Decay of the 1^+ Isomer in ^{24}Al

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(Received February 15, 1979)

The 1^+ isomer in ^{24}Al is found to be located at 426 keV slightly different from the previous assignment. The 1^+ isomer decays by β transitions with branching ratio of $22\pm3\%$ and by emission of a 426-keV γ ray with $78\pm3\%$. The log (ft) value of the β transition from ^{24m}Al(1^+) to the 9962-kVe level in ^{24}Mg is obtained to be 3.5 ± 0.1, indicating a super-allowed transition. The reduced transition probability B(M3) of the $1^+\rightarrow4^+$ γ transition is deduced to be 264 ± 13 $(e\hbar/2Mc)^2$fm^4. Correction for spin magnetic moments in M3 moments are discussed.

[RADIOACTIVITY ^{24m}Al [from ^{24}Mg(p, n)]; measured I_γ, E_γ, $T_{1/2}$, Excitation functions, β- and γ-branchings; deduced log (ft), B(M3).]

§1. Introduction

Isospin symmetry can be used to study the nuclear structure of 0d-1s shell nuclei. As for the $A=24$ isobars the 4^+ ground states in ^{24}Al and ^{24}Na and the 4^+ state at 9515 keV in ^{24}Mg constitute $T=1$ isospin triplet.[1)] The first-excited 1^+ isomer in ^{24}Al ($T_{1/2}=128$ msec) and in ^{24}Na ($T_{1/2}=20$ msec) are also two members of isospin triplet,[1)] and the other member should be located at around 9.94 MeV in ^{24}Mg. This state is to be observed in the β decay of ^{24m}Al(1^+). The weak 9962-keV γ ray with a half-life of 228 ± 90 msec has been observed in the delayed-γ-ray study after the ^{24}Mg(p, n)^{24}Al reaction,[3)] and the 9962-keV level has been proposed to be $1^+(T=1)$. To confirm this assignment from the log (ft) value the branching ratio of ^{24}Al(1^+) to the 9962-keV level should be measured.

The reduced transition probability of the $1^+\rightarrow4^+$ M3 γ transition in ^{24}Al can be deduced from the lifetime and the γ decay branching ratio of the 1^+ isomer. The M3 transition probabilities in ^{24}Al and ^{24}Na will provide information on the nuclear structure of the $A=24$ nuclei.

At the first stage of the present work we found that the 1^+ isomer in ^{24}Al is located at 426 keV, not at 439 keV as assigned previously.[1)] We then remeasured the β- and γ-decay branching ratios of ^{24m}Al(1^+).

§2. Experimental Procedure

The experiment was performed by using 26-MeV proton beam from the IMS (The Institute of Medical Science, University of Tokyo) cyclotron. ^{24m}Al was produced by the ^{24}Mg(p, n)^{24}Al reaction. The target was ^{24}MgO powder enveloped by a 2-μm thick mylar foil. The enrichment was more than 99%. Carbon contamination was carefully eliminated at and around the target position so that the short-lived β emitter ^{12}N may not be produced by the ^{12}C(p, n)^{12}N reaction. Gamma rays were detected with a 40-cc Ge(Li) detector which had the energy resolution of 2.7 keV at 1330 keV. Beta rays were detected by a counter telescope of plastic scintillators described later.

To determine the energy level of the 1^+ isomer in ^{24}Al 1) time spectra and 2) excitation functions of the delayed γ rays were measured. The β- and γ-decay branching ratios were determined by comparing the yield of the $T_{1/2}=128$ msec component of the β rays with the yield of the 426-keV γ ray in the time spectra. High-energy delayed γ rays were measured to study the β-decay branch of ^{24m}Al(1^+) to its anologue state in ^{24}Mg.

2.1 *Time spectra*

The cyclotron beam was pulsed macroscopically by an external beam pulsing system.[4)] The proton beam passed through the pulsing system for only 50 msec out of 1 sec and was deflected away for the succeeding 950 msec. A saw-tooth generator was triggered synchronously with the macroscopic beam pulse and its pulse height was sampled when a signal from the detectors was fed to the linear gate. The energy of the γ rays were selected by the digital gate mode of PDP-11/40 computer.

