nuclei, including ^{28}Mg. However, its validity is in some doubt for ^{28}Mg because of its qualitatively incorrect prediction for the ratio $B(E2)(4^+ \to 2^+)/B(E2)(2^+ \to 0^+)$. A measurement of the quadrupole moment of the 2_1^+ level would be useful, since the predictions of the shell model (0.17 b) and the triaxial model (−0.14 b) have opposite signs, but unfortunately such a measurement is not feasible with the techniques currently available.

ACKNOWLEDGMENTS

The authors thank D. Kurath for providing them with the results of the triaxial model calculation. We also thank M. J. A. de Voigt and B. H. Wildenthal for making their ^{28}Mg results available prior to publication.

---

†Work supported by the Lockheed Independent Research Fund.

[1]B. H. Wildenthal, J. B. McGrory, and P. W. M. Glaudemans, Phys. Rev. Lett. **26**, 96 (1971).

[2]J. B. McGrory and B. H. Wildenthal, Phys. Lett. **34B**, 373 (1971).

[3]D. Kurath, Phys. Rev. C **5**, 768 (1972).

[4]R. Middleton and D. J. Pullen, Nucl. Phys. **51**, 77 (1964).

[5]L. F. Chase, Jr., *et al.*, Bull. Am. Phys. Soc. **12**, 555 (1967); J. A. Becker, in *The Structure of Low-Medium Mass Nuclei,* edited by J. P. Davidson (University Press of Kansas, Lawrence, 1968), pp. 1–22; L. F. Chase, Jr., *Nuclear Research with Low Energy Accelerators* (Academic, New York, 1967), p. 445.

[6]A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).

[7]M. J. A. de Voigt and B. H. Wildenthal, to be published in Nucl. Phys.

[8]R. A. Chalmers, IEEE Trans. Nucl. Sci. **16**, 132 (1969).

[9]R. K. Bardin, California Institute of Technology Report No. Ba61 (unpublished).

[10]J. Lindhard, M. Scharff, and H. E. Schiøtt, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 33, No. 14 (1963).

[11]A. E. Blaugrund, Nucl. Phys. **88**, 501 (1966).

[12]J. H. Ormrod, J. R. MacDonald, and H. E. Duckworth, Can. Phys. 43, 275 (1965); B. Fastrup, P. Hvelplund, and C. A. Sautter, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 35, No. 10 (1966).

[13]C. P. Swann, Phys. Rev. C **4**, 1489 (1971); D. Vitoux, R. C. Haight, and J. X. Saladin, Phys. Rev. C **3**, 718 (1971); O. Haüsser, B. W. Hooton, D. Pelte, and T. K. Alexander, Can. J. Phys. **48**, 35 (1970); S. J. Skorka, D. Evers, J. Hertel, J. Morgenstern, T. W. Retz-Schmidt, and H. Schmidt, Nucl. Phys. **81**, 370 (1966).

PHYSICAL REVIEW C VOLUME 7, NUMBER 5 MAY 1973

Study of the Energy Levels of ^{69}Ga Using Nuclear Photoexcitation

R. Moreh, O. Shahal, J. Tenenbaum, A. Wolf, and A. Nof

Nuclear Research Center, Negev, Beer Sheva, Israel

(Received 10 October 1972)

Elastic and inelastic scattering of monochromatic photons were used for studying nuclear energy levels in ^{69}Ga; the photons were produced by thermal neutron capture in copper and vanadium. The decay of one resonance at 7306 keV excited by the copper γ source and another resonance at 6874 keV excited by the vanadium γ source were studied in detail and 30 low-lying levels were observed from the ground state up to 3.4 MeV, 17 of which are believed to be new levels in ^{69}Ga. The angular distribution of some elastic and inelastic lines were measured and the following spin determinations were made (keV, J^π): 320, $\frac{1}{2}^-$, $(\frac{3}{2}^-)$; 574, $\frac{5}{2}^-$; 872, $\frac{3}{2}^-$; 1488, $\frac{3}{2}^-$, $\frac{7}{2}^-$; 1525 $(\frac{1}{2}, \frac{3}{2})$; 1891, $\frac{3}{2}^-$;(1978), $(\frac{1}{2}, \frac{3}{2})$; 2457, $\frac{3}{2}$; 2484, $\frac{5}{2}$; (2565), $(\frac{1}{2}, \frac{3}{2})$; 2660, $\frac{3}{2}$; 3051, $(\frac{3}{2}, \frac{7}{2})$; 3076, $\frac{5}{2}$; 3318, $(\frac{7}{2})$; 6874, $\frac{1}{2}^{(+)}$ and 7306, $\frac{5}{2}^+$, where parentheses denote uncertain J^π assignments. The parity of the 7306-keV level was directly determined using a Compton polarimeter. The total radiative width of the 7306-keV level was measured and found to be $\Gamma = 0.105 \pm 0.020$ eV. For the 6874-keV level, a positive correlation coefficient was obtained, $\rho = 0.69$, between the (γ,γ') and (d,n) transition strengths leading to the same final states in ^{69}Ga. The levels of ^{69}Ga are compared with recent theoretical calculations.

I. INTRODUCTION

In the past few years, the technique of nuclear photoexcitation using neutron capture γ rays, has been employed for studying the energies and spectroscopic properties of nuclear levels in several isotopes.[1–8] In the present work, the same technique is used for studying the energy levels of ^{69}Ga using γ sources obtained from thermal neutron capture in copper and vanadium. The deexcitation of the 7306-keV level of ^{69}Ga excited by the γ rays of copper had been studied in detail.

