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Lifetimes of States in ^{62,64}Cu and ^{67,70}Ga

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Abstract

The Doppler shift attenuation method of lifetime determination has been employed following the ^{62,64}Ni(p, nγ)^{62,64}Cu and ^{67,70}Zn(p, nγ)^{67,70}Ga reactions. The lifetime of the ^{62}Cu state at 637 keV was found to be 220^{+400}_{-110} fs; lower limits of 230 and 250 fs were set for the levels at 426 and 548 keV respectively. For ^{64}Cu, a lower limit of 175 fs was set for both the 609 and 663 keV states. Lifetimes in ^{67}Ga were determined for the indicated levels as: 828 keV, 280^{+200}_{-100} fs; 911 keV, 370^{+300}_{-130} fs; 1412 keV, 900^{+2500}_{-400} fs; 1519 keV, 750^{+1500}_{-400} fs; 1555 keV, 190^{+60}_{-50} fs; 1639 keV, 150^{+50}_{-40} fs; 2041 keV, 150^{+90}_{-60} fs; and 2174 keV, 80^{+40}_{-30} fs. Lower limits of 600 and 110 fs were set on the lifetime values for the 1202 and 1978 keV levels respectively. Similarly, lower limits on the lifetimes of the ^{70}Ga levels at 1203 and 1245 keV were set at 320 and 720 fs, while values for the 1312 and 1446 keV levels of ^{70}Ga were found to be 245^{+75}_{-35} and 390^{+810}_{-132} fs.

1. Introduction

A program utilizing the (p, nγ) reaction to study the properties of odd–odd nuclei in the top portion of the 1f–2p shell region has been established in our laboratory for the past three years. This program has consisted of singles and coincidence γ-ray measurements, using Ge(Li) detectors, to determine level positions and their decay schemes, and also angular distribution measurements to determine the corresponding level angular momenta and γ-transition multipole mixing ratios. These measurements have been reported by Davidson *et al.* (1970*a*, 1970*b*) and Najam *et al.* (1971, 1973).

The above program has been extended to the determination of the mean lifetime of excited states using both direct timing measurements and the attenuated Doppler shift technique. The measurement of the mean lifetime of the 879 keV level of ^{70}Ga using the direct timing technique with a pulsed proton beam has been published in a separate article (Carlson *et al.* 1973). The present paper discusses the measurements obtained using the Doppler shift attenuation method (DSAM) of lifetime determination. Mean lifetime values have been determined for levels in ^{62}Cu, ^{64}Cu and ^{70}Ga. Benefits and uncertainties associated with the application of the DSAM to the low recoil velocity (p, nγ) reaction are discussed in Section 2*a*, while the experimental details are given in Section 2*b*. Additional measurements have been made using the

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$^{67}Zn(p, n\gamma)^{67}Ga$ reaction to determine the γ-decay properties of the low lying levels in ^{67}Ga. Branching ratios for seven levels not established in previous β-decay studies (Zoller *et al.* 1969) and the results of the DSAM measurements are presented in Section 3.

2. Experimental Method

(*a*) *Technique*

The DSAM measurements discussed in this paper consisted of measuring the energy of γ-rays using one or two Ge(Li) spectrometers in singles as a function of the angle between the incident proton beam and the γ-ray detector. The energy of the γ-transition is given by the well-known first-order Doppler shift equation

$$E(\theta) = E(90^\circ)\{1 + \beta F(\tau)\cos\theta\}, \tag{1}$$

where $E(\theta)$ is the γ-ray energy as observed at an angle θ to the incident proton beam, β is the effective recoil velocity of the recoiling nuclei under study (in units of c) and $F(\tau)$ is the attenuation coefficient, which depends on the initial recoil velocity as well as on the material in which the ion is slowing down. The coefficient $F(\tau)$ was calculated as a function of the mean lifetime τ by a computer program which used the electronic and nuclear stopping powers of Lindhard *et al.* (1963) and the treatment of the mean scattering angle of the ion as given by Blaugrund (1966). The experimental value for $F(\tau)$ was obtained from energy observations at two angles $\theta_1 = 0^\circ$ and $\theta_2 = 120^\circ$ or 133° from equation (1) as

$$F(\tau) = \{E(\theta_1) - E(\theta_2)\}/\{\beta E(90^\circ)(\cos\theta_1 - \cos\theta_2)\} \tag{1a}$$

or from a linear least square fit to equation (1) for three or more angles of observation.

