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IN-BEAM STUDY OF ^{144}Gd

M. A. J. MARISCOTTI

Institut für Kernphysik, Kernforschungsanlage Jülich, Jülich, West Germany
and
Comisión Nacional de Energía Atómica, Buenos Aires, Argentina

H. BEUSCHER †, W. F. DAVIDSON, Y. GONO, H. M. JÄGER, R. M. LIEDER, M. MÜLLER-VEGGIAN, A. NESKAKIS and D. R. HAENNI

Institut für Kernphsyik, Kernforschungsanlage Jülich, Jülich, West Germany

and

D. R. ZOLNOWSKI

Cyclotron Institute, Texas A&M University, College Station, Texas

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Abstract: A level scheme of ^{144}Gd has been established using the ^{144}Sm(α, 4nγ) reaction and in-beam spectroscopy methods. Excitation functions, γ-ray angular distributions, γ-γ coincidence spectra, γ-spectra time related to the cyclotron beam bursts and conversion coefficients for the delayed transitions have been measured.

The level scheme comprises 11 levels with spins up to $I = 12$. Two isomers, a 13 ± 2 ns, 7^- state at 2471.4 keV and a 145 ± 30 ns, 10^+ state at 3433.0 keV have been observed. The former has similar excitation energy as the 7^- isomers in ^{142}Sm, ^{140}Nd and ^{138}Ce and it may arise from the $\{\nu d_{3/2}^{-1} \times \nu h_{11/2}^{-1}\}$ configuration although its lifetime seems to indicate some degree of collectivity. The 10^+ state has a similar excitation energy as the 10^+ isomer found in ^{138}Ce and probably has a dominant $\nu h_{11/2}^{-2}$ configuration. Below the 10^+ isomer in ^{144}Gd only two excited states have positive parity; the hitherto known first 2^+ and 4^+ states. The 11^+ and 12^+ states must include four-particle configurations or they have to be of collective nature. The latter possibility is supported by the considerable E2/M1 mixture ($\approx 20\,\%$) observed for the 11^+ to 10^+ transition. An analysis of the systematics of ground band levels in the $N = 80$ isotones shows the same gradual behavior between the two VMI solutions previously found for the Te isopes.

E | NUCLEAR REACTION ^{144}Sm(α, 4nγ), E = 60–110 MeV; measured E_γ, I_γ, $\sigma(E_\alpha, E_\gamma, \theta_\gamma, t)$, γ-γ coin, I_{ce}. ^{144}Gd deduced levels, J, π, $T_{1/2}$, ICC, γ-mixing. Ge(Li) detectors, Si(Li) steering magnet, β-spectrometer.

1. Introduction

The present study of ^{144}Gd was undertaken with the purpose of obtaining new information on the properties of the transitional $N = 80$ isotones where considerable

† Also Cyclotron Institute, Texas A&M University, College Station, Texas.

admixture of single particle and collective degrees of freedom is expected and has indeed been found [1,2]). In fact ^{144}Gd, the heaviest $N = 80$ isotone so far studied, exhibits the largest E_4/E_2 ratio and a plot of 2^+ and 4^+ energies as functions of Z shows ^{144}Gd lying below the values extrapolated from the lighter isotones. On the other hand high-spin two-neutron-hole states, involving the $h_{\frac{11}{2}}$ orbit, are expected to predominate in the single-particle states.

The only previous existing information on ^{144}Gd was obtained by Habs *et al.* [3]) who reported the first 2^+ and 4^+ states at 742.6 and 1743.2 keV respectively. At the same time recent investigations [1,2,4]) have provided additional information on ^{142}Sm, ^{140}Nd and ^{138}Ce. These studies have revealed the existence of low-lying odd-parity states giving rise to a 7^- isomeric state in the three nuclei. In addition a 10^+ isomer has been discovered [2,4]) in ^{138}Ce. Both 7^- and 10^+ isomeric states are thought to have two-neutron-hole configurations. However for the 7^- state contradictory evidence is derived from the measured lifetimes [1]).

In the present work high-spin states in ^{144}Gd were reached through the (α, 4n) reaction on the very neutron-deficient ^{144}Sm isotope. We find a 7^- and a 10^+ isomeric state analogous to those in the lighter isotones. Other odd-parity states are also observed while the upper even-parity members of the ground state band are not populated. The decay of the residual nucleus is seen to take place through the proposed levels with an unusually small amount of side feeding. At the same time the states above the isomers show a high degree of alignment in the plane perpendicular to the beam axis.

As expected both single particle and collective properties are intermingled in the observed structure of ^{144}Gd.

A description of the measurements and results is given in sect. 2 and 3. The most relevant aspects emerging from the results are discussed in sect. 4 and a summary of the conclusions is presented in sect. 5.

2. Experimental measurements and results

A self-supporting target of ^{144}Sm was exposed to the α-particle beam of the Jülich isochronus JULIC at different energies between 60 and 110 MeV. Different runs were carried out with the purpose of determining excitation functions, γ-γ coincidences, γ-ray angular distributions and the time correlation between the γ-rays and cyclotron beam pulses. In addition conversion coefficients for the delayed transitions were obtained from in-beam measurements of delayed conversion electron spectra at the Texas A & M Cyclotron.

A 62 cm^3 Ge(Li) detector with a resolution of 2.1 keV at 1.33 MeV was used for the excitation function and angular distribution measurements. The γ-γ coincidence experiments were carried out with larger detectors of 77 cm^3 and 106 cm^3. For the timing measurements, a small detector of 0.9 cm^3 and resolution of $\lesssim$ 1.0 keV in the low energy (0–300 keV) range was also used. The electronic and accumulating system and the data analysis are the same as in previous experiments and have already been described elsewhere [5]). The γ-γ coincidence data were recorded event by event on magnetic tapes in a 3- or 4-parameter mode and sorted out in a PDP-15 computer.

The energies reported in this paper can be considered to be accurate within ± 0.2 keV while the error on the γ-ray intensities varies with the intensity of the line. The intensities of the most prominent lines were determined to about 10 % certainty.

2.1. EXCITATIONS FUNCTIONS

Single γ-ray spectra were obtained for incident α-particle energies of 60, 66, 70, 76, 80, 83, 90, 98, 105 and 110 MeV. These energy values are approximate to within 3 MeV. The γ-ray spectrum corresponding to the beam energy of 66 MeV is shown in fig. 1. In these measurements the detector was placed at an angle of 125°. The peak areas were normalized to the area of the 1660.7 keV line, the strongest line from the (α, α') reaction. Other contributions to the intensity of this line were ruled out as other known [6]) transitions of ^{144}Sm were not observed with the corresponding intensities. The validity of this procedure lies on the reasonable assumption that the cross section for the inelastic scattering reaction varies slowly with energy, compared with the cross section for the compound nucleus process such as the (α, xn) reaction.

The measured excitation functions are shown in fig. 2. They are plotted in an arbitrary scale for twelve γ-rays assigned to ^{144}Gd. In addition as an illustrative comparison we have included curves corresponding to lines from the $(\alpha, 3n)^{145}$Gd and $(\alpha, 2n\alpha)^{142}$Sm reactions also observed in this work. The former reach the maximum at about 50 MeV [ref. [3])], while the latter are seen to peak at about 100–110 MeV. The $(\alpha, 4n)$ reaction leading to ^{144}Gd is most intense between 65 and 70 MeV.