2.2 Excitation functions

Only delayed γ rays were measured because the delayed component of the 426-keV and the 439-keV γ rays were of current interest and the prompt events of the 439-keV γ rays which came from the $5/2^+ \to 3/2^+$ transition in ^{23}Na must be omitted. The yields of the γ rays were measured at proton incident energies 17, 20, 23 and 26 MeV. Aluminum foils were used to degrade the primary proton energy. The yields of the γ rays in each run were normalized by integrating the proton beam current.

2.3 β- and γ-decay branching ratios

For the β-ray detection a counter telescope of two plastic scintillators was used. The first plastic scintillator was of 2-mm thickness with $7 \times 7\ cm^2$ area and the second one was of 3-mm thickness with a 2.5 cm radius.

The β-ray detection efficiency of the telescope was defined by the solid angle of the second counter. The efficiency of the Ge(Li) detector at 426 keV was determined by measuring the γ rays from the γ-ray sources ^{133}Ba and ^{152}Eu. The β counter and the Ge(Li) detector were placed at 90° to the beam in the oposite sides of the target at the distance of 10.5 cm and 14.1 cm, respectively, from the target position. The relative efficiency of the β-ray and the γ-ray detectors were also checked by measuring the β ray and the γ ray from the radioisotope ^{198}Au.

The time spectrum of the β rays with all energy was measured and was divided into the $T_{1/2}=2.07$ sec component and the $T_{1/2}=128$ msec component. The time spectrum of the 426-keV γ ray was measured at the same time. The yield of the β ray with $T_{1/2}=128$ msec and the yield of the 426-keV γ ray provide, after the normalization of the detector efficiencies, the β- and γ-decay branching ratio of the 1^+ state in ^{24}Al.

2.4 High-energy delayed γ rays

The most feasible way to determine the decay branch of the 1^+ isomer to its analogue state is to measure the high-energy delayed γ rays. Delayed γ rays up to 14 MeV were measured by the Ge(Li) detector. The γ rays from the radioisotope ^{152}Eu and the 6143 keV prompt γ rays of the $3^- \to 0^+$ transition in ^{16}O accompanying the $^{16}O(p, p')^{16}O$ reaction were used for the energy calibration. The present data on the energies of the γ lines in ^{24}Mg succeeding the β decay of the ground state of ^{24}Al coincided with the previous data[1)] within errors of ± 3 keV. Gamma-ray detection efficiency up to 2 MeV of the Ge(Li) detector was obtained by measuring the γ rays from ^{133}Ba and ^{152}Eu and was extrapolated to the higher-energy part. The known γ decay branches of the 9515 keV and the 8436 keV levels in ^{24}Mg[1)] were used to check the efficiency of the detector. The differences between the present data and the previous ones on these decay branches were less than 8%.

§3. Experimental Results

3.1 Energy level of the 1^+ isomer in ^{24}Al

It has been reported that the 1^+ isomer in ^{24}Al is located at 439 keV and its half-life is 129±msec.[1)] However, care must be taken since the 439-keV delayed γ ray comes also from ^{23}Na which is fed through β decay of ^{23}Mg produced by the $^{24}Mg(p, pn)^{23}Mg$ reaction. In the delayed-γ-ray spectrum there is a peak at 426 keV as well as at 439 keV (see Fig. 1). The time spectrum of the 426-keV γ ray showed an exponential decay with a half-life of 128 ± 6 msec while that of the 439-keV γ ray was flat. The latter seems to come solely from the β decay of ^{23}Mg with $T_{1/2}=12$ sec.

