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LIFETIMES AND *g*-FACTORS OF THE 6⁻ AND 7⁻ ISOMERS IN ^{66}Ga AND ^{68}Ga †

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Abstract: The 6^- and 7^- isomeric states in ^{66}Ga and ^{68}Ga at 1440.9 and 1229.6 keV, respectively, have been populated with the (^{13}C, 2np) and (^{15}N, n2p) reactions on natural Fe. The half-lives of these states have been measured to be $T_{1/2}(6^-, {}^{66}\text{Ga}) = 57.3 \pm 1.2$ ns and $T_{1/2}(7^-, {}^{68}\text{Ga}) = 64 \pm 2$ ns. Using previous data on the hyperfine field of Ga in Fe, the *g*-factors of these states have been determined by means of the TDPAD method. The results are $g(6^-, {}^{66}\text{Ga}) = 0.129 \pm 0.003$ and $g(7^-, {}^{68}\text{Ga}) = 0.105 \pm 0.003$. These values are in very good agreement with the independent particle model if one assumes the $\{\pi f_{5/2}, \nu g_{9/2}\}_{6^-, 7^-}$ and $\{\pi p_{3/2}, \nu g_{9/2}\}_{6^-}$ configurations and uses the empirical proton and neutron *g*-factors from odd-*A* neighboring nuclei instead of the Schmidt values. The large disagreements with experiment when Schmidt values are used show that core polarization effects are important in these nuclei.

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NUCLEAR REACTIONS ^{56}Fe(^{13}C, 2np), E = 35–60 MeV; ^{56}Fe(^{15}N, n2p), E = 50–75 MeV; measured $\gamma(\theta, H, t)$. ^{66,68}Ga levels deduced $T_{1/2}$, g. TDPAD. Natural target, Ge(Li) detector. Pulsed beam.

1. Introduction

The excited states of the odd-odd nuclei $^{66}_{31}\text{Ga}_{35}$ and $^{68}_{31}\text{Ga}_{37}$ were studied by Pomar *et al.* [1]) using the reactions ^{64}Zn(α, np) and ^{66}Zn(α, np). Isomeric states of spin 6^- in ^{66}Ga (1440.9 keV, $T_{\frac{1}{2}} \approx 100$ ns) and 7^- in ^{68}Ga (1229.6 keV, $T_{\frac{1}{2}} \approx 85$ ns) were found [1, 2]). Level schemes for both nuclei were established [1, 2]) (see fig. 1) on the basis of the usual experimental evidence and the decay modes of the 6^- and 7^- isomeric states have been proposed. In both nuclei a sequence of positive-parity states up to $J^\pi = 4^+$ have been observed.

The positive-parity states in these isotopes may be described as arising from the coupling of protons and neutrons in the $f_{\frac{5}{2}}$ and $p_{\frac{3}{2}}$ orbits while the first odd-parity

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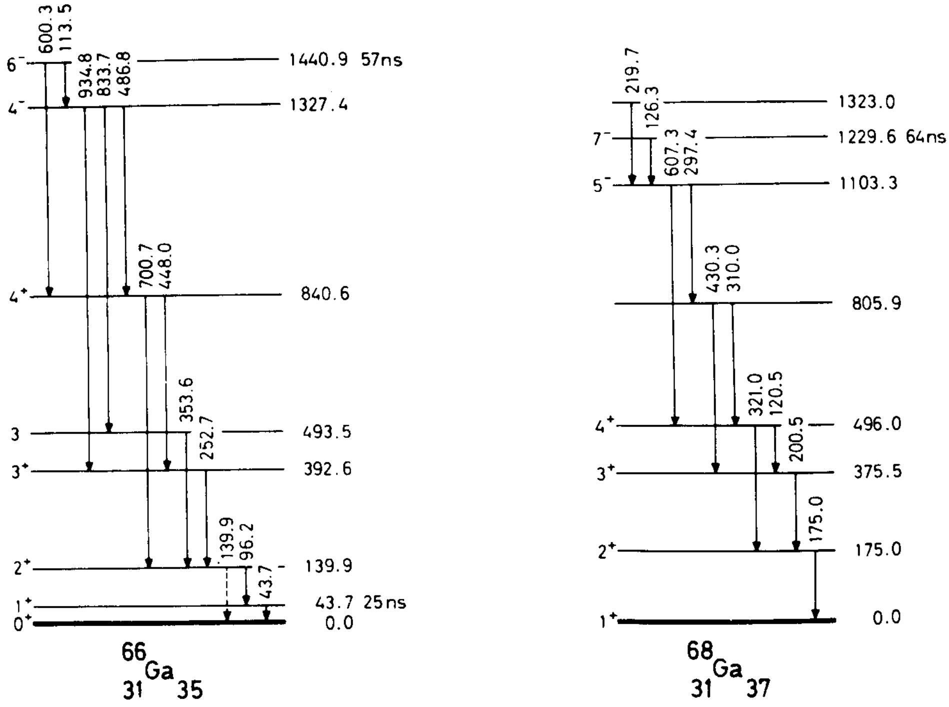


Fig. 1. Level scheme of ^{66}Ga and ^{68}Ga as reported in ref. [1]).