The advantages of using the $(p, n\gamma)$ reaction in singles are:

(1) the experimental apparatus is very simple as no complex coincidence or neutron γ-ray discrimination electronics are required, and

(2) the threshold technique leads to a clean direct feeding of the level under study by the neutrons; there is no indirect feeding by γ-ray decay of higher energy levels to complicate the data analysis.

Several difficulties are presented by the low recoil velocities, $\beta = 0\cdot12$–$0\cdot19\,\%$, of the nuclei under study. The full ($F(\tau) = 1\cdot0$) Doppler shift calculated from equation (1) is quite small: for a 1 MeV γ-ray and $\beta = 0\cdot15\%$, equation (1) gives the result $E(0^\circ) - E(90^\circ) = 1\cdot5$ keV. It is therefore necessary to monitor any gain or baseline shifts of the electronics system, and this is accomplished by including γ-rays from standard sources, such as ^{22}Na, ^{60}Co or ^{88}Y, in any spectrum. A further uncertainty arises since the stopping power dE/dX for the particular combination of recoiling ion and slowing-down medium is not usually known experimentally. Measurements by Ormrod *et al.* (1965) have shown that there is a periodic oscillation with the Z of the recoiling ion about the theoretical stopping power. These oscillations can be as large as 20%. Furthermore, it has been shown by Bell *et al.* (1969) that it is necessary to introduce an energy-dependent reduction factor to the Lindhard *et al.* (1963) nuclear stopping power in order to predict measured range values. For the small β values used here this correction factor appears to be as low as 0·75. Thus the stopping power used in the computer calculations of $F(\tau)$ generally takes the form

$$dE/dX = f_e(dE/dX)_e + f_n(dE/dX)_n,$$

where the correction factors f_e and f_n multiply the corresponding theoretical values of Lindhard *et al.* Although the range predictions indicate the need for the f_n factor, the situation with regard to mean lifetimes is not so clear. A comparison of mean lifetimes derived from low recoil velocity ($\beta = 0\cdot002$) and medium to high recoil velocity ($\beta = 0\cdot02$) experiments does not show up the expected dependence on f_n. The scatter in reported mean lifetime values of $\sim 50\%$ about the mean overshadows the anticipated effect of $\sim 15\%$. The present analysis uses $f_e = f_n = 1\cdot0 \pm 0\cdot15$.

A further difficulty in calculating $F(\tau)$ arises through the uncertainty in the angular distribution of the outgoing recoil ions. Häusser *et al.* (1968) have shown that the effective recoil velocity is sensitive to an asymmetry in the recoil angular distribution about 90° in the centre of mass system. If we (quite generally) write this angular distribution in the form

$$W(\phi) = 1 + \sum_{i \geqslant 1} a_i \mathrm{P}_i(\cos\phi)$$

then the averaged forward component of the recoil velocity, v_{cm}, in the c.m.s. system is, by the orthogonality of the Legendre polynomials,

$$(v_{cm}/4\pi) \oint W(\phi)\cos\phi \, d\Omega = \tfrac{1}{3} v_{cm} a_1 .$$

Therefore, if V_{cm} is the velocity of the centre of mass, the averaged forward component in the laboratory system must be

$$V_{cm} + \tfrac{1}{3} a_1 v_{cm} .$$

If we neglect γ-ray triple correlation effects, the above expression is the effective average forward velocity producing Doppler shifts, and the mean observed γ-ray energy is given by

$$E(\theta) = E(90°)\{1 + F(\tau) c^{-1} (V_{cm} + \tfrac{1}{3} a_1 v_{cm}) \cos\theta\} .$$

The axially symmetric recoil velocity distribution leads to a Doppler broadening of the γ-ray energies, but not to a change in the mean observed energy. The v_{cm} has been made small in the present experiment by studying the levels using a proton bombarding energy close to threshold. The relevant values for the Doppler shift runs are set out below.