To ascertain that the 426-keV γ ray belongs to ^{24}Al, the excitation functions were measured (see Fig. 2). The excitation functions of the delayed γ rays in ^{24}Mg reflect the yields of ^{24}Al and ^{24m}Al with the reaction Q-values of -14.6 MeV and -15.0 MeV, respectively. The excitation function of the 426-keV γ ray showed the same feature as those of the γ transitions in ^{24}Mg, and therefore the 426-keV γ ray accompanies the (p, n) reaction. On the other hand the yield of the 439-keV γ ray becomes maximum at $E_p=24.5$ MeV which is about 3 MeV higher than the other γ rays, reflecting

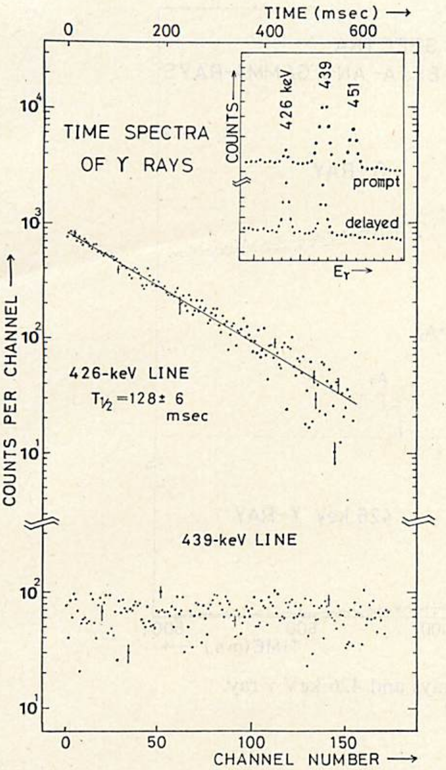

Fig. 1. Time spectra of the 426-keV and 439-keV γ rays.

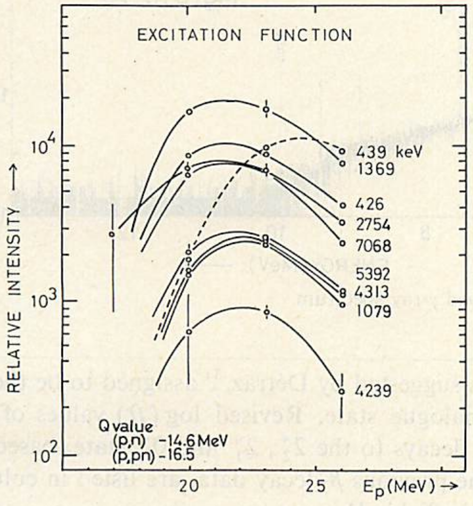

Fig. 2. Excitation functions of the delayed γ rays.

the reaction Q-value of -16.5 MeV of the ^{24}Mg(p, pn)^{23}Al reaction. The 1^+ isomer in ^{24}Al was therefore assigned to be located at 426 keV, not at 439 keV. Its half-life is 128 ± 6 msec, in good agreement with the previous value.

3.2 β- and γ-decay branching ratios

The β-ray time spectrum was fitted to a function

$$A_1 \exp(-0.693\times t/T_1) + A_2 \exp(-0.693\times t/T_2) + A_3, \quad (1)$$

where $T_1=128$ msec and $T_2=2.07$ sec (see Fig. 3). From the yield of the β ray with $T_{1/2}=$ 128 msec and that of the 426-keV γ ray the β- and γ-decay branching ratios of the 1^+ isomer were obtained to be $N_\beta=22\pm3\%$ and $N_\gamma=78\pm3\%$. The error is mainly the systematic one arising from low-energy β rays stopped in the first plastic scintillator.

3.3 High-energy delayed γ rays

The energy spectrum of the high-energy delayed γ rays is shown in Fig. 4. Intensities of the γ rays are listed in Table I. (see also Fig. 5). Candidate for the analogue state of the 1^+ isomer in ^{24}Al was looked for at around 9.94 MeV, and the only peak observed was located at 9962 ± 4 keV, which was the same peak as

Table I. High-energy delayed γ rays.