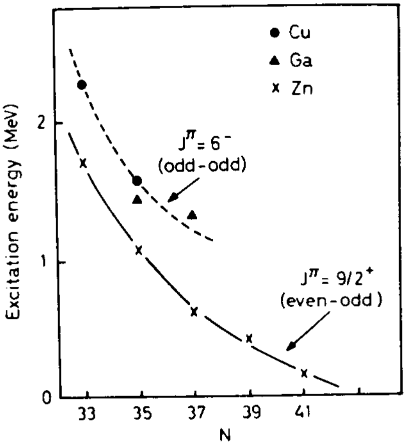


Fig. 2. Energies of the first 6^- states in doubly odd nuclei ^{62,64}Cu and ^{66,68}Ga as a function of N. The excitation energies of the first $\frac{9}{2}^+$ states in the odd-A Zn isotopes are shown for comparison.

excited states are expected to share configurations in which the odd neutron is in the $g_{\frac{9}{2}}$ orbital.

As shown in fig. 2 a plot of the energy of the first 6^- state in the doubly odd nuclei ^{62}Cu, ^{64}Cu, ^{66}Ga and ^{68}Ga as a function of N reveals a tendency similar to that of the $\frac{9}{2}^+$ first excited states of the neighboring odd Zn isotopes. Since these $\frac{9}{2}^+$ states are known to be rather pure $g_{\frac{9}{2}}$ neutron shell-model states, the indicated similarity seems to confirm that the lowest negative-parity states in ^{66}Ga and ^{68}Ga involve the $\nu g_{\frac{9}{2}}$ configuration.

In the present work the g-factors of the ^{66}Ga 6^- and ^{68}Ga 7^- states have been measured in order to investigate the above-mentioned assumption. As the wave functions of these high-spin levels are probably very pure, a measurement of their magnetic moments could add evidence for these assignments and serve as a good test of the validity of the shell model for odd-odd nuclei in this region of the periodic table.