^{67}Ga	$E_p = 3\cdot50$ MeV	$E_x = 1\cdot411$ MeV	$\tfrac{1}{3} a_1 v_{cm}/V_{cm} = 0\cdot09\, a_1$
^{62}Cu	5·32	0·426	$0\cdot07\, a_1$
^{64}Cu	3·20	0·609	$0\cdot09\, a_1$
^{70}Ga	3·00	1·312	$0\cdot15\, a_1$

Also, for these runs just a few hundred keV above threshold, the compound nucleus reaction mechanism is expected to dominate over a direct reaction one. If the reaction proceeded completely via a compound nuclear mechanism, and if the target were thick enough that the effect of Ericsson fluctuations were averaged out, then the outgoing neutron angular distribution would be symmetrical about 90° in the c.m.s. system and we would have $a_1 = 0$. An estimate of the magnitude of the direct reaction cross section for the ^{62}Ni(p, n)^{62}Cu* ($J^\pi = 3^+$, $E_x = 426$ keV) reaction at $E_p = 5\cdot5$ MeV compared with the Hauser–Feshbach cross section has been given by Carlson *et al.* (1972). The result indicates that the direct reaction component is less than 0·1 times the Hauser–Feshbach one, and therefore that a_1 is less than 0·05. Due to these two effects the value of the $\frac{1}{3}a_1 v_{\rm cm}$ term is less than 0·01 that of the $V_{\rm cm}$ term. We have therefore assumed $a_1 = 0$ in the analysis of the present data.

(*b*) *Details*

^{62}Cu. Targets of approximately 0·9 mg cm^{-2} thickness, obtained by evaporating 99·0% enriched ^{62}NiO onto 125 μm thick tantalum backings, were used in this part of the study. The reaction yield was restricted to the front portion of the target by keeping the proton beam energy close to threshold for the level of interest. Since the mean range of the ^{62}Cu atoms was only $\sim$20 μg cm^{-2}, all the recoiling ^{62}Cu nuclei were stopped in the target material. Four independent sets of measurements were made with a 30 cm^3 Ge(Li) detector placed $\sim$7 cm from the target. In each set, several γ-spectra were obtained at 0° and 120° or 133° to the beam direction. The first three sets consisted of measurements at $E_p \approx 5\cdot32$, 5·425 and 5·51 MeV. To monitor the gain stability of the system, γ-rays from the combinations of ^{57}Co, ^{61}Cr, ^{137}Cs and ^{65}Zn sources placed near the target were recorded simultaneously with the γ-ray spectra from the ^{62}Ni(p, nγ)^{62}Cu reaction.

^{64}Cu. Measurements for this nucleus were made using the same arrangement as for the ^{62}Cu study. The targets used were of $\sim$0·8 mg cm^{-2} thickness and were fabricated by successive evaporations of (98·6%) isotopically enriched ^{64}Ni onto 50 μm thick tantalum backings. Gamma-ray Ge(Li) detector spectra were recorded at 0° and 133° to the beam direction. Reference lines from ^{57}Co and ^{137}Cs or ^{54}Mn were used as standards to detect any gain instability.

^{70}Ga. Self-supporting ^{70}Zn targets of about 1·8 mg cm^{-2} mounted on a copper frame were used in the DSAM lifetime measurements in ^{70}Ga. The targets were prepared by rolling metallic zinc foil enriched to 68% in isotope 70. Tungsten backings were mounted on the rear of the target frame to stop the beam. Gamma-ray spectra were recorded using a 40 cm^3 Ge(Li) detector placed at a distance of $\sim$7 cm from the target. Several such spectra were obtained at 0°, 90° and 133° to the beam direction. Gamma rays from the ^{88}Y, ^{60}Co and ^{22}Na sources were used to provide a continuous energy calibration.

^{67}Ga. The targets used for this study were 150 μg cm^{-2} of zinc evaporated onto a tungsten backing. The zinc was enriched to 58% in mass 67. Gamma-ray spectra were obtained using a 40 cm^3 Ge(Li) detector at nine proton energies between 2·8 and 4·1 MeV, which correspond to excitation energies between 0·97 and 2·29 MeV in ^{67}Ga. These spectra, taken at 55° to the incident beam direction, were used to obtain decay schemes and branching ratios for the observed levels.