E_γ (keV)	Location	Intensity	
		Present	ref. 1
1079	$4_4\to4_3$	13.9±0.3	16.6±1.6
1117		10.7±0.3	
1172		7.6±0.2	
1298		5.4±0.2	
1340		8.2±0.2	
1369	$2_1\to0$	100.0±1.0	100.0±0.5
1468		22.1±0.4	
1633		3.2±0.2	
1771	$4_2\to2_2$	0.2±0.2	
2222		1.6±0.1	
2630		4.9±0.3	
2754	$4_1\to2_1$	39.2±0.6	45 ±4
2870	$2_2\to2_1$	1.7±0.3	1.5±0.4
3200	$4_3\to3$	4.1±0.3	3.7±0.5
3505	$4_4\to4_2$	1.9±0.2	2.4±0.4
3867	$3_1\to2_1$	5.3±0.2	5.8±0.6
4197	$4_3\to2_2$	3.2±0.2	4.6±0.5
4239	$2_2\to0$	2.7±0.3	3.7±0.4
4313	$4_3\to4_1$	13.2±0.6	15.6±1.6
4641	$4_2\to2_1$	2.4±0.2	3.7±0.7
5392	$4_4\to4_1$	14.1±0.9	21 ±2
6128		1.9±0.2	
7068	$4_3\to2_1$	49.5±4.0	42 ±4
7629		1.0±0.2	
7648		0.9±0.2	
7850		0.8±0.2	
9962	$1\to0$	0.39±0.1	

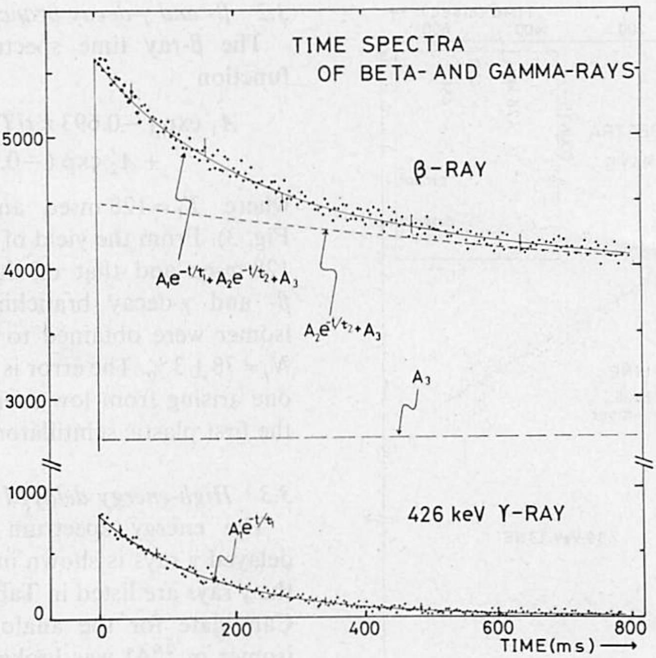

Fig. 3. Time spectra of the β rays and 426-keV γ ray.

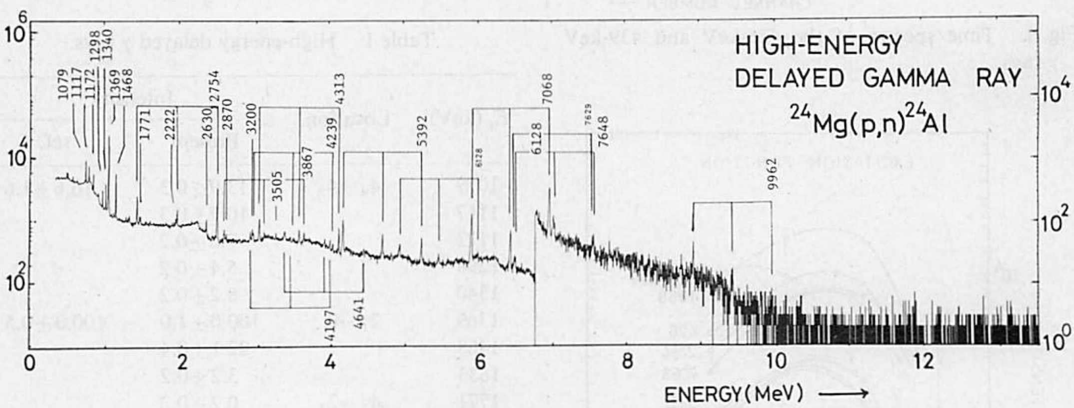

Fig. 4. High-energy delayed γ-ray spectrum.

reported by Détraz.[3] The β decay branch of ^{24m}Al(1^+) is 22% and the branch to the 9962-keV level amounts to 1.2 ± 0.3% out of 22%.