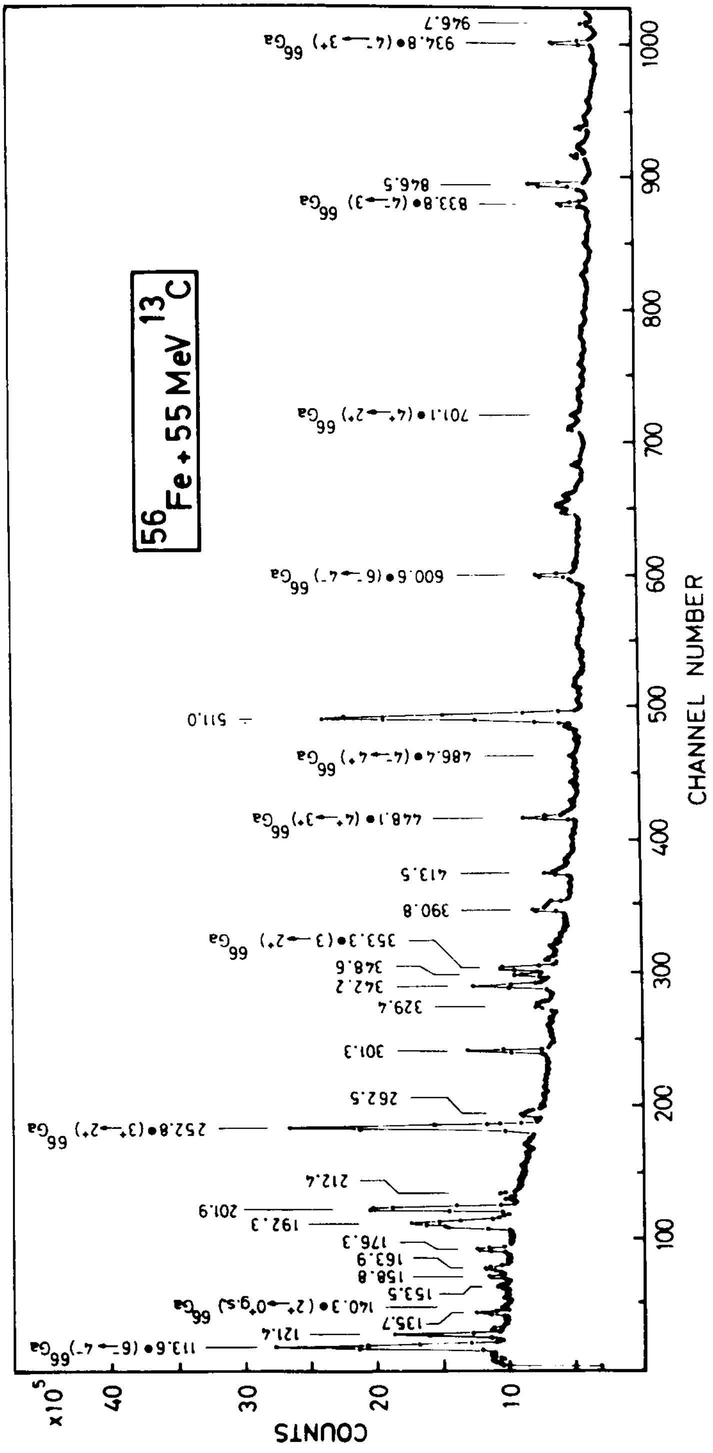
2. Experimental procedures and results

As observed in the experiments described in ref. ^{1}) the reaction (α, np) can be employed with targets of ^{64}Zn and ^{66}Zn to populate the above-mentioned negative-parity states in ^{66}Ga and ^{68}Ga. However, in order to have the product nucleus in a ferromagnetic environment the ^{56}Fe(^{13}C, 2pn)^{66}Ga and ^{56}Fe(^{15}N, n2p)^{68}Ga reactions were used instead. A target of natural Fe (91 % abundant in ^{56}Fe) was bombarded with ^{13}C and ^{15}N beams from the Brookhaven National Laboratory MP Tandem Accelerator.

The target was a 0.025 mm thick natural iron strip, placed across the pole pieces of a small ($\approx$ 1000 G) permanent magnet used to saturate the internal hyperfine field. The interaction between this field and the magnetic moment of the product nuclei causes their precession, which was observed externally through the rotation of the angular distribution of the emitted γ-rays by the time differential perturbed angular distribution (TDPAD) method. Several independent runs were performed with ^{13}C and ^{15}N beams using a single, 10 % efficiency, Ge(Li) detector, repeatedly placed in sequence at $+45°$ and $-45°$ with respect to the beam direction.

Fig. 3 shows typical single γ-ray spectra for both reactions. The excitation functions of the relevant γ-rays were determined and are shown in fig. 4. From these curves the optimum energies of bombardment were determined to be 55 MeV for ^{13}C and 60 MeV for ^{15}N.

The half-lives of the ^{66}Ga 6^- and ^{68}Ga 7^- levels were remeasured to improve the accuracy of the previously reported values ^{1,2}). The time distribution measurements were performed using the pulsed beam facility of the tandem accelerator. The width of the beam pulses was about 7 ns and the repetition rate was 4 MHz. The time-to-amplitude converter was calibrated by means of a model TC850 Tennelec time calibrator ^{3}). The results, shown in fig. 5, yield the values


^{56}Fe + 55 MeV ^{13}C
COUNTS
x10^5
10
20
30
40
CHANNEL NUMBER
100
200
300
400
500
600
700
800
900
1000
113.6 • (6$^-$→4$^-$) ^{66}Ga
121.4
135.7
140.3 • (2$^+$→0$^+$g.s.) ^{66}Ga
153.5
158.8
163.9
176.3
192.3
201.9
212.4
252.8 • (3$^+$→2$^+$) ^{66}Ga
262.5
301.3
329.4
342.2
348.6
353.3 • (3→2$^+$) ^{66}Ga
390.8
413.5
448.1 • (4$^+$→3$^+$) ^{66}Ga
486.4 • (4$^-$→4$^+$) ^{66}Ga
511.0
600.6 • (6$^-$→4$^-$) ^{66}Ga
701.1 • (4$^+$→2$^+$) ^{66}Ga
833.8 • (4$^-$→3) ^{66}Ga
846.5
934.8 • (4$^-$→3$^+$) ^{66}Ga
946.7