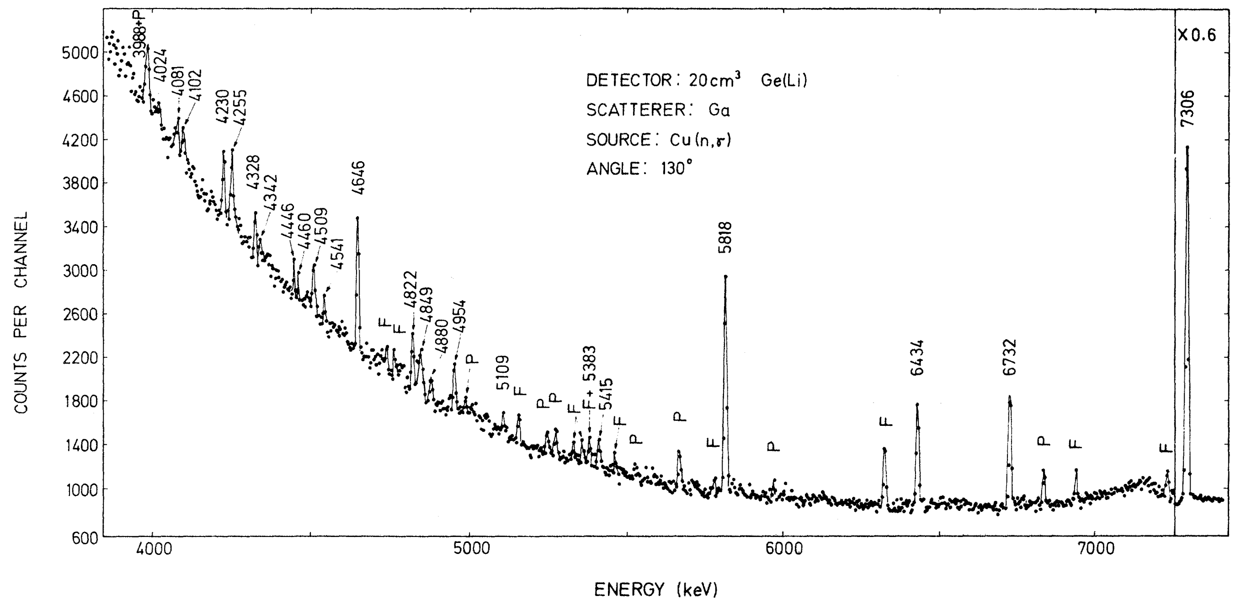

FIG. 1. High-energy part of the scattered γ spectrum from a Ga target at an angle of 140° measured by a 20-cm^3 Ge(Li) detector. The γ source was obtained from the Cu(n,γ) reaction. γ lines denoted by P and F refer to photopeaks and first-escape peaks, respectively; other lines refer to double-escape peaks.

The positioning of 17 new levels was made by relying on the assumption that strong high-energy γ rays are primary transitions from the 7306-keV resonance. In the case of vanadium γ source, two resonances were excited (one in ^{69}Ga and the other in ^{71}Ga), of which only one γ line at 6874 keV (in ^{69}Ga) was strongly scattered. Therefore, no new levels were deduced from the resonances excited by the γ rays of V, because of the ambiguities involved in this process. Hence, the information obtained from the 6874-keV resonance was only employed to confirm the existence of new levels populated by the decay of the 7306-keV resonance.

The ^{69}Ga energy levels were studied both experimentally[9-14] and theoretically.[9,15-17] The experimental information was summarized by Couch

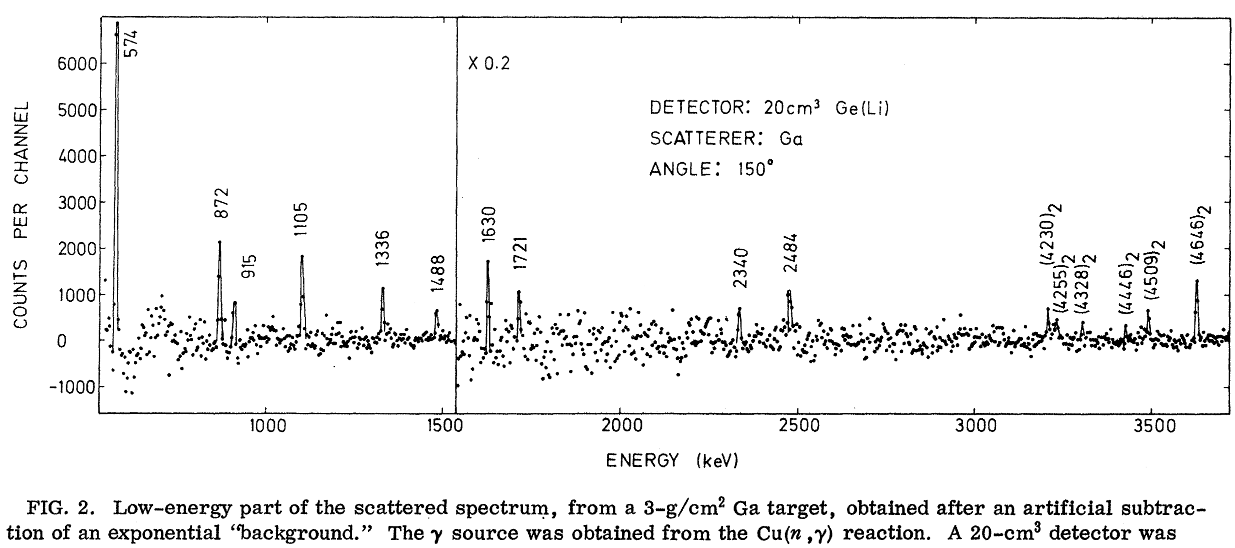

FIG. 2. Low-energy part of the scattered spectrum, from a 3-g/cm^2 Ga target, obtained after an artificial subtraction of an exponential "background." The γ source was obtained from the Cu(n,γ) reaction. A 20-cm^3 detector was used at a scattering angle of 150°. γ lines denoted by a subscript 2 refer to double-escape peaks; other lines refer to photopeaks.

et al.[12]; it includes experiments carried out using the $(n,n'\gamma)$ reaction, the β^+ decay of ^{69}Ge, the β^- decay of ^{69}Zn, the ^{68}Zn(d,n) reaction, and the ^{69}Ga (γ,γ') reaction using low-energy γ rays. In these studies, some information about the spins of 11 levels in ^{69}Ga was obtained. In the present work, some of these earlier results were confirmed and in addition, the spin assignments for 10 other levels in ^{69}Ga were made.

II. EXPERIMENTAL METHOD

The γ source was obtained from thermal neutron capture in metallic disks of either copper or vanadium. The disks were placed near the reactor core along a horizontal tangential beam tube of the Israel Research Reactor (IRR-2). In each γ source, five disks were used of 8 cm diam and 2 cm thick. Details of the experimental arrangement and the scattering system were described elsewhere.[8] The detectors used in the present measurements were 20- and 30-cm^3 Ge(Li) diodes; the energy resolution was around 8 keV at 7 MeV.

III. RESULTS

A. Energy Spectrum and Identification of Scattering Isotope

A typical energy spectrum of the scattered photons from a Ga target as obtained by using a copper γ source is shown in Fig. 1. A natural Ga target (60.4% ^{69}Ga and 39.6% ^{71}Ga) of 10g/cm^2 thick and 7.5 cm diam was used. About 10-mm thickness of lead was placed in front of the Ge(Li) detector for filtering out the large number of low-energy pulses obtained from atomic interactions of the direct γ beam with the scatterer.