§4. Discussions

4.1 β decay of the 1^+ isomer in ^{24}Al

The log (ft) value of the $1^+\rightarrow9962$ keV β transition is 3.5 ± 0.1, indicating a super-allowed transition (see Table I). The log (ft) values of the super-allowed β transitions from the ground state of ^{24}Al to the 9515-keV level and the 8436-keV level are 3.48 and 3.99,[1] respectively. The 9962-keV level is, therefore, as suggested by Détraz,[3] assigned to be the 1^+ analogue state. Revised log (ft) values of the β decays to the 2_2^+, 2_1^+ and 0^+ state, based on the previous β-decay data, are listed in column 6 in Table II.

4.2 The M3 transition in ^{24}Al

From the lifetime and the γ-decay branch the γ-decay partial half-life of the 1^+ isomer in ^{24}Al was deduced to be 164 ± 7 msec. The reduced transition probabilitiy B(M3) obtained is

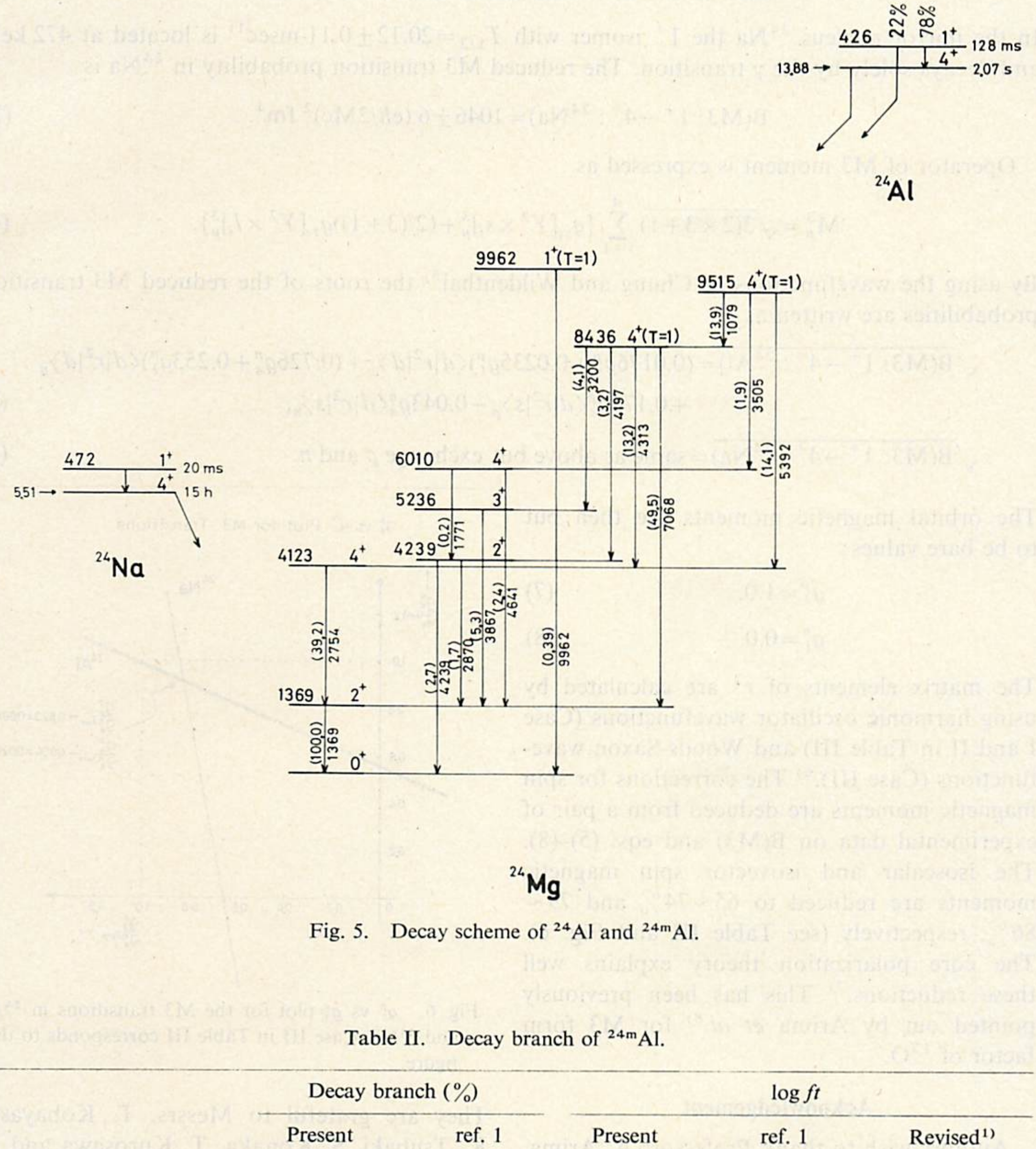

Fig. 5. Decay scheme of ^{24}Al and ^{24m}Al.

Table II. Decay branch of ^{24m}Al.

		Decay branch (%)		log *ft*		
		Present	ref. 1	Present	ref. 1	Revised[1)] value
γ decay		78 ±3	93 ±2			
β decay		22 ±3	7 ±2			
Daughter level (keV)	I^π					
9962	$1^+(T=1)$	1.2±0.3		3.5±0.1		
4239	2^+	3.1±2.0[2)]	0.7±0.2		6.07±0.15	5.60±0.15
1369	2^+	5.9±4.0[2)]	1.9±0.5		6.18±0.15	5.71±0.15
0	0^+	11.8±6.3[3)]	4.4±1.2		6.01±0.15	5.54±0.15