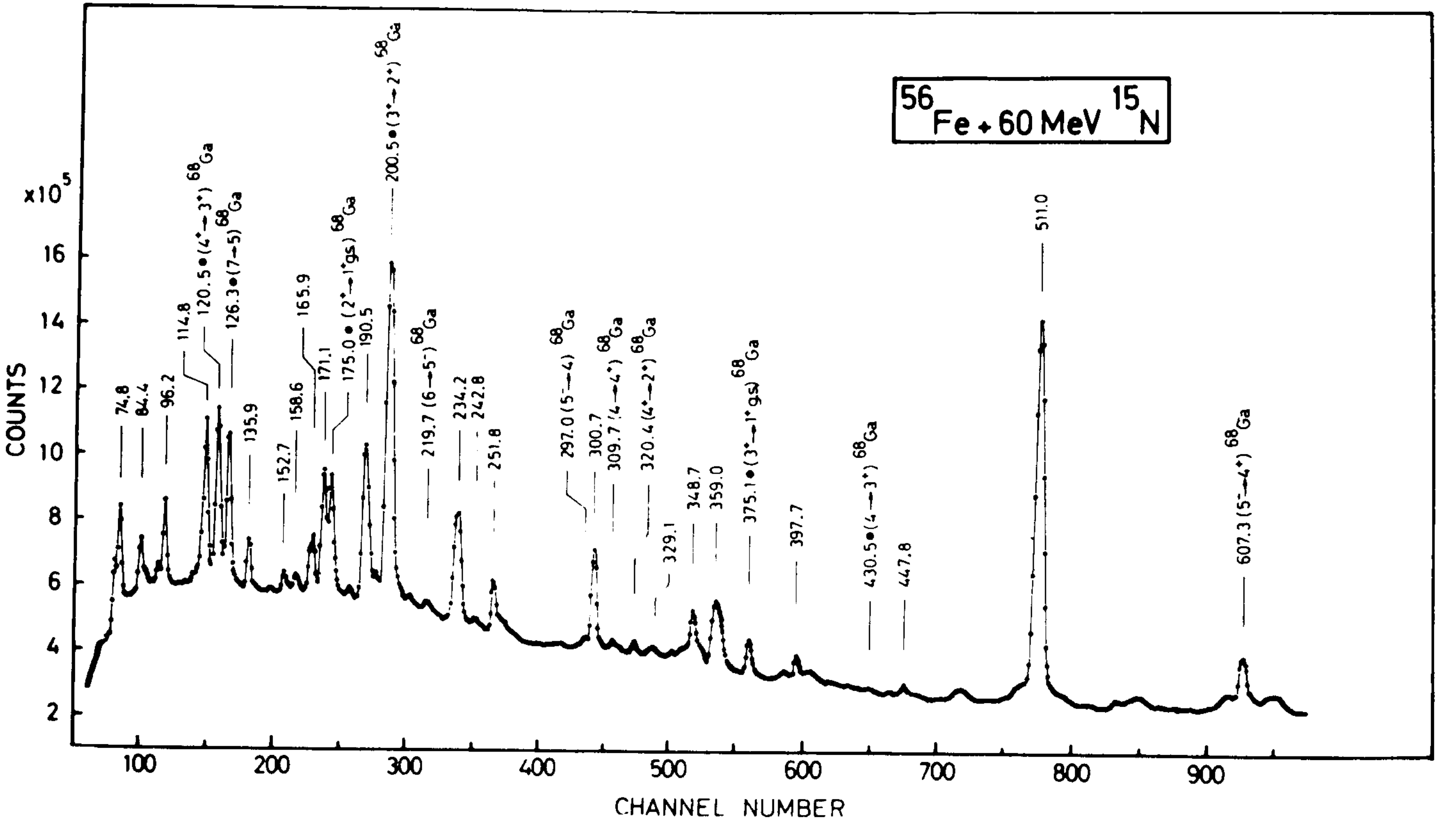


Fig. 3. Singles γ-ray spectra obtained with ^{13}C and ^{15}N beams at bombarding energies of 55 and 60 MeV, respectively.