Gamma-ray spectra for the DSAM measurements were obtained at angles of 0°, 90° and 133° and for proton beam energies from 2·8 to 4·1 MeV in order to keep the proton energy close to threshold for the individual levels of interest. Combinations of ^{65}Zn, ^{22}Na, ^{88}Y and ^{226}Ra γ-sources were used to provide a continuous energy calibration. The finite thickness of the target was taken into account in the computer calculation of the $F(\tau)$ values by dividing the target into five equal sections and averaging the $F(\tau)$ value obtained assuming that the (p, n) interaction took place in the centre of the respective section. Since the target thickness is approximately 15 times the mean range of the ^{67}Ga atoms the assumption of uniform cross section across the target leads to an uncertainty of less than 3% in the calculated value of $F(\tau)$. The $F(\tau)$ calculations were also carried out for a ZnO target. Complete oxidation of the target would increase the derived lifetime by less than 10% relative to the values quoted for the pure metal target.

Table 1. Excitation energies and branching ratios for ^{67}Ga levels

(a) Comparison of excitation energies (keV)

Present work	Previous results[A] Z	BS	F	Present work	Previous results[A] Z	BS	F
167·0±0·4	167·01±0·05	168±2	166			1735±5	
359·3±0·3	359·5 ±0·2	360±2	358		1809·4±0·6	1808±4	1810
828·1±0·3	828·3 ±0·3	827±2	828				1919
910·9±0·3	911·2 ±0·3	910±3	911	1976·3±1·0	1976·2±0·5		
	1081·3 ±0·3	1081±3	1082	1977·9±0·5		1974±4	1976
1202·1±0·3	1203·0 ±1·0	1202±3	1203	2040·9±0·4		2037±4	2033
		1240±5				2069±4	2063
1412·5±0·3		1411±3	1413			2120±5	2120
1519·1±0·4		1517±4	1517			2139±5	
1554·6±0·3	1556·0 ±1·0	1553±4	1552	2173·8±0·5		2169±5	2173
1639·2±0·4	1639·9 ±0·7	1637±4	1640			2186±6	

(b) Branching ratios

Initial E_i (keV)	Final E_f (keV)	E_γ (keV)	Branching ratio (%)	Initial E_i (keV)	Final E_f (keV)	E_γ (keV)	Branching ratio (%)
1202	g.s.	1202	73±3	1555	g.s.	1555	44±5
	359	843	27±3		359	1196	56±5
1412	g.s.	1412	63±4	1978	1202	776	100
	359	1053	37±4	2041	g.s.	2041	100
	911	501	< 10	2174	g.s.	2174	100
1519	359	1160	100				

[A] References: Z, Zoller *et al.* (1969); BS, Bass and Stelson (1970); F, Finckh *et al.* (1970).

3. Results

(a) ^{67}Ga *Decay Scheme*

The excitation energies determined in the present work are given in Table 1*a*, while branching ratios are given in Table 1*b* for seven levels of ^{67}Ga not established in the β-decay study of Zoller *et al.* (1969). Only the ground state and 359 keV level decays are indicated for the 1202 keV level. The strong 1039 keV γ-ray from ^{66}Zn masks a possible weak decay branch to the 167 keV level (E_γ = 1035 keV). The placement of the 843·0 keV γ-ray is based on the consistency of the branching ratio of this transition and the 1202·1 keV one at six different energies between $E_p = 3\cdot1$ and 3·9 MeV. These measurements indicate that the 843·0 keV γ-ray is not a background line due to ^{27}Al.

The $501 \cdot 6$ keV transition from the $1412 \cdot 5$ keV to the $910 \cdot 9$ keV level is listed as having an intensity of less than 10%. This is due to the presence of a line of this energy below the threshold for populating the $1412 \cdot 5$ keV level.

The 776 keV γ-ray is placed as the sole decay of a 1978 keV level. This level is not the 1976 keV one observed by Zoller *et al.* (1969), which decays solely to the ground state. The γ-decay of this level ($E_\gamma = 1976 \cdot 3$ keV) was also observed in the present study.

