ rays feeding the ground state.

Previous spin and parity (J^π) assignments for the resonances below 6 keV from neutron transmission[3] and capture cross section measurements[4] are summarized in Table II. We can exclude J=0 and J=2 for both the 2.609 and 3.383 keV resonances on the basis of the observation of strong γ rays to the 1212 keV, 0$^-$ state from these resonances. We can also exclude the 0$^+$ assignment for the 5.714 keV resonance since a strong γ ray from this resonance was observed populating the 2$^-$ ground state. The J^π assignments for the bound states of ^{90}Y are those given in a recent compilation.[5] The ^{89}Y ground state has J^π = 1/2$^-$.

The definite positive parity assignment proposed by Morgenstern *et al.*[3] (from the absence of interference between resonance and potential scattering) for the 3.383-keV resonance was changed by Boldeman *et al.*[4] to a tentative negative parity assignment. The argument was as follows. Boldeman *et*

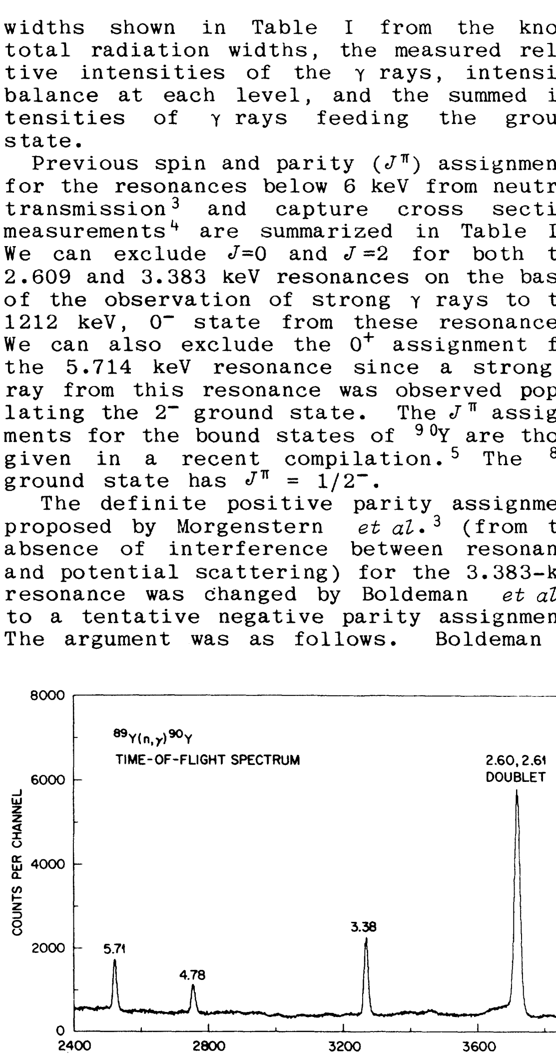

FIG. 1. Time-of-flight spectrum for all γ-ray events above 100 keV. The resonance energies are in keV.