1) The log (*ft*) values in ref. 1 have been revised by using the present results; $E_x(1^+)=426$ keV, $T_{1/2}=128$ msec, $N_\beta(\text{total})=22\pm3\,\%$ and $N_\beta(1^+\to9962\text{ keV})=1.2\pm0.3\,\%$.

2) The β yield has been determined as the difference between the γ yields from and to the level.

3) Remaining 11.8% has been assumed to feed the ground state.

$$B(M3: 1^+ \to 4^+ : {}^{24}Al) = 264 \pm 13\ (e\hbar/2Mc)^2\ fm^4. \tag{2}$$

In the mirror nucleus ^{24}Na the 1^+ isomer with $T_{1/2} = 20.12 \pm 0.11$ msec[1] is located at 472 keV and decays solely by the γ transition. The reduced M3 transition probability in ^{24}Na is

$$B(M3: 1^+ \to 4^+ : {}^{24}Na) = 1046 \pm 6\ (e\hbar/2Mc)^2\ fm^4. \tag{3}$$

Operator of M3 moment is expressed as

$$M^3_\mu = \sqrt{3(2\times 3+1)} \sum_{i=1}^{A} \{g_{s_i}[Y^2 \times s_i]^3_\mu + (2/(3+1)) g_{l_i}[Y^2 \times l_i]^3_\mu\}. \tag{4}$$

By using the wavefunctions of Chung and Wildenthal[5] the roots of the reduced M3 transition probabilities are written as

$$\sqrt{B(M3: 1^+ \to 4^+ : {}^{24}Al)} = (0.0176 g^p_s + 0.0235 g^p_l)\langle d|r^2|d\rangle_p + (0.726 g^n_s + 0.253 g^n_l)\langle d|r^2|d\rangle_n$$
$$+ 0.176 g^p_s \langle d|r^2|s\rangle_p - 0.043 g^n_s \langle d|r^2|s\rangle_n, \tag{5}$$

$$\sqrt{B(M3: 1^+ \to 4^+ : {}^{24}Na)} = \text{same as above but exchange } p \text{ and } n. \tag{6}$$