Table 2. Summary of experimental parameters and deduced mean lifetimes for ^{62}Cu, ^{64}Cu and ^{70}Ga

Nucleus	E_p (keV)	$\beta = V_0/c$ (%)	Level (keV)	E_γ (keV)	$F(\tau)$	τ (fs)
^{62}Cu	5320	$0 \cdot 17$	$426 \cdot 1$	$385 \cdot 3$	$<0 \cdot 12$	>230
	5425	$0 \cdot 17$	$548 \cdot 2$	$548 \cdot 2$	$<0 \cdot 10$	>250
	5510	$0 \cdot 17$	$637 \cdot 2$	$596 \cdot 4$	$0 \cdot 14 \pm 0 \cdot 08$	220^{+400}_{-110}
^{64}Cu	3200	$0 \cdot 13$	$609 \cdot 0$	$609 \cdot 0$	$<0 \cdot 15$	>175
	3230	$0 \cdot 13$	$663 \cdot 2$	$663 \cdot 2$	$<0 \cdot 15$	>175
^{70}Ga	3000	$0 \cdot 11$	$1203 \cdot 4$	$1203 \cdot 4$	$0 \cdot 04 \pm 0 \cdot 07$	>320
		$0 \cdot 11$	$1244 \cdot 5$	$1244 \cdot 5$	$<0 \cdot 05$	>720
		$0 \cdot 11$	$1311 \cdot 6$	$1311 \cdot 6$	$0 \cdot 14 \pm 0 \cdot 03$	245^{+75}_{-35}
		$0 \cdot 11$	$1446 \cdot 1$	$1446 \cdot 1$	$0 \cdot 08 \pm 0 \cdot 05$	390^{+810}_{-132}

Table 3. Magnetic dipole transition strengths

The indicated strengths are for an assumed pure M1 transition

Nucleus	Transition (keV)	M1 strength (W.u.)	Nucleus	Transition (keV)	M1 strength (W.u.)
^{62}Cu	$637 \cdot 2 \rightarrow$ g.s.	$0 \cdot 02$	^{64}Cu	$663 \cdot 2 \rightarrow$ g.s.	$<0 \cdot 20$
	$637 \cdot 2 \rightarrow 40 \cdot 8$	$0 \cdot 59$		$609 \cdot 0 \rightarrow$ g.s.	$<0 \cdot 45$
	$637 \cdot 2 \rightarrow 243 \cdot 4$	$0 \cdot 19$			
	$637 \cdot 2 \rightarrow 287 \cdot 9$	$0 \cdot 05$	^{70}Ga	$1446 \rightarrow$ g.s.	$3 \cdot 8 \times 10^{-2}$
	$548 \cdot 2 \rightarrow$ g.s.	$<0 \cdot 35$		$1446 \rightarrow 651$	$9 \cdot 8 \times 10^{-3}$
	$548 \cdot 2 \rightarrow 40 \cdot 8$	$<0 \cdot 49$		$1446 \rightarrow 691$	$2 \cdot 8 \times 10^{-2}$
	$548 \cdot 2 \rightarrow 243 \cdot 4$	$<0 \cdot 05$		$1312 \rightarrow$ g.s.	$5 \cdot 8 \times 10^{-2}$
	$548 \cdot 2 \rightarrow 287 \cdot 9$	$<0 \cdot 36$		$1245 \rightarrow$ g.s.	$<2 \cdot 3 \times 10^{-2}$
	$426 \cdot 1 \rightarrow 40 \cdot 8$	$<2 \cdot 0$		$1203 \rightarrow$ g.s.	$<5 \cdot 7 \times 10^{-2}$

(*b*) *DSAM Results*

The results of the DSAM measurements on ^{62}Cu, ^{64}Cu and ^{70}Ga are presented in Table 2. In ^{62}Cu the mean lifetime could be determined only for the $637 \cdot 2$ keV state. The lifetime value of 220^{+400}_{-110} fs corresponds to an M1 strength of $\sim 0 \cdot 6$ Weisskopf units (W.u.) for the transition to the $40 \cdot 8$ keV level. The strengths of the other branches (assuming they are pure M1) are $\sim 0 \cdot 05$ W.u. (to the 288 keV level), $\sim 0 \cdot 2$ W.u. (to the 243 keV level) and $\sim 0 \cdot 02$ W.u. (to the ground state). Lower limits of 230 and 250 fs were obtained for the lifetimes of the $426 \cdot 1$ and $548 \cdot 2$ keV levels. In ^{64}Cu, measurements on the ground state transitions from the $609 \cdot 0$ and $663 \cdot 2$ keV