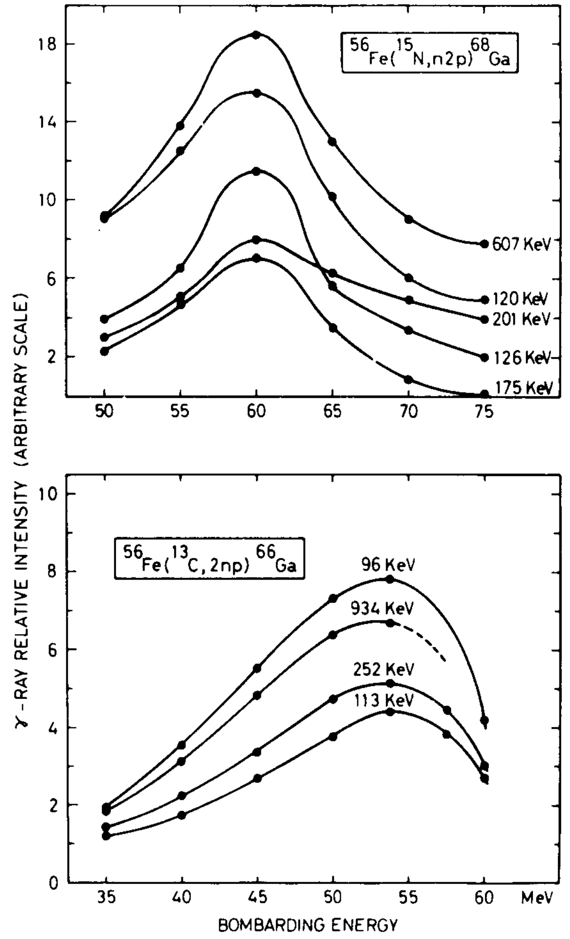


Fig. 4. The γ-ray excitation functions for ^{66}Ga and ^{68}Ga.

$$T_{\frac{1}{2}}(J^{\pi} = 6^-, {}^{66}\mathrm{Ga}) = 57.3 \pm 1.4 \text{ ns},$$

$$T_{\frac{1}{2}}(J^{\pi} = 7^-, {}^{68}\mathrm{Ga}) = 64 \quad \pm 2 \quad \text{ns}.$$

Because of the precession of the nuclear magnetic moment in a magnetic field, the γ-ray counting rate at an angle θ with respect to the beam is

$$N(\theta, t) = (N_0/\tau)\exp(-t/\tau)W(\theta, t),$$

where τ is the mean life of the state and its angular distribution is given by

$$W(\theta, t) = \sum_{k \text{ even}} g_k(t)A_k P_k[\cos(\theta \pm \omega_L t)].$$

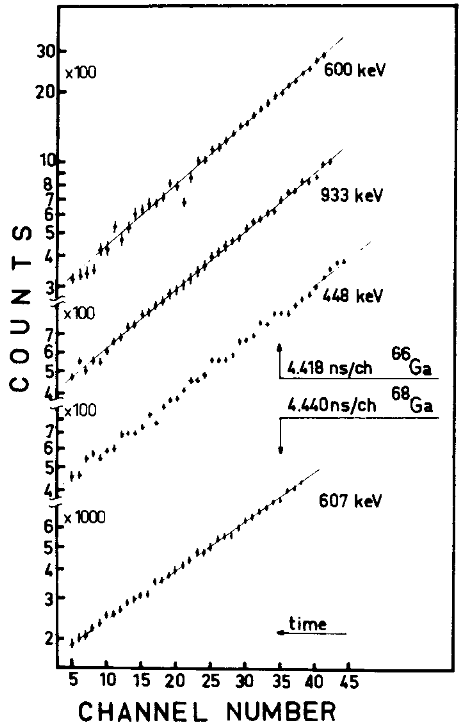


Fig. 5. Results of in-beam time distribution measurements for γ-rays assigned to ^{66}Ga and ^{68}Ga.

Here the coefficients $g_k(t)$ describe the attenuation of the angular distribution with time and $\omega_L/2\pi$ is the Larmor precession frequency. In our case $\theta = \pm 45°$ and the distributions can be combined in the expression

$$R(t) = \frac{W(+45°, t) - W(-45°, t)}{W(+45°, t) + W(-45°, t)} = \frac{A_2 \sin(2\omega_L t)}{4A_0 P_0 + A_2},$$

where we have assumed $A_4 = 0$.

Normalization of the TDPAD spectra was achieved by forcing the function $R(t)$ to oscillate around its zero value. This procedure was consistent with the normalization using the integrated beam current.

Figs. 6 and 7 show the experimental results for both nuclei. The solid lines are the best fits to the experimental points and correspond to the function

$$R(t) = K[\sin 2\omega_L t + \exp(-\lambda T) \sin 2\omega_L (t+T)],$$

where T is the time elapsed between two successive beam bursts and the contribution from the previous beam burst (approximately 7 %) is accounted for by the second term. Table 1 shows the resulting values of ω_L, $T_{\frac{1}{2}}$ and A_2 coefficients.