Figure 1 consists of one elastic line at 7306 keV which corresponds to a strong intensity line in the Cu(n,γ) spectrum.[18] Several of the remaining lines were found to correspond to primary transitions to low-lying levels in ^{69}Ga. Further, none of the high-energy lines of Fig. 1 were found to correspond to any of the known low-lying levels of the other stable isotope, ^{71}Ga. This indicates that ^{69}Ga is the only isotope responsible for resonance scattering of the copper capture γ rays.

Figure 2 shows the low-energy part of the scattered spectrum from a γ source of Cu, using a 3-g/cm^2-thick Ga target obtained after an artificial subtraction of an exponential background. Only a 4-mm-thick absorber of lead was placed in front of the Ge(Li) detector for filtering out photons of energies below 500 keV.

Table I lists the results of γ lines of high- and low-energy spectra together with the intensities of the high-energy lines obtained using a Cu γ source.

The scattered radiation spectrum from Ga using a V(n,γ) source was found to consist of two independent resonances of which the resonance at 6874 keV was found to correspond to resonance scattering from ^{69}Ga, as evidenced by several inelastic transitions. The other resonance at 7310 keV was found to photoexcite the ^{71}Ga isotope, as evidenced by three inelastic transitions. This resonance was, in fact, very weakly excited and could be detected only through its inelastic components. Table II lists the results of γ line energies and intensities obtained using a V γ source.

B. Decay Scheme

In order to construct the decay scheme and hence the energy levels of ^{69}Ga (Table III), it must be noted that a single level at 7306 keV is excited by the incident Cu capture γ rays, as may be seen by comparing the line energies of the scattered spectrum with the line energies of the Cu(n,γ) reaction.[18] It is assumed that the high-energy γ lines are all due to primary γ transitions deexciting the resonance level. The justification of this

TABLE I. γ energies of the scattered radiation from a Ga target; the γ source was obtained from the Cu(n,γ) reaction. The branching ratios of the assumed primary transitions are given and are accurate to ±15%. The γ energies of the low-energy spectrum are listed under secondaries. Daggers indicate unidentified transitions.

γ line energy (primaries) (keV)	Branching ratios (%)	γ line energy (secondaries) (keV)
7306 ± 2	52.0	2484 ± 4
6732 ± 2	3.6	2340 ± 4
6434 ± 2	3.0	1721 ± 3
5818 ± 2	6.0	1630 ± 3†
5415 ± 3	0.8	1488 ± 2
5383 ± 3	0.1	1336 ± 2
5109 ± 3	0.5	1105 ± 2
4954 ± 3	1.3	915 ± 2
4880 ± 3	1.0	872 ± 2
4849 ± 2	1.9	574 ± 2
4822 ± 2	2.0	
4646 ± 2	4.2	
4541 ± 3	0.6	
4509 ± 3	2.0	
4460 ± 3	0.4	
4446 ± 4	0.8	
4342 ± 3	0.4	
4328 ± 2	1.2	
4255 ± 3	3.6	
4230 ± 4	3.4	
4102 ± 4	2.2	
4081 ± 6	2.2	
4024 ± 6	1.0	
3988 ± 6	4.1	

TABLE II. γ energies of the scattered radiation from a Ga target using V γ rays. Intensities are normalized relative to the 6874-keV resonance line. Asterisks denote transitions believed to correspond to a possible resonance at 7310-keV resonance in ^{71}Ga. Daggers indicate unidentified transitions.

γ line energy (primaries) (±4 keV)	Relative intensity (±20 %)
7310*	20
6874	100
6554	205
6346*	37
6202*	11
6002	80
5349	20
4980	10
4896	25
4653†	20
4619†	20
4543†	12
4417	15
4309	10
4214	15

assumption and the discussion of other factors which could apparently contribute to some lines in the scattered spectrum were considered in detail in earlier publications[1]; it was concluded that all high-energy γ lines are inelastic transitions proceeding to low-lying levels in the scattering isotope.

Figure 3 shows the decay scheme obtained using the above procedure; out of 23 measured inelastic lines, only 6 transitions correspond to known levels, while the remaining 17 transitions are believed to correspond to new levels. Figure 3 also shows the decay of the relatively strong resonance at 6874 keV excited by γ rays of vanadium. The other resonance at 7310 keV excited by the V γ rays is due to ^{71}Ga and hence is not shown in Fig. 3. It should be emphasized again that no attempt was made to deduce new levels from the scattered spectrum using V γ rays because of the ambiguity in associating a given γ transition with a specific resonance level. As a result, only transitions which were found to correspond to within 3 keV to the energy levels in ^{69}Ga were considered and included in the decay scheme; all other lines were

TABLE III. Energy levels, spins and parities in ^{69}Ga from the (γ, γ') reaction. For comparison, the values obtained in the literature (Ref. 12) are also shown. Parentheses indicate uncertainties.

Present work (keV)	J^π	Literature (keV)	J^π	Present work (keV)	J^π	Literature (keV)	J^π
320 ± 2	$\frac{1}{2}^-$, $(\frac{3}{2})^-$	318.4 ± 0.5	$\frac{1}{2}^-$	2484 ± 2	$\frac{5}{2}$	···	···
574 ± 2	$\frac{5}{2}^-$	573.9 ± 0.5	$\frac{5}{2}^-$	(2565 ± 5)	$(\frac{1}{2}, \frac{3}{2})$	2563 ± 15	···
872 ± 2	$\frac{3}{2}^-$	871.7 ± 0.5	$\frac{3}{2}^-$	2660 ± 2	$\frac{3}{2}$	2660 ± 15	···
···	···	1027 ± 0.5	$(\frac{1}{2})^-$	2765 ± 3	···	···	···
1105 ± 2	···	1106.4 ± 0.5	$\frac{1}{2}^-$, $\frac{3}{2}^-$	2798 ± 3	···	···	···
1336 ± 2	···	1336.1 ± 0.5	$\frac{7}{2}^-$	2846 ± 3	···	···	···
1488 ± 2	$\frac{3}{2}^-$, $\frac{7}{2}^-$	1487.5 ± 0.5	$(\frac{1}{2})^+$, $(\frac{5}{2})^-$	2860 ± 4	···	···	···
1525 ± 3	$(\frac{1}{2}, \frac{3}{2})$	1525.2 ± 0.5	···	···	···	2932 ± 15	$(\frac{5}{2})^+$
1721 ± 3	···	1723.2 ± 0.5	$(\frac{5}{2})^-$	2964 ± 3	···	···	···
1891 ± 2	$\frac{3}{2}^-$	1891.1 ± 0.5		2978 ± 2	···	···	···
1923 ± 3	···	1923.2 ± 0.5		3051 ± 3	$(\frac{3}{2}, \frac{7}{2})$	···	···
(1978 ± 4)	$(\frac{1}{2}, \frac{3}{2})$	1979 ± 15		3076 ± 4	$\frac{5}{2}$	(3092 ± 15)	···
···	···	2022.2 ± 0.5	$(\frac{9}{2})^-$	3204 ± 4	···	···	···
···	···	2042.6 ± 0.5	$(\frac{1}{2})^-$	3225 ± 6	···	···	···
2197 ± 3	···	···		3282 ± 6	···	···	···
2352 ± 3	···	···		3318 ± 6	$(\frac{7}{2})$	···	···
2426 ± 3	···	···		6874 ± 2	$\frac{1}{2}$	···	···
2457 ± 2	$\frac{3}{2}$	···		7306 ± 2	$\frac{5}{2}^+$	···	···