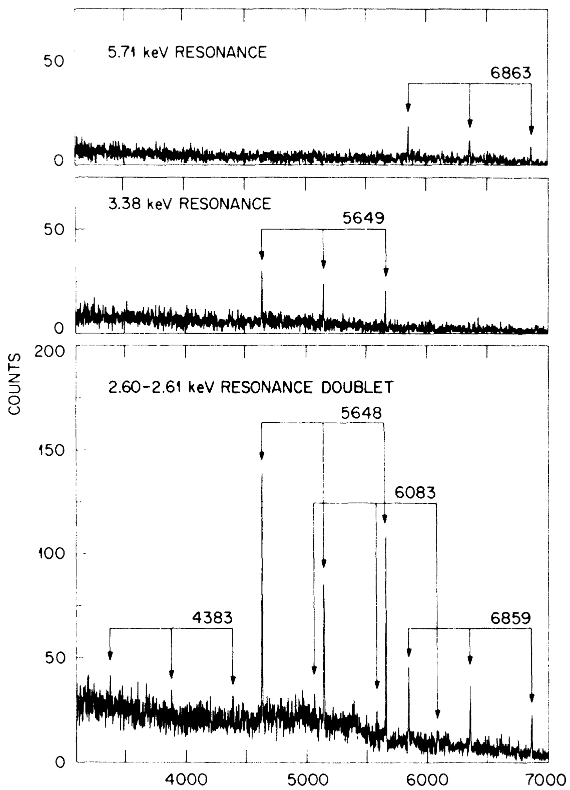

FIG. 2. High-energy portions of γ-ray spectra (without off-resonance background subtractions) from several resonances in ^{89}Y. All γ-ray energies are in keV. The primary transitions were very weak in the spectrum (not shown here) from the 4.78-keV resonance.

al.[4] determined the average total radiation widths (Γ_γ) to be ≈320 meV and ≈120 meV, respectively, for the 13 *p*-wave and 9 *s*-wave resonances below 31 keV. Since they found Γ_γ = 60 ± 6 meV for the 3.383-keV resonance, they suggested an *s*-wave or negative parity assignment for this resonance. (The *d*-wave possibility is excluded by penetrability arguments.) It is easy to show that the known[4] *p*-wave radiation widths are consistent with a Porter-Thomas distribution of ν = 9 degrees of freedom and, therefore, the probability of obtaining a radiation width < 60 meV from this class is < 0.5%.

We have carried out neutron transmission measurements to verify the J^π assignments for the low-lying resonances in ^{89}Y. A "thin" metal target of 0.0193 atoms/b and a "thick" metal target of 0.0967 atoms/b were employed in these measurements. Neutrons were detected with a 1.27-cm thick ^{6}Li glass detector at 78.20 m from the ORELA pulsed neutron source. The transmission data were analyzed with an *R*-matrix least squares fitting computer program MULTI[6] (which also folds in the Doppler broadening and experimental energy resolution) to extract neutron widths of the observed resonances. Values given in Refs. 3 and 4 were employed as starting parameters in this iterative procedure. Fig. 4 shows the transmission data in selected energy regions for both targets, together with the transmission curve calculated from the deduced resonance parameters, which are given in Table III. Listed are the resonance energy, the orbital angular momentum (ℓ), the spin and parity (J^π) values for all except the weak 7.3-keV resonance, the quantity $g\Gamma_n$ obtained from the area of the