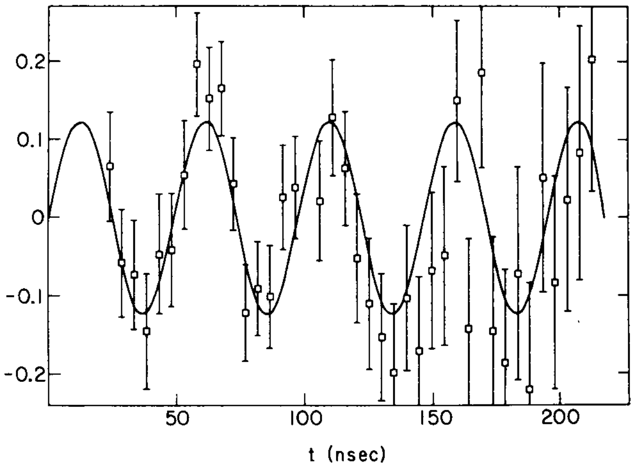


Fig. 6. Larmor precession of the 6^- isomeric state in ^{66}Ga observed through the rotation of the angular distribution of the 448 keV γ-ray.

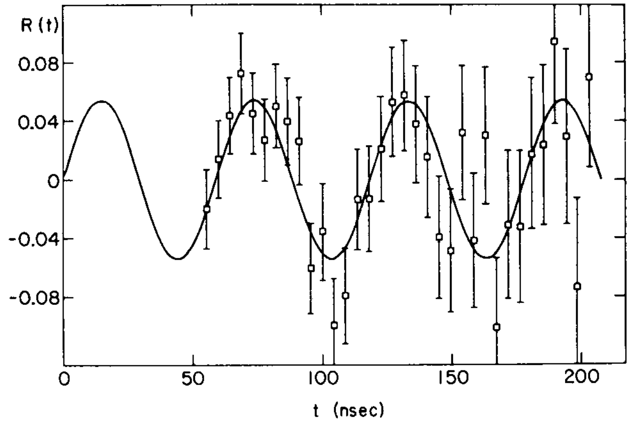


Fig. 7. Larmor precession of the 7^- isomeric state in ^{68}Ga observed through the rotation of the angular distribution of the 607.3 keV γ-ray.

The g-factors are obtained from the relation

$$g = \frac{\omega_L \hbar}{\mu_N B},$$

where B is the magnetic field at the site of the nucleus. Using the spin-echo technique, Kontani and Itoh [4]) have measured the absolute value of the hyperfine magnetic field of Ga in Fe at 4.2°K to be $|B(\text{Ga/Fe}, T = 4.2°\text{K})| = 110 \pm 3$ kG. By taking into account the Fe magnetization curve [5]) a correction of $-2.6\ \%$ must be applied to obtain the magnetic field at room temperature. This yields $|B(\text{Ga/Fe, room } T)| = 107 \pm 3$ kG. Królas [6]) used the g-factor of the known 43.7 keV isomeric

TABLE 1

Larmor frequency and related data for the isomeric 6^- and 7^- states in ^{66}Ga and ^{68}Ga

Nucleus	Line (keV)	Period (ns)	$T_{1/2}$ (ns)	A_2	ω_L (MHz)
	933	48.9(0.7)	57.6(1.6)	−0.035(0.006)	64.2(0.9)
^{66}Ga	834	49.8(0.8)	56.5(2.7)	−0.031(0.006)	63.1(1.0)
	600	45.7(1.6)	54.6(2.7)	0.017(0.007)	68.7(2.4)
	448	48.5(0.5)	60.2(2.8)	−0.056(0.008)	64.8(0.6)
average		48.7(0.4)	57.3(1.2)		64.5(0.1)
^{68}Ga	607	59 (1)	64 (2)	−0.10 (0.01)	53.2(0.1)

TABLE 2

The g-factors for the 6^- and 7^- isomeric states of ^{66}Ga and ^{68}Ga obtained in the present work

Nucleus	J^π	g-factor determined by using magnetic field B from		Weighted average
		ref. [4])	ref. [6])	
^{66}Ga	6^-	0.125(0.004)	0.143(0.008)	0.129(0.003)
^{68}Ga	7^-	0.103(0.003)	0.118(0.007)	0.105(0.003)

state in ^{66}Ga to determine the sign and magnitude of the same quantity, obtaining a somewhat different value $B(\text{Ga/Fe, room } T) = -94 \pm 5$ kG. With these values of the magnetic field and our results for the Larmor precession frequency we obtain the g-factors shown in table 2.