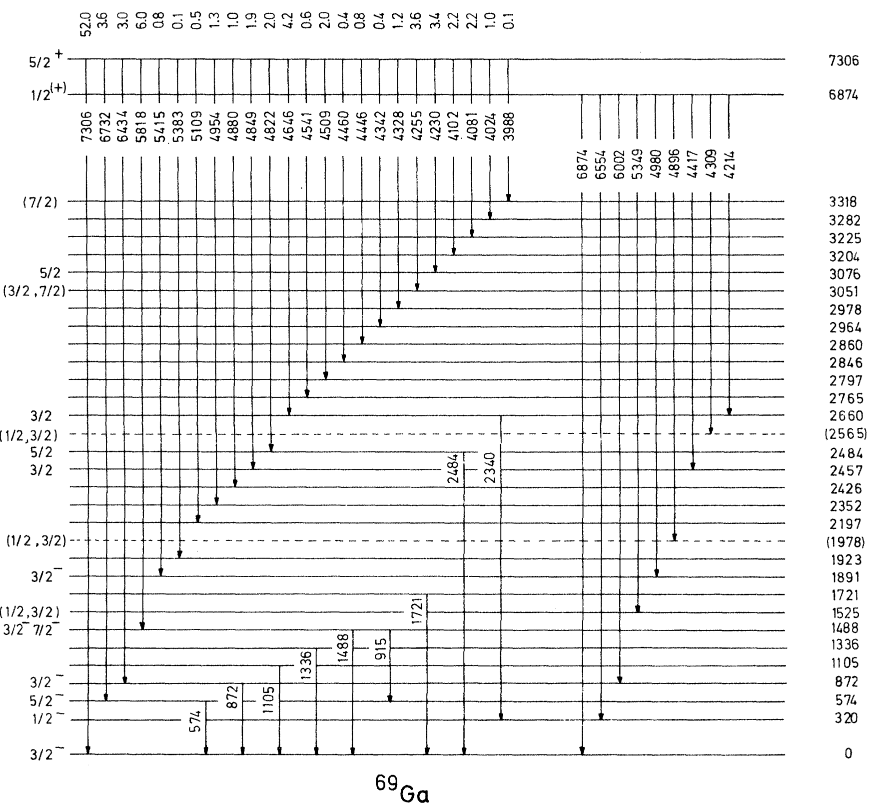

FIG. 3. Decay scheme of two resonance levels of ^{69}Ga. The branching ratios and levels energies for the 7306-keV resonance were constructed by assuming that all high-energy γ lines in the scattered spectrum are emitted in primary transitions; broken lines and parentheses indicate uncertainties. Most probable spins and parities for some levels assigned from the results of the present work are given.

disregarded.

By comparing the γ line energies of the low energy spectrum (Table I) with known low-lying energy levels of ^{69}Ga, it was possible to identify several secondary transitions leading to the ground state and some low-lying states. In fact the energies of the low-lying levels[10] at 1106, 1336, and 1721 keV were inferred from the low-energy spectrum by assuming that ground-state transitions are involved. These three levels were not populated directly here and are believed to be fed by low-energy transitions not observed in the present measurements. Some of the γ line energies were found to fit to more than one difference between level energies and are not mentioned in the decay scheme owing to the obvious uncertainties involved in this procedure.

C. Angular Distributions

The angular distribution of the strong elastic and inelastic lines of the scattered lines from the Cu(n,γ) and V(n,γ) sources are shown in Figs. 4 and 5, respectively. These distributions are fitted with curves of the form $W(\theta) = 1 + AP_2(\cos\theta)$ using the method of least squares. Since the J^π of the ^{69}Ga ground state is $\frac{3}{2}^-$, the theoretical angular distributions of the scattered lines should be iden-

TABLE IV. Theoretical values of the angular distribution coefficients A for ^{69}Ga corresponding to all possible spin sequences of the form $\frac{3}{2} \to J \to J_f$, where $\frac{3}{2}$ is the spin of the ^{69}Ga ground state; pure dipole transitions are assumed.

J	J_f	A
$\frac{5}{2}$	$\frac{7}{2}$	0.05
$\frac{5}{2}$	$\frac{5}{2}$	−0.16
$\frac{5}{2}$	$\frac{3}{2}$	0.14
$\frac{3}{2}$	$\frac{5}{2}$	−0.04
$\frac{3}{2}$	$\frac{3}{2}$	0.160
$\frac{3}{2}$	$\frac{1}{2}$	−0.20
$\frac{1}{2}$	$\frac{1}{2}$	0
$\frac{1}{2}$	$\frac{3}{2}$	0