Table 4*a*. Mean lifetimes for ^{67}Ga levels

Level (keV)	E_γ (keV)	Run	E_p (MeV)	$F(\tau)$	Average τ (ps)
828	828	1	2·8	0.14 ± 0.10	$0.28\,^{+0.20}_{-0.10}$
		2	3·2	0.15 ± 0.04	
		5	3·2	0.08 ± 0.04	
911	911	1	2·8	0.13 ± 0.08	$0.37\,^{+0.30}_{-0.13}$
		2	3·2	0.06 ± 0.04	
		5	3·2	0.09 ± 0.04	
1202	1202	2	3·2	0.03 ± 0.03	>0.6 (2σ)
		3	3·5	0.00 ± 0.02	
		5	3·2	0.06 ± 0.03	
1412	1412	3	3·5	0.02 ± 0.03	$0.90\,^{+2.5}_{-0.4}$
		4	3·8	0.07 ± 0.04	
		6	3·8	0.02 ± 0.04	
1519	1160	3	3·5	0.02 ± 0.03	$0.75\,^{+1.5}_{-0.4}$
		4	3·8	0.08 ± 0.04	
		6	3·8	0.07 ± 0.04	
1555	1555	3	3·5	0.17 ± 0.04	$0.19\,^{+0.06}_{-0.05}$
		4	3·8	0.18 ± 0.05	
		6	3·8	0.16 ± 0.05	
1639	1472	4	3·8	0.21 ± 0.05	$0.15\,^{+0.05}_{-0.04}$
		6	3·8	0.21 ± 0.05	
1978	776	6	4·1	0.05 ± 0.12	>0.11 (2σ)
2041	2041	6	4·1	0.21 ± 0.05	$0.15\,^{+0.09}_{-0.06}$
2174	2174	6	4·1	0.35 ± 0.06	$0.08\,^{+0.04}_{-0.03}$

levels led to the lower limit of 175 fs for both states. In ^{70}Ga, the ground state decays of the 1311·6 and 1446·1 keV levels led to lifetime values of $245\,^{+75}_{-35}$ and $390\,^{+810}_{-132}$ fs respectively. Lower limits of 320 and 720 fs were obtained for the 1203·4 and 1244·5 keV levels. Table 3 presents the transition strengths corresponding to the above lifetimes.

The mean lifetimes and strengths of states in ^{67}Ga are presented in Tables 4*a* and 4*b* respectively. The lifetime values do not allow restrictions to be placed on the range of spin values determined from particle studies, other than that the 911 keV level spin is 3/2 or 5/2 but not 7/2. This restriction comes from the decay of the 911 keV level to the $J^\pi = 1/2^-$, 167 keV level and also from the decay of the $J^\pi = 1/2^-$ or $3/2^-$, 1639 keV level to the 911 keV one.

4. Discussion

Shell model calculations of ^{58,60,62}Cu have been carried out by Phillips and Jackson (1968). They reproduced the magnetic moments for ^{60,62}Cu and the energy level spectrum of ^{58}Cu moderately well, but the excited states of ^{60,62}Cu were reproduced poorly. We know of no shell model calculation for ^{64}Cu. Giesler *et al.*

Table 4*b*. Transition strengths for ^{67}Ga levels

Initial E_i (keV)	Final E_f (keV)	E_γ (keV)	Strength (W.u.) assuming: Pure M1	Pure E2
828	g.s.	828	0·17	378
	167	661	0·035	122
	359	469	0·098	1·12
911	g.s.	911	0·10	195
	167	744	0·041	11·3
	359	552	0·015	75
1202	g.s.	1202	<0·019	<19
	359	843	<0·019	<42
1412	g.s.	1412	0·008	5·9
	359	1053	0·001	15
1519	359	1160	0·027	32
1555	g.s.	1555	0·019	12
	359	1196	0·065	70
1639	g.s.	1639	0·006	3·7
	167	1472	0·006	4·8
	359	1280	0·008	7·3
	828	811	0·063	150
	911	728	0·26	780
	1081	558	0·015	74
1978	1202	776	<0·6	<1600
2041	g.s.	2041	0·025	9·3
2174	g.s.	2174	0·037	12

(1972) have discussed the ^{62}Cu levels in terms of a simplified shell model picture. They speculate (based on β-decay measurements) that the dominant configuration of the 637 keV level is $[(\pi p_{3/2})^1, (\nu p_{1/2})^1]_{J=1}$. This configuration is consistent with the presently observed strong (B(M1) = 0·6 W.u.) transition to the predominantly $[(\pi p_{3/2})^1, (\nu p_{3/2})^{-1}]_{J=2}$ state at 40·8 keV.