3. Discussion and results

The g-factors reported above enable us to examine whether the 6^- and 7^- isomeric states in ^{66}Ga and ^{68}Ga are well described by the shell model. As mentioned in the introduction, there is some evidence from energy systematics (fig. 2) that this may indeed be the case.

Within the framework of the shell model there is only one possible configuration to explain a low-lying 7^- state such as that found in ^{68}Ga, namely $\{\pi f_{\frac{5}{2}}, \nu g_{\frac{9}{2}}\}_{7^-}$ and two configurations for a 6^- state in ^{66}Ga, which are $\{\pi f_{\frac{5}{2}}, \nu g_{\frac{9}{2}}\}_{6^-}$ and $\{\pi p_{\frac{3}{2}}, \nu g_{\frac{9}{2}}\}_{6^-}$.

For a doubly odd nucleus the g-factor is given by

$$g = \tfrac{1}{2}(g_p + g_n) + (g_p - g_n)\frac{J_p(J_p+1) - J_n(J_n+1)}{2J(J+1)},$$

where g_p and g_n are the g-factors of the odd proton and neutron, and J_p and J_n are the angular momenta of the proton and neutron, respectively.

For the proton and neutron g-factors we can use the Schmidt values computed for the corresponding assumed single-particle configurations. However, the sys-

TABLE 3

Data for g-factor of odd-A neighbors of ^{66}Ga and ^{68}Ga

Nucleus	J	Exp	Schmidt	Bodenstedt [b]
$^{73}_{33}$As	$\frac{5}{2}^-$	0.65 [a]	$0.345(\pi f_{5/2})$	0.806
$^{69}_{31}$Ga	$\frac{3}{2}^-$	1.34 [d]		
$^{67}_{31}$Ga		1.23 [d]		
average		1.28	$2.529(\pi p_{3/2})$	0.773
^{67}Zn$_{37}$		−0.243(0.004) [c]		
^{67}Ge$_{35}$	$\frac{9}{2}^+$	−0.210(0.007) [c]		
^{69}Ge$_{37}$		−0.222(0.001) [c]		
average		−0.225(0.001)	$-0.425(\nu g_{9/2})$	−0.234

[a] Nucl. Data Sheets 1, no. 6 (1966) B1-6-57.
[b] See ref. [9].
[c] See ref. [10].
[d] See ref. [11].

TABLE 4

The g-factors of the 6^- and 7^- isomeric states in the odd-odd ^{66}Ga and ^{68}Ga

Nucleus	Configuration	Schmidt [a]	Emp [b]	Exp
^{68}Ga	$\{\pi f_{5/2}, \nu g_{9/2}\}_{7^-}$	−0.150	+0.087	0.105(0.003)
^{66}Ga	$\{\pi f_{5/2}, \nu g_{9/2}\}_{6^-}$	−0.187	+0.046	20 % } 0.129(0.003) [c]
^{66}Ga	$\{\pi p_{3/2}, \nu g_{9/2}\}_{6^-}$	+0.314	+0.150	80 %

[a] Value obtained using the result of the pure single-particle model (see table 3) for g_p and g_n.
[b] Value obtained using the empirical data for g_p and g_n from neighboring odd-A nuclei (see table 3).
[c] See text.

tematics show that, in general, the experimental values depart considerably from those predicted by the Schmidt formula.

It has long been recognized that such deviations are mainly due to core polarization effects [7-9]. By taking these into account, the agreement with the measured g-factors of odd-A nuclei is considerably improved.

In our case of odd-odd nuclei these effects are best taken into account by using the g_p and g_n values experimentally determined for the corresponding states in the odd-A neighbors. Table 3 shows the available data for such nuclei. The Schmidt predictions and the value obtained by using an effective spin g-factor $g_{s,\,\mathrm{eff}}$ proposed by Bodenstedt [9] to include the core polarization effect are also shown. It is seen that for these nuclei the deviations from the Schmidt values are large while the use of $g_{s,\,\mathrm{eff}}$ yields a reasonable agreement.