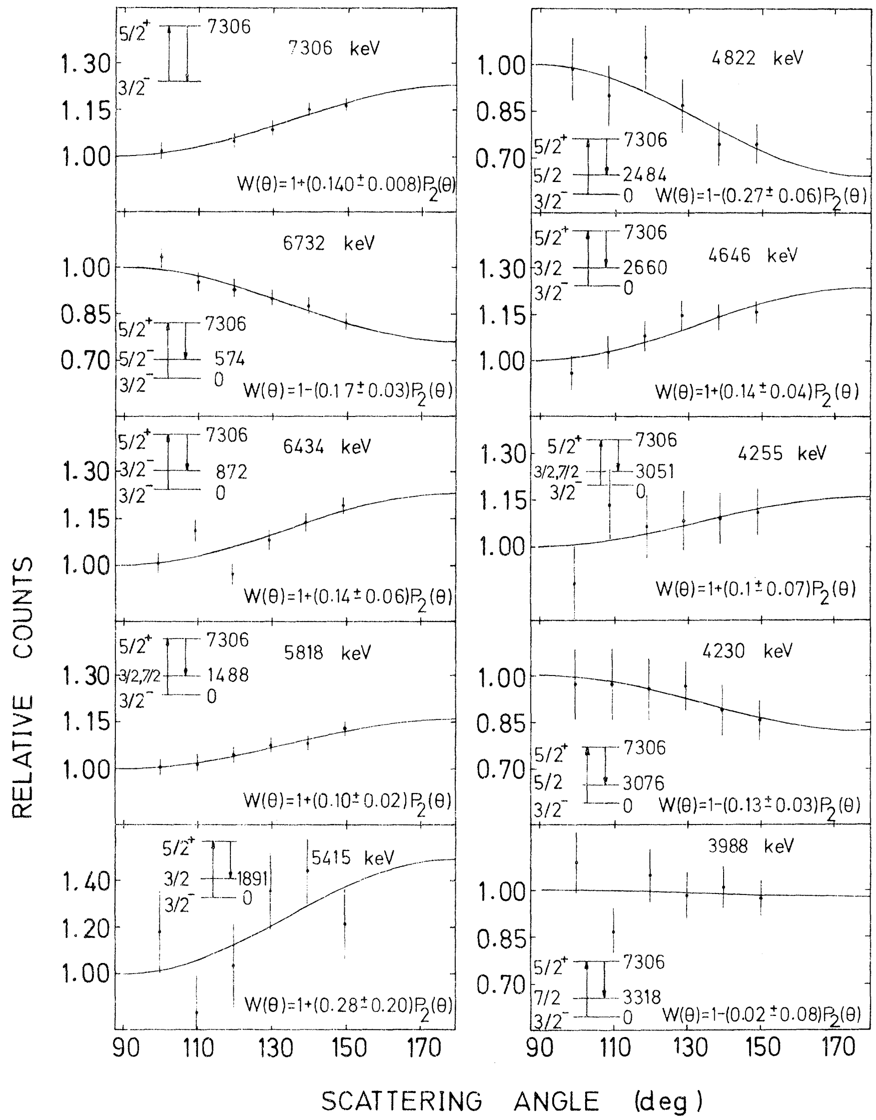

FIG. 4. Angular distributions of the elastic and inelastic transitions deexciting the 7306-keV level in ^{69}Ga as measured using a 20-cm^3 Ge(Li) detector. The solid lines have the form $W(\theta)=1+AP_2(\cos\theta)$ and are least-square fits to the experimental distribution. In each case the corresponding γ-γ cascade is indicated.

tical to that of the sequence $\frac{3}{2}\rightarrow J\rightarrow J_f$, where J and J_f are the spins of the resonance and final states, respectively. Table IV lists the theoretical values of A corresponding to all possible γ-γ cascades formed by pure dipole transitions. These values were used for comparison with the experimental values and hence for deducing the spins of the levels.

The character of the elastic line at 7306 keV was found, by polarization measurements (see next section), to be $E1$. Therefore, the competing high-intensity transitions are believed to be $E1$, and the contribution of the $M2$ admixtures are expected to be small and may be neglected. All spin assignments obtained in the present work were therefore deduced under the assumption of pure dipole transitions. It should be noted, however, that small $M2$ admixtures[19] are known to occur in some $E1$ transitions; when this possibility is accounted for, other spin assignments can be made and are given in parentheses in Table III.

We hereby deal with the ^{69}Ga levels that were strongly excited in the present work.

6874-keV level. This level was excited by the V(n,γ) source. Its angular distribution (Fig. 5) is effectively isotropic which indicates that its spin

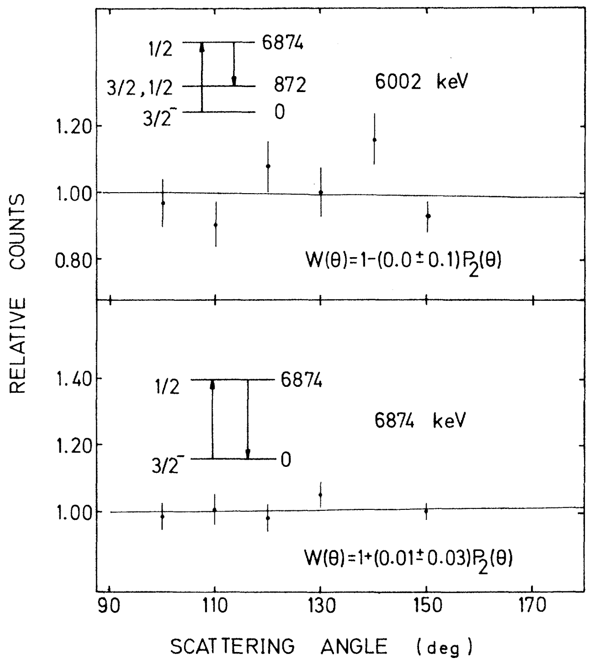

FIG. 5. Angular distribution of the elastic and one inelastic transition deexciting the 6874-keV level in ^{69}Ga as measured using a 30-cm^3 Ge(Li) detector. See caption to Fig. 4.

is $J=\frac{1}{2}$. It follows that the distribution of any inelastic line deexciting this resonance level should also be isotropic as shown in Fig. 5, irrespective of the spin value of the final state. However, the expected dipole nature of the transitions restricts the spin values of the final states to $J_f=\frac{1}{2}$ and $\frac{3}{2}$, in agreement with previous results.[12] The parity of the 6874-keV level could not be determined by polarization measurements, because its spin is $\frac{1}{2}$. However, the character of the 6874-keV transition was inferred to be $E1$ on the basis of comparing its radiation strength Γ_f/E_f^3 with an average determined from the decay of the 7306-keV level (see Sec. IIIE).

7306-keV level. This level was excited by the Cu(n,γ) source. The coefficient of the experimental distribution of the 7306-keV γ line, $A=0.14$, is precisely equal to the theoretical value corresponding to the sequence $\frac{5}{2}(1)\frac{5}{2}(1)\frac{3}{2}$. This fact determines the spin of the 7306-keV level to be $J=\frac{5}{2}$ and shows that the transition involved is pure dipole. It should be remarked in this connection that an ambiguity in the determination of J could very easily arise in this case because the theoretical value of A corresponding to the sequence $\frac{3}{2}(1)\frac{3}{2}(1)\frac{3}{2}$ is $A=0.16$, and therefore a very careful and refined measurement was necessary in the present case for obtaining a reliable value of A and hence of J. This result combined with the $E1$ character of this transition (see below) indicates that the parity of this level is even. It is expected therefore that all levels populated by strong transitions should be $J_f^\pi=\frac{3}{2}^-$, $\frac{5}{2}^-$, or $\frac{7}{2}^-$. In addition, since the 6874-keV resonance is $J=\frac{1}{2}$, therefore the spin of any low-lying level in ^{69}Ga populated by both the 7306- and the 6874-keV resonances can be unambiguously determined to be $J=\frac{3}{2}$.