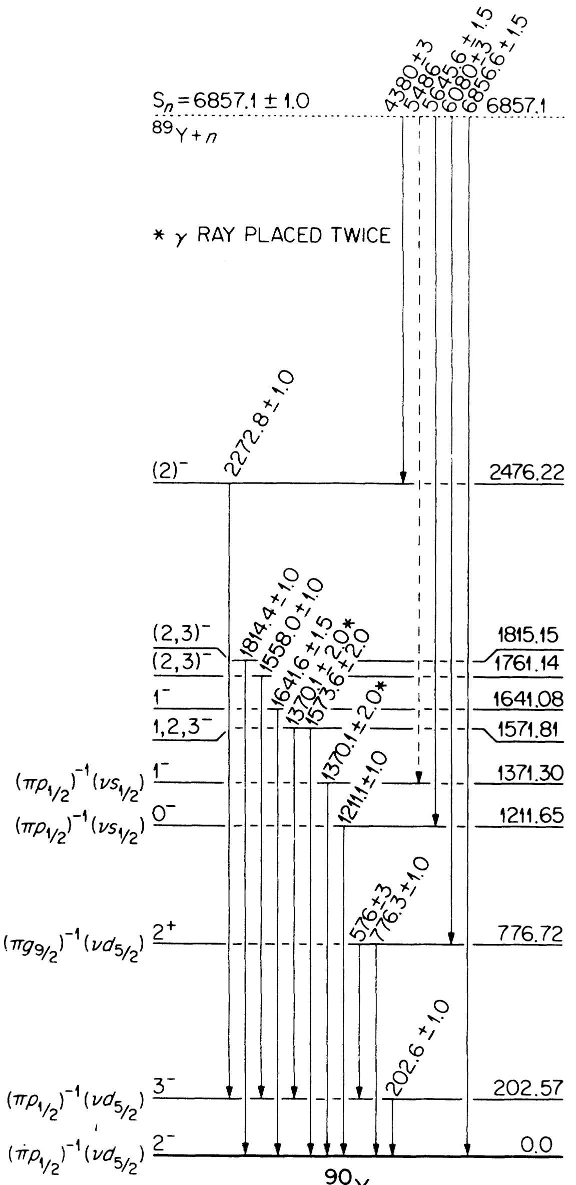

FIG. 3. Level scheme for ^{90}Y. All energies are in keV. The shell model proton-hole, neutron-particle configurations are shown on the left.

TABLE I. Radiation widths for primary transitions in the $^{89}Y(n,\gamma)^{90}Y$ reaction.

E_n (keV)	J	$\Gamma_{total\ \gamma}$[a] (meV)	$\Gamma_{6.86\ \gamma}$ (meV)	$\Gamma_{6.08\ \gamma}$ (meV)	$\Gamma_{5.65\ \gamma}$ (meV)	$\Gamma_{5.49\ \gamma}$ (meV)	$\Gamma_{4.38\ \gamma}$ (meV)	Γ_{others}[b] (meV)
2.599[c]	1^-	125 *10*	142 *16*	15 *6*	453 *62*	<8	15 *6*	<6
2.609[c]	1^+	500 *50*						
3.38	1^+	56 *6*	<3	<4	56 *6*	<4	<4	<2
5.71[d]	1^+	180 *18*	125 *13*	<6	<6	<6	<10	55
	2^+	108 *11*	76 *8*	<4	<4	<4	<6	32

[a]See also Table III. In our notation, 125 *10* ≡ 125 ± 10, etc.
[b]Represents the difference between the summed intensities of observed γ rays feeding the ground state and those de-exciting the capturing state. The intensity of the 202.6 keV γ ray (which was not well-resolved from a strong 198.1 keV background line) was deduced from the summed intensities of γ rays feeding the 202.57 keV state.
[c]Unresolved in the present experiment.
[d]Resonance of positive parity and spin restricted to 1 or 2.

transmission dip, the quantity $g\Gamma_n\,\Gamma_\gamma/\Gamma$ obtained from previous ORELA capture measurements,[4] and, for sufficiently strong resonances, the deduced value for $g\Gamma_\gamma$. Resonances were identified as *s*-wave ($\ell=0$) or *p*-wave ($\ell=1$) on the basis of a careful shape analysis designed to detect the presence or absence of interference between resonance and potential scattering. Even though the probability that the 3.383-keV resonance is *p*-wave was estimated as only 1 in 200 (see previous paragraph), we find that this resonance is definitely a *p*-wave or positive parity resonance as shown in Fig. 4(d). The $\nu = 9$ value discussed previously reduces to $\nu = 6$ if the above resonance is included in the Porter-Thomas analysis of the 14 *p*-wave resonances below 31 keV. Correspondingly, the probability of obtaining a radiation width < 60 meV increases to 2% when $\nu = 6$.

III. DISCUSSION

Even though the 2.599 keV, 1^- resonance and the 2.609 keV, 1^+ resonance were not resolved in the present (n,γ) experiment, several conclusions can be drawn from Table I. Two γ rays of energies 6.86 and 5.65 MeV account for 595 meV out of a total radiation width of 625 meV for the 2.6-keV doublet. These γ rays lead respectively to the 0.0 MeV, 2^- state and the 1.21 MeV, 0^- state in ^{90}Y. The weak 6.08 and 4.38 MeV γ rays account for the remaining 30 meV. Two *M*1 transitions must account for at least ≈ 95 meV out of 125 meV total radiation width associated with the 2.599 keV, 1^- resonance. Therefore, either the 6.86 MeV or the 5.65 MeV transition must carry away at least 47 meV of *M*1 strength. In the case of the 3.38 keV resonance (see Table I), the 5.65 MeV transition has an *E*1 strength of 56 meV, and in the case of the 5.71 keV resonance, the 6.86-MeV transition carries an *E*1 strength of 125 or 76 meV, depending on the spin of this resonance.