In table 4, the g-factors measured in the present work are compared to those obtained by assuming g_p and g_n as given by either the pure single-particle model (under column labelled "Schmidt"), or the experimental values obtained from neighboring nuclei (column labelled "Emp"). It is seen that a reasonable agreement is obtained with the empirical g_p and g_n for the 7^- state in ^{68}Ga assuming the $\{\pi f_{\frac{5}{2}}, \nu g_{\frac{9}{2}}\}_{7^-}$ configuration while the Schmidt prediction yields the opposite sign. The measured g-factor for the 6^- state in ^{66}Ga is close to the calculated value assuming the $\{\pi p_{\frac{3}{2}}, \nu g_{\frac{9}{2}}\}_{6^-}$ configuration and the empirical figures for g_p and g_n. However a small mixing of the $\{\pi f_{\frac{5}{2}}, \nu_{\frac{9}{2}}\}_{6^-}$ term cannot be ruled out. In fact if one assumes that the wave function is

$$\Psi_{6^-}(^{66}\mathrm{Ga}) = \sqrt{1-\beta^2}\{\pi p_{\frac{3}{2}}, \nu g_{\frac{9}{2}}\}_{6^-} + \beta\{\pi f_{\frac{5}{2}}, \nu g_{\frac{9}{2}}\}_{6^-},$$

the present measurement yields $\beta^2 = 0.20$.

In summary, the g-factors determined in this work support the assumption that the 6^- and 7^- isomeric states in ^{66}Ga and ^{68}Ga can be described in terms of simple shell-model configurations involving the $g_{\frac{9}{2}}$ neutron orbit and $p_{\frac{3}{2}}$ and $f_{\frac{5}{2}}$ proton orbits, but the polarization effects, not taken into account in the extreme single-particle description, appear to be important.

After the present measurements were completed, a thesis work by Leitz [10]) came to our attention. Using a 40 kG magnet and the ^{63}Cu(α, nγ)^{66}Ga and ^{65}Cu(α, nγ)^{68}Ga reactions, Leitz determined the g-factors of the 6^- and 7^- states in ^{66}Ga and ^{68}Ga, embedded in a copper matrix, to be $g(6^-, {}^{66}\mathrm{Ga}) = 0.123 \pm 0.03$ and $g(7^-, {}^{68}\mathrm{Ga}) = 0.102 \pm 0.02$. The g-factors reported by Leitz and those obtained in the present work using the Kontani and Itoh value of the hyperfine magnetic field in iron (see table 2) are in very good agreement. Using the g-factors reported by Leitz and our values for the Larmor precession frequencies we can make an independent estimate of the hyperfine magnetic field in iron which is $B(\mathrm{Ga/Fe}, \text{room } T) = -109 \pm 2$ kG, in excellent agreement with Kontani's value reported in ref. [4]).

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References

1) C. Pomar, Thesis, University of Cuyo, Argentina, 1976, unpublished;
C. Pomar, Y. Gono, H. M. Jäger, P. Kleinheinz, R. M. Lieder, M. A. J. Mariscotti, M. Müller-Veggian and A. Neskakis, to be published
2) L. Harms Ringdahl, J. Sztarkier and Z. P. Zawa, Phys. Scripta **9** (1974) 15
3) P. Thieberger, Ark. Fys. **22** (1962) 127
4) M. Kontani and J. Itoh, J. Phys. Soc. Japan **20** (1965) 1737; **19** (1964) 1984; **22** (1967) 345
5) R. S. Preston, S. S. Hanna and J. Heverle, Phys. Rev. **128** (1962) 2207
6) K. Królas, Int. Conf. on hyperfine interactions studied in nuclear reactions and decay, Uppsala, Sweden, 1974, ed. E. Karlsson and R. Wäppling, p. 151
7) H. Noya, A. Arima and H. Horie, Prog. Theor. Phys. (Kyoto) Suppl. 8 (1958) 33
8) R. J. Blin-Stoyle, Proc. Phys. Soc. **A66** (1953) 1158

9) E. Bodenstedt and J. D. Rogers, in Perturbed angular correlations, ed. E. Karlsson, E. Matthias and K. Siegbahn (North-Holland, Amsterdam, 1964) p. 91

10) H. Bertschat, H. Haas, W. Leitz, V. Leithäuser, K. H. Maier, H. E. Mahnke, E. Recknagel, W. Semmler, R. Sielemann, B. Spellmeyer and Th. Wichert, Proc. Int. Conf. on nuclear moments and and nuclear structure, Osaka, 1972, ed. H. Horie and K. Sugimoto, p. 217

11) V. S. Shirley, in Hyperfine interactions in excited nuclei, ed. G. Goldring and R. Kalish (Gordon and Breach, NY, 1971)

12) W. Leitz, Thesis Freien Universität, Berlin, 1973, unpublished; and Spring Meeting of the German Physical Society, Heidelberg, 1973, p. 152