320-, 574-, and 872-keV levels. The spins of these levels are reported in the literature.[12] The 320-keV level was populated only through the decay of the 6874-keV resonance, and hence its spin could be either $\frac{1}{2}$ or $\frac{3}{2}$, which agrees with the known value $J^\pi=\frac{1}{2}^-$.

The 574-keV level was populated only via the 7306-keV resonance; the corresponding angular distribution (Fig. 4) determines its spin as $\frac{5}{2}$ (Table IV), in agreement with previous results.[12]

The 872-keV level was populated by both the 6874- and 7306-keV resonances which fixes its spin as $\frac{3}{2}$. Further, the measured coefficient A of the corresponding γ line (Fig. 4) confirms this determination. It should be noted that some controversy existed in the literature regarding the spin of this level which was believed for some time[10] to have a spin value $\frac{5}{2}$. This problem was only recently resolved[11]; the present measurement confirms the recent assignment.

1488-keV level. This level was populated only via the 5818-keV transition from the 7306-keV resonance. The value $A=0.10\pm0.02$ (Fig. 4) falls midway between 0.14 and 0.05, and hence the 1488-keV level may be assigned either $\frac{3}{2}$ or $\frac{7}{2}$. The character of this transition is expected to be $E1$ because its radiation strength I_f/E_f^3 is of about the same magnitude as other $E1$ transitions deexciting the 7306-keV level. Here, I_f and E_f signify the relative intensity and the energy of the transition. Earlier assignments[12] for this level were $J^\pi=\frac{1}{2}^+$ and $J^\pi=\frac{5}{2}^-$. It should be noted, however, that the results of Couch *et al.*[12] indicate that (d,n) angular distributions are consistent with $l_p=3$ for the 1488-keV level. Therefore a $J^\pi=\frac{7}{2}^-$ assignment appears to be favored by both the (γ,γ') and (d,n) data.

1525-keV level. This level was populated by the decay of the 6874-keV resonance only and hence its spin could be either $\frac{1}{2}$ or $\frac{3}{2}$. The fact that this level was not populated by the 7306-keV resonance suggests a higher preference to a spin value $\frac{1}{2}$.

1891- and 2660-keV levels. These two levels were populated by the decay of both the 6874- and 7306-keV resonances, and hence their spin is determined to be $J=\frac{3}{2}$. The measured distribution of the corresponding γ lines at 5415- and 4646-

keV (Fig. 4) confirms these assignments.

1978- and 2565-keV levels. The energies of these two levels as reported by Couch *et al.*,[12] are accurate to within ±15 keV. In fact the 1978-keV level was identified[12] with the well-established level at 2022 keV. The present results, however, favor the existence of an independent level at 1978 keV because a γ line was observed whose energy matches the difference between the 6874-keV resonance and 1978 keV. A somewhat similar situation occurs with regard to the 2565-keV level which was apparently populated only through the 6874-keV resonance. The spin of these two levels is therefore either $\frac{1}{2}$ or $\frac{3}{2}$. Because of the ambiguities involved, the existence of these two levels is considered uncertain.

2484- and 3076-keV levels. These are new levels populated by the decay of the 7306-keV resonance only. The angular distribution of the corresponding γ lines at 4822- and 4230-keV (Fig. 4) is in good agreement with a spin value $\frac{5}{2}$ for the two levels.

3051-keV level. This level is a new level populated by the decay of the 7306-keV resonance only. The coefficient of the angular distribution of the γ line at 4255 keV contains a large uncertainty and effectively overlaps the theoretical value of A for the spin sequences $\frac{3}{2}(1)\frac{5}{2}(1)\frac{3}{2}$ and $\frac{3}{2}(1)\frac{5}{2}(1)\frac{7}{2}$, which means that this level can be either $\frac{3}{2}$ or $\frac{7}{2}$.

3318-keV level. This is also a new level populated by the decay of the 7306-keV resonance. The angular distribution of the corresponding γ line at 3988 keV agrees with a spin assignment $J=\frac{7}{2}$.

D. Radiative Widths and Scattering Cross Sections

In a previous publication,[8] it was noted that in order to measure the radiative width of a resonance level, it is necessary to carry out a set of five experiments in which the angular distribution, the temperature variation of the scattering cross section, the nuclear self-absorption, the ground-state branching ratio, and the absolute scattering cross section $\langle\sigma_r\rangle$ should be measured. These experiments determine the four parameters of the resonance level, namely, the spin J, the distance δ between the peaks of the incident energy line and the resonance level in ^{69}Ga, the ground-state partial radiative width Γ_0 and total radiative width Γ. The fifth experiment is used for checking the consistency of the four parameters. For the 7306-keV level, the parameters which best fitted all experiments were:

$$\Gamma=0.105\pm0.020 \text{ eV}, \quad \Gamma_0/\Gamma=0.46\pm0.06,$$

$$\delta=6.2\pm0.5 \text{ eV}, \quad \langle\sigma_r\rangle=80\pm5 \text{ mb}.$$

For the 6874-keV level, the scattered intensity was relatively weak and only higher and upper limits for some parameters could be obtained:

$$0.01<\Gamma_0<0.05 \text{ eV}, \quad \Gamma_0/\Gamma<0.2,$$

$$\delta=10\pm1 \text{ eV}, \quad \langle\sigma_r\rangle=3\pm1 \text{ mb}.$$

E. Parities of the 7306- and 6874-keV Levels

The parity of the 7306-keV level was established by measuring the polarization of the elastically scattered photons, using a Compton polarimeter. Details of this type of measurement were described earlier.[8,20] Assuming $E1$ radiation, the theoretical degree of polarization P of the scattered 7306-keV photons at 90° to the incident beam corresponding to the sequence $\frac{3}{2}(1)\frac{5}{2}(1)\frac{3}{2}$ is $P=0.63$. The calculated ratio $N_{\parallel}/N_{\perp}=(P+R)/(PR+1)$ obtained by assuming $E1$ radiation and an asymmetry ratio[8,20] $R=1.14$ is $N_{\parallel}/N_{\perp}=1.030$. This value of