The photon strength function is usually defined as $k(M1) = \langle\Gamma_\gamma\rangle/DE_\gamma^3$ and $k(E1) = \langle\Gamma_\gamma\rangle/DE_\gamma^3 A^{2/3}$, where $\langle\Gamma_\gamma\rangle$ refers to the average partial radiation width in eV, *D* to the spacing (in eV) of resonances with the same spin and parity, and E_γ to the γ-ray energy in MeV. Bollinger[7] has estimated that, for medium and heavy nuclei, $k(M1) \approx 1.8 \times 10^{-8}$ MeV^{-3} and $k(E1) \approx 3 \times 10^{-9}$ MeV^{-3}. A more recent survey by McCullagh

TABLE II. Spin and parity assignments for the low-lying neutron resonances in ^{89}Y.

Ref. 4 E_n(keV)[a]	Ref. 3 $g\Gamma_n$(eV)[a]	Ref. 3 J^π[b]	Ref. 4 J^π[c]	Present J^π[d]
2.599 *5*	0.73 *18*	(1^-)	1^-	1^-
2.609 *5*	0.75 *13*	(+)	$(1)^+$	1^+
3.383 *7*	0.28 *4*	$(1,2)^+$	(1^-)	1^+
4.779 *9*	0.042 *6*	+		$1,2^+$
5.714 *10*	0.15 *3*	+		$1,2^+$

[a]In our notation, 2.599 *5* ≡ 2.599 ± 0.005, 0.73 *18* ≡ 0.73 ± 0.18, etc.
[b]From peak cross section and shape analysis in neutron transmission measurements.
[c]For the 2.599 and 2.609 keV resonances, from Γ_n in capture and $g\Gamma_n$ (Ref. 3). The 3.383 keV resonance is discussed in the text.
[d]From neutron transmission measurements and from the γ-ray decay pattern of the resonances (See also Table III).