The orbital magnetic moments are then put to be bare values;

$$g^p_l = 1.0, \tag{7}$$

$$g^n_l = 0.0. \tag{8}$$

The matrix elements of r^2 are calculated by using harmonic oscillator wavefunctions (Case I and II in Table III) and Woods-Saxon wavefunctions (Case III).[6] The corrections for spin magnetic moments are deduced from a pair of experimental data on B(M3) and eqs. (5)–(8). The isoscalar and isovector spin magnetic moments are reduced to 65~74% and 79~86%, respectively (see Table III and Fig. 6). The core polarization theory explains well these reductions.[7] This has been previously pointed out by Arima *et al.*[8] for M3 form factor of ^{17}O.

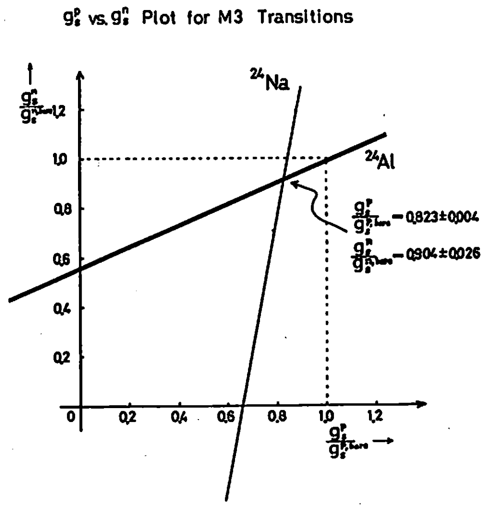

Fig. 6. g^p_s vs g^n_s plot for the M3 transitions in ^{24}Al and ^{24}Na. Case III in Table III corresponds to this figure.

Acknowledgement

Authors wish to thank Professors A. Arima, Y. Shida and Mr. T. Suzuki for the discussions. They are grateful to Messrs. T. Kobayashi, K. Tsubaki, S. Konaka, T. Kurosawa and N. Kodama with whom the first stage of this

Table III. Corrections for spin magnetic moments in the M3 transitions in ^{24}Al and ^{24}Na.

	Experiment (%)			Theory[1] (%)
	Case I[2]	Case II[3]	Case III[4]	
$\delta g^0_s/g^{0,\text{bare}}_s$	−30.6±2.1	−25.7±2.3	−35.2±2.0	−31.4
$\delta g^1_s/g^{1,\text{bare}}_s$	−21.0±0.7	−16.4±0.7	−14.4±0.7	−20.6

1) ref. 7.
2) Harmonic oscillator wavefunctions are used. Experimental charge radius $\langle r^2\rangle^{1/2} = 3.035$ fm is adopted. $\hbar w = 12.00$ MeV.
3) Harmonic oscillator wavefunctions are used. Experimental point radius $\langle r^2\rangle^{1/2} = 2.956$ fm is adopted. Proton- and neutron-finite size and center of mass motion are corrected. $\hbar w = 12.65$ MeV.
4) Woods-Saxon wavefunctions are used.

experiment was performed.

References

1) P. M. Endt and C. van der Leun: Nucl. Phys. **214** (1973) 1.
2) A. J. Armini, J. W. Sunier, R. M. Polichar and J. R. Richardson: Phys. Lett. **21** (1966) 335; A. J. Armini, J. W. Sunier and J. R. Richardson: Phys. Rev. **165** (1968) 1194.
3) C. Détraz: Nucl. Phys. **A188** (1972) 513.
4) Y. Yoshida, H. Nakayama, K. Nakai and T. Yamazaki: Nucl. Instrum. & Methods **138** (1976) 579.
5) W. Chung and B. H. Wildenthal: private communication and in preparation.
6) B. A. Brown, S. Massen and P. F. Hodyson: submitted to J. Phys.
7) B. A. Brown, T. A. Shibata, W. Chung and B. H. Wildenthal: in preparation.
8) A. Arima, Y. Horikawa, H. Hyuga and T. Suzuki: Phys. Rev. Lett. **40** (1978) 1001.