Kisslinger and Kumar (1967) and Almar *et al.* (1972) have calculated the energy level spectrum of odd-mass gallium isotopes in a particle–quadrupole phonon coupling model. Since the calculations of Almar *et al.* are more extensive than (though in accord with) the calculation of Kisslinger and Kumar, the following discussion will compare the Almar *et al.* calculation for levels of ^{67}Ga below 2 MeV with the present experimental data. Both the experimental spectrum and the theoretical one (for a coupling strength of a = 0·5 MeV) are presented in Fig. 1. It is seen that there is a very close correspondence between the theory and experiment for all levels of established spin up to the 1202 keV level. This comparison will be further improved if the 911 keV state is found to have J = 5/2 rather than 3/2, and if the 1202 keV state has J = 7/2, as implied by its γ-ray decay scheme. The first theoretical J = 9/2 state might be associated with the 1517 keV J = 5/2, 7/2 or 9/2 state which decays solely to the 1202 keV one. Similarly the second theoretical J = 9/2 state at ~2·0 MeV might be associated with the state of 1977·9 keV which also γ-decays only to the 1202 keV level.

Almar *et al.* (1972) have used their three-proton wavefunctions to calculate M1 and E2 decay strengths for low lying ^{69}Ga levels. We are in communication with those authors on the possibility of doing likewise for ^{67}Ga decays.

A recently published paper (Najam *et al.* 1973) describes angular correlation and decay scheme measurements for ^{70}Ga, and conclusions regarding level spins and decay mixing ratios. Discussion of the ^{70}Ga level lifetimes is more appropriately included in that paper.

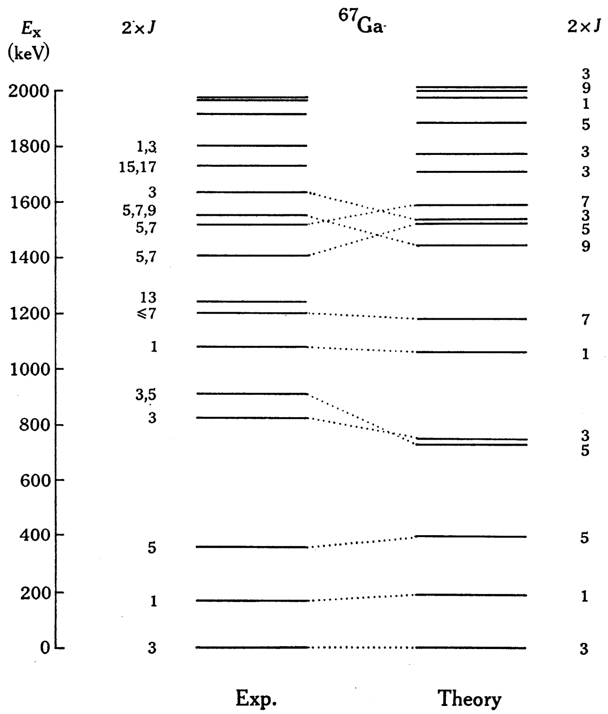

Fig. 1. Comparison of the calculated negative parity energy levels from Almar *et al.* (1972) with the present experimental spectrum for ^{67}Ga.

5. Conclusions

The present work has shown that the (p, nγ) reaction is very useful in elucidating the decay schemes, and obtaining lifetimes via the Doppler shift attenuation method, for low lying states of nuclei in the $60 < A \leqslant 70$ mass region. The decay schemes of seven levels in ^{67}Ga, not established in β-decay studies, have been obtained, together with lifetime values (or limits) for 3 levels in ^{62}Cu, 2 levels in ^{64}Cu, 10 levels in ^{67}Ga and 4 levels in ^{70}Ga. The energy level calculation for ^{67}Ga of Almar *et al.* (1972) has been shown to be in good agreement with the experimental spectrum for levels below 2 MeV.

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