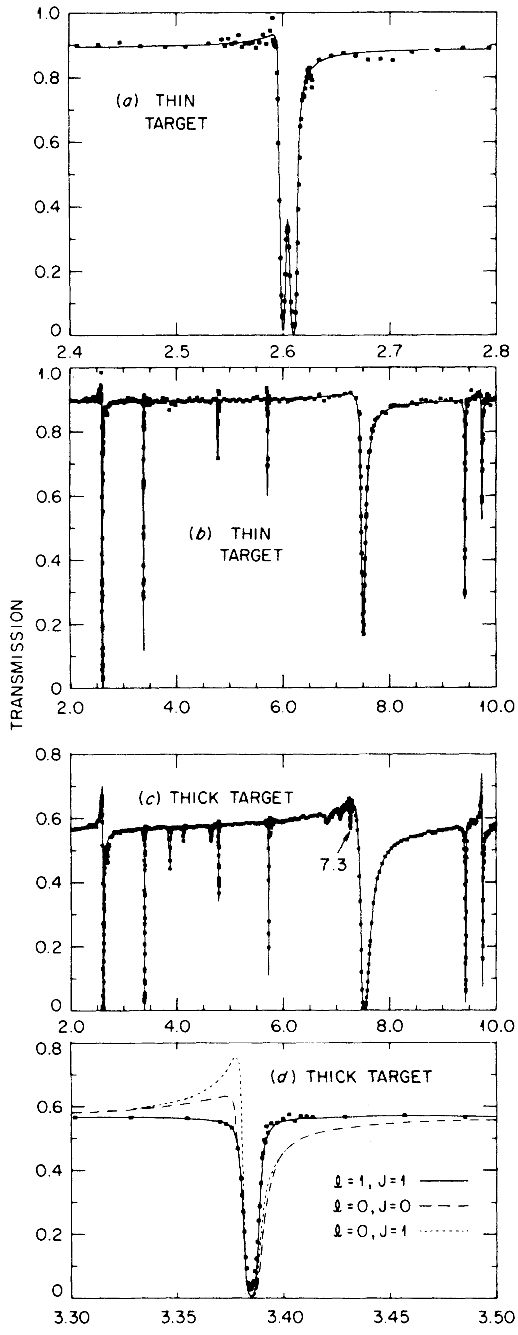

FIG. 4. Neutron transmission data obtained at a flight path of 78.20 m with a thin (0.0193 atoms/b) and a thick (0.0967 atoms/b) metal ^{89}Y target. Also shown are calculated curves based on the deduced resonance parameters. Weak peaks, not explicitly included in Table III, arise from impurities in the targets.

and Chrien[8] has yielded $k(M1) = (3.0 \pm 0.4) \times 10^{-8}$ MeV^{-3} and $k(E1) = (2.9 \pm 0.3) \times 10^{-9}$ MeV^{-3}. If we use the latter k values and $D \approx 1.33$ keV (Ref. 9) for $J=1$ states,

TABLE III. Resonance parameters of ^{89}Y.

E_n[a] (keV)	ℓ[b]	J^{π}[b]	$g\Gamma_n$[c] (eV)	$g\Gamma_n\Gamma_\gamma/\Gamma$[d]	Γ_γ[e] (meV)
2.600 *4*	0	1^-	0.642 *15*	82 *8*	125 *10*
2.610 *4*	1	1^+	1.058 *30*	277 *30*	500 *50*
3.383 *5*	1	1^+	0.438 *9*	38 *4*	56 *6*
4.779 *6*	1	$1,2^+$	0.034 *4*	28 *3*	
5.715 *7*	1	$1,2^+$	0.145 *8*	70 *7*	
7.267 *15*			0.06 *2*	1	
7.512 *8*	0	0	14.5 *6*	28 *3*	112 *12*
9.424 *8*	1	1^+	2.173 *55*	113 *11*	159 *16*
9.743 *9*	0	1^-	1.144 *38*	83 *8*	119 *12*

[a]Resonance energy. In our notation 2.600 *4* ≡ 2.600 ± 0.004, etc.
[b]From a detailed analysis of the magnitude and shape of the transmission dip.
[c]From the area of the transmission dip.
[d]From previous (Ref. 4) capture cross section measurements.
[e]Total radiation width calculated for those resonances with definite g values. $g = (2J+1)/4$ for the present case.

we obtain predicted $\langle\Gamma_\gamma\rangle$ values of (7 ± 1) meV and (13 ± 2) meV, respectively, for the 5.65 and 6.86 MeV $M1$ transitions. If these transitions are $E1$, the predicted $\langle\Gamma_\gamma\rangle$ values become (14 ± 2) meV and (25 ± 3) meV, respectively. (The predicted values are 60% of the above values if $J=2$). The measured radiation widths for these two transitions (see previous paragraph) are considerably larger than expected; but the $M1$ and $E1$ enhancements are only suggestive, since we have studied very few resonances and, therefore, may not have the correct values for the *average* partial radiation widths.

The low-lying states in ^{90}Y can be interpreted[10-13] in terms of simple shell-model states as shown in Fig. 3. If a 1^- capturing state also has a simple configuration of the type $(\pi p_{1/2})^{-1}(\nu s_{1/2})$, an $E1$ transition to the 777 keV, 2^+ state would not be expected. It is tempting to invoke such arguments to explain the near absence of the 6.08 MeV, $E1$ transition from the 2.599-keV, 1^- resonance. In thermal neutron capture, however, the 6.08-MeV transition does dominate the γ-ray spectrum and accounts for nearly 2/3 of the total primary intensity.[2] It can be easily shown that the known 1^- resonances account for < 2 mb of the thermal capture cross section[2] of 1040 ± 22 mb. The contribution due to potential capture is expected[9] to be only ≈100 mb. It follows that thermal capture is probably due to a bound state (a negative energy resonance) and that this state has a complex configuration.