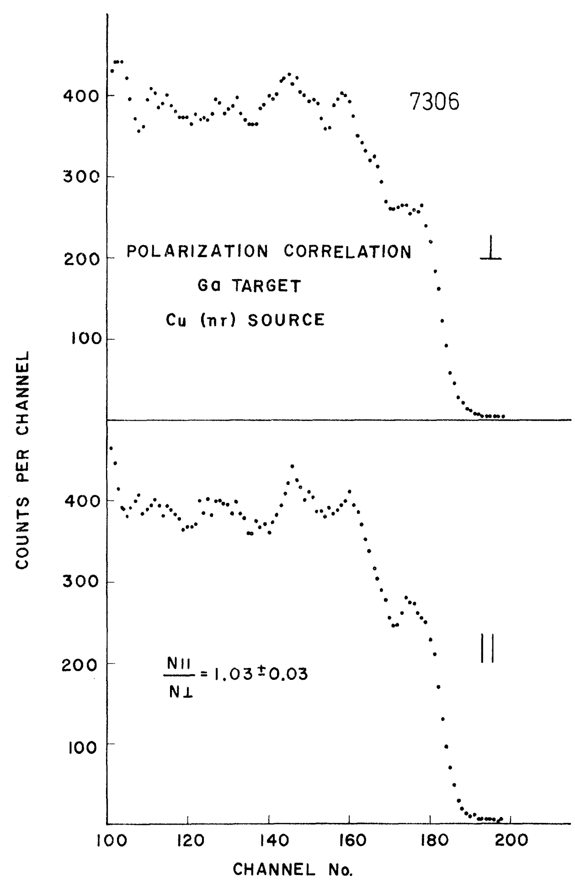

FIG. 6. Sum-coincidence spectra obtained with the NaI detectors in planes perpendicular (⊥) and parallel (||) to the resonance scattering plane. Both $N_{\perp}$ and $N_{\parallel}$ refer to the area under the photopeak and first-escape peak.

R includes finite geometry corrections.[8,20] For $M1$ radiation, $P = 1.58$ and $N_{\parallel}/N_{\perp} = 0.97$. The measured value is $N_{\parallel}/N_{\perp} = 1.03 \pm 0.03$, as obtained from Fig. 6 which shows the sum-coincidence spectra for the elastic γ line at 7306 keV at two perpendicular planes; the running time being 96 h. This result indicates that the elastic radiation is $E1$, and hence the parity of the 7306-keV level is even.

The parity of the 6874-keV level was inferred from a comparison of the values of Γ_f/E_f^3 for the 6874-keV elastic and the 6554-keV inelastic transitions with a value $\langle \Gamma_f/E_f^3 \rangle = 0.047$ eV MeV^{-3} obtained by averaging over the 7306-keV elastic, 6732- and 6434-keV inelastic lines, known to be $E1$ transitions. Here Γ_f and E_f refer to the partial radiation width and the energy of the corresponding transition. Using a reasonable value, $\Gamma_0 = 0.02$ eV, for the 6874-keV level, one obtains $\Gamma_f/E_f^3 = 0.06$ and 0.14 eV MeV^{-3} for the 6874- and 6554-keV transitions, respectively, which indicates that these two transitions are also $E1$, and hence the parity of the 6874-keV resonance is very likely to be even.

IV. DISCUSSION

A. Correlation Between (γ, γ') and (d, n) Reaction Widths

The existence of large positive correlations between the reaction widths from the (n,γ) and the (d,p) reactions are well established and are known to occur in several nuclides.[21–23] It was also noted that a positive correlation may also occur between the (γ,γ') and (d,p) reaction widths, and some experimental evidence[24] was presented favoring the existence of such correlations. It is therefore of interest to test whether there exists a similar correlation between the (γ,γ') and (d,n) reaction widths leading to the same final states in ^{69}Ga. The (γ,γ') transition strengths I_f/E_f^3, were calculated from the decay of each of the two resonances at 6874- and 7306-keV (Tables I and II). The corresponding (d, n) strengths $(2J_f+1)S_f$, where S_f is the usual spectroscopic factor, were taken from the ^{68}Zn(d, n) reaction reported by Couch *et al.*[12] The correlation coefficient $\rho(x_f, y_f)$ is defined by

$$\rho(x_f, y_f) = \frac{\sum_f (x_f - \bar{x})(y_f - \bar{y})}{[\sum_f (x_f - \bar{x})^2 \sum_f (y_f - \bar{y})^2]^{1/2}},$$

where $x_f = I_f/E_f^3$ and $y_f = (2J_f + 1)S_f$. The values of ρ obtained for the two resonance levels were:

6874 keV: $\rho = 0.69$, 98.5% percentile of $\rho = 0$;

7306 keV: $\rho = 0.19$, 80% percentile of $\rho = 0$.

Effectively, only the 6874-keV resonance yields a statistically significant positive correlation.

The group of levels that were included in the calculation of ρ were selected by assuming that all low-lying levels populated in the present work are of odd parity. Table V lists the values of the parameters of all the assumed $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels that were included in calculating the ρ of the 6874-keV resonance ($\frac{1}{2}^+$); the (d, n) transition strengths of the $l_p = 1$ neutron groups are also given.

The case of the 7306-keV resonance ($\frac{5}{2}^+$) is more complex because the low-lying levels populated by its decay are $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$. These levels are populated by the ^{68}Zn(d, n) reaction by two neutron groups, namely, $l_p = 1$ and $l_p = 3$. It appears, however, that all known[12] $l_p = 3$ levels were either not populated by the (γ,γ') reaction, such as the 1336- and 1723-keV levels, or relatively weakly populated, such as the 574-keV level. This fact reduces the value of ρ; it also smears any correlation which might exist between (γ,γ') and (d, n) transitions leading to $J^\pi = \frac{3}{2}^-$, $l_p = 1$ levels.

The positive correlation may be explained by using a simple-minded picture[24] in which the 6874-keV resonance level in ^{69}Ga is viewed as a particle-hole $E1$ excitation of protons. Accordingly, one $p_{3/2}$ proton in the configurations $p_{3/2}^3$, $p_{1/2}^2(0)p_{3/2}$ and $f_{5/2}^2(0)p_{3/2}$ of the $\frac{3}{2}^-$, ^{69}Ga ground state[17] is excited to the $3s_{1/2}$ orbit to form a $J^\pi = \frac{1}{2}^+$ level. The new system, which effectively consists of a ^{68}Zn core + $3s_{1/2}$ proton, will selectively prefer single-particle proton transitions of the form $3s_{1/2} \rightarrow 2p_{1/2,\,3/2}$. Obviously, the intensity of such transitions is dependent on the spectroscopic factor of the $J^\pi{}_f = \frac{1}{2}^-$ and $\frac{3}{2}^-$ final states,

TABLE V. Comparison of the transition strengths from the 6874-keV level in the (γ,γ') reaction with the corresponding values from the ^{68}Zn(d, n) reaction (Ref. 12); only levels believed to be $\frac{1}{2}^-$ or $\frac{3}{2}^-$ and for which $l_p = 1$ are included. Asterisks denote strengths estimated from the (d, n) spectrum given by Couch *et al.* (Ref. 12).

Level energy (keV)	(γ,γ') Reaction E_f (keV)	I_f/E_f^3	(d, n) Reaction $(2J+1)S_f$
0	6874	0.31	1.62
320	6554	0.71	1.20
872	6002	0.37	0.30
1027	5874	0.0	0.17
1525	5349	0.09	0.0
1891	4980	0.08	0.0
1978	4896	0.17	0.20
2457	4417	0.17	0.0
2565	4309	0.20	0.20*
2660	4214	0.13	0.10*

and hence should be correlated to the $l_p=1$ neutron intensities in the ^{68}Zn(d, n) reaction. It is clear that photons may also excite a particle hole of neutrons in the ground state of ^{69}Ga. In such a case, the correlation between the intensities of the γ transitions and the neutron groups in the (d, n) reaction should be drastically reduced. This may partially explain the absence of correlation in the 7306-keV level.

B. Energy Levels of ^{69}Ga

The ^{69}Ga nucleus consists of 38 neutrons and 31 protons. The energy levels of ^{69}Ga were calculated by several authors.[9,15-17,25] It appears that the best description of the low-lying levels of ^{69}Ga may be obtained by coupling three protons in the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ orbits (outside $Z=28$) to the quadrupole vibrations of the ^{66}Ni core.[17] The lowest three states of ^{69}Ga are expected to be principally formed by coupling the ^{66}Ni ground state to the proton configuration $p_{3/2}{}^3(J=\frac{3}{2})$, $p_{3/2}{}^2(0)p_{1/2}(J=\frac{1}{2})$, and $p_{3/2}{}^2(0)f_{5/2}(J=\frac{5}{2})$. These states were in fact identified with the ground, 319- and 574-keV levels, respectively, using the ^{68}Zn(d, n) reaction.[12]

The coupling of the 2^+, 1.4-MeV excited state, of ^{66}Ni to the $p_{3/2}{}^3$ proton configuration yield four states with spins $J=\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. Other states may also be formed by coupling the ground state or the 2^+ state of ^{66}Ni to proton configurations of the form $p_{3/2}{}^2(2)p_{1/2}$, $p_{3/2}{}^2(2)f_{5/2}$, $p_{1/2}{}^2(0)p_{3/2}$ and $f_{5/2}{}^2(0)p_{3/2}$. It should be noted that each state of ^{69}Ga is expected to be a linear combination of several configurations with a dominant contribution of one principal configuration.

It is not intended here to make a detailed comparison between theory and experiment because the (γ,γ') reaction is not suited for identifying the configuration components in the states of ^{69}Ga. It may be noted, however, that the possibility of assigning either $\frac{1}{2}^+$ or $\frac{5}{2}^-$ to the 1488-keV level[12] may be excluded (Table III). Further, in the work of Paradellis and Hontzeas[15] the 1891-keV level was also identified with theoretically predicted $\frac{5}{2}^-$ level. The present results show, beyond doubt (Table III) that this identification[15] is false.

A gross-structure comparison may be made between theory and experiment by assuming that all low-lying levels strongly populated in the present work are of odd parity. It may be noted that the number of measured levels below about 2 MeV whose J^π values are known to be $\frac{1}{2}^-$ or $\frac{3}{2}^-$ is 8 or probably 9, which is equal to the number of levels predicted by Parr,[17] by Almar *et al.*,[25] and by Paradellis and Hontzeas.[15] However, the predicted number of $\frac{5}{2}^-$ and $\frac{7}{2}^-$ levels below 2 MeV is 8,[15] 6,[25] and 5[17] compared with a total of four known experimental levels. It is very likely that more experimental work will reveal more high-spin levels below or around 2 MeV in ^{69}Ga. This comparison roughly shows that the above theoretical description and the number of degrees of freedom used is adequate for reproducing the energy levels of ^{69}Ga below and around 2 MeV.

[1]R. Moreh and A. Wolf, Phys. Rev. 182, 1236 (1969).
[2]R. Moreh and A. Nof, Phys. Rev. C 2, 1938 (1970).
[3]Y. Schlesinger, M. Hass, B. Arad, and G. Ben-David, Phys. Rev. 178, 2013 (1969).
[4]N. Shikazono and Y. Kawarasaki, Nucl. Phys. A118, 114 (1968).
[5]G. P. Estes and K. Min, Phys. Rev. 154, 1104 (1967).
[6]V. E. Michalk and G. A. McIntyre, Nucl. Phys. A137, 115 (1969).
[7]R. Cesareo *et al.*, Nucl. Phys. A132, 512 (1969).
[8]R. Moreh, S. Shlomo, and A. Wolf, Phys. Rev. C 2, 1144 (1970).
[9]J. K. Temperley, D. K. McDaniels, and D. V. Wells, Phys. Rev. 139, B1125 (1965).
[10]W. H. Zoller, G. E. Gordon, and W. B. Walters, Nucl. Phys. A124, 15 (1969).
[11]S. Raman and R. G. Couch, Phys. Rev. C 1, 744 (1970).
[12]R. G. Couch, G. A. Biggerstaff, F. G. Perey, and S. Raman, Phys. Rev. C 2, 149 (1970).
[13]D. E. Velkley, K. C. Chang, A. Mitter, J. D. Brandenberger, and M. T. McEllistrem, Phys. Rev. 179, 1090 (1969).
[14]H. Langhoff and Frevert, Nucl. Phys. A111, 225 (1970).
[15]T. Paradellis and S. Hontzeas, Can. J. Phys. 49, 1750 (1971).
[16]B. S. Reehal and R. A. Sorensen, Phys. Rev. C 2, 819 (1970).
[17]V. Paar, Phys. Letters 39B, 466 (1972).
[18]N. C. Rasmussen, Y. Hukai, T. Inouye, and V. J. Orphan, Massachusetts Institute of Technology Report No. 85 (unpublished).
[19]R. Moreh, A. Nof, O. Shahal, and A. Wolf, Phys. Letters 36B, 71 (1971).
[20]R. Moreh and J. Rajewski, Nucl. Instr. Methods 98, 13 (1972).
[21]L. V. Groshev and A. M. Demidov, Yadern. Fiz. 4, 785 (1966).
[22]R. E. Chrien, K. Rimawi, and J. B. Garg, Phys.Rev. C 3, 2054 (1971).
[23]A. M. Lane, in *Statistical Properties of Nuclei*, edited by J. B. Garg (Plenum, New York, 1971), p. 271.
[24]R. Moreh and A. Wolf, in *Statistical Properties of Nuclei* (See Ref. 23), p. 257.
[25]R. Almar *et al.*, Phys. Rev. C 6, 187 (1972).