In the (n,γ) reaction with low-energy neutrons, the partial radiation widths from adjacent resonances are almost always uncorrelated with each other. However, in a study of the $^{35}Cl(n,\gamma)^{36}Cl$ and the $^{56}Fe(n,\gamma)^{57}Fe$ reactions, Chrien and Kopecký[14] found similar γ-ray spectra from neighboring capture states of opposite parity. A similar effect was observed recently in ORELA measurements[15] of the $^{58}Fe(n,\gamma)^{59}Fe$ reaction. In the present case, since we did not obtain the γ-ray spectra from the 2.60-keV, 1^- resonance and the 2.61-keV, 1^+ resonance separately, we cannot assert that the spectra are similar, but we can state that they are not too dissimilar in the sense that the 1^- resonance does prefer to decay via strong $M1$ transitions (or transition) to negative parity states (or state) instead of the usually preferred $E1$ decay modes.

This research was sponsored by the Division of Basic Sciences, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

---

*Permanent address: Nuclear Research Centre-Negev, Beer-Sheva, Israel.
†Permanent address: Nuclear Research Center, Cairo, Egypt.

[1]S. Raman, M. Mizumoto, and R. L. Macklin, Phys. Rev. Lett. 39, 598 (1977); S. Raman, M. Mizumoto, G. G. Slaughter, and R. L. Macklin, Phys. Rev. Lett. 40, 1306 (1978); M. Mizumoto, S. Raman, R. L. Macklin, G. G. Slaughter, J. A. Harvey, and J. H. Hamilton, Phys. Rev. C 19, 335 (1979).
[2]D. Deckman, R. K. Sheline, and E. T. Jurney, private communication, results obtained at the Los Alamos Omega West Reactor. See also V. J. Orphan, N. C. Rasmussen, and T. L. Harper, Gulf General Atomic Report No. GA-10248 (1970) for results obtained at the Massachusetts Institute of Technology.
[3]J. Morgenstern, R. N. Alves, J. Julien, and C. Samour, Nucl. Phys. A123, 561 (1969).
[4]J. W. Boldeman, B. J. Allen, A. R. de L. Musgrove, and R. L. Macklin, Nucl. Sci. Eng. 64, 744 (1977).
[5]C. M. Lederer, V. S. Shirley, E. Browne, J. A. Dairiki, R. E. Doebler, A. A. Shihab-Eldin, L. J. Jardine, J. K. Tuli, and A. B. Buyrn, *Table of Isotopes, Seventh Edition* (Wiley, New York, 1978).
[6]G. F. Auchampaugh, Los Alamos Scientific Laboratory Report No. LA-5473-MS, 1974 (unpublished).
[7]L. M. Bollinger, in *Proceedings of the (Asilomar) International Conference on Photonuclear Reactions and Applications*, edited by B. L. Berman (NTIS, Springfield, Va., 1973) p. 783.
[8]C. M. McCullagh and R. E. Chrien, *Neutron Capture Gamma-Ray Spectroscopy*, edited by R. E. Chrien and W. R. Kane (Plenum, New York, 1979) p. 687, and private communication.
[9]J. E. Lynn, *The Theory of Neutron Resonance Reactions* (Clarendon, Oxford, 1968). See Table 4.1 on p. 109 and Fig. 7.12 on p. 338.
[10]N. Mishra, C. Fred Moore, and C. E. Watson, Nucl. Phys. A110, 353 (1968).
[11]W. Lins, J. Ernst, N. Takahashi, E. Grosse, and D. Proetel, Nucl. Phys. A179, 161 (1972).
[12]R. E. Goans and C. R. Bingham, Phys. Rev. C 5, 914 (1972).
[13]S. Cochavi, S. Gilad, M. A. Moinester, J. Alster, M. Buenerd, and P. Martin, Nucl. Phys. A233, 73 (1974).
[14]R. E. Chrien and J. Kopecký, Phys. Rev. Lett. 39, 911 (1977).
[15]J. C. Wells, Jr., S. Raman and G. G. Slaughter, Phys. Rev. C 18, 707 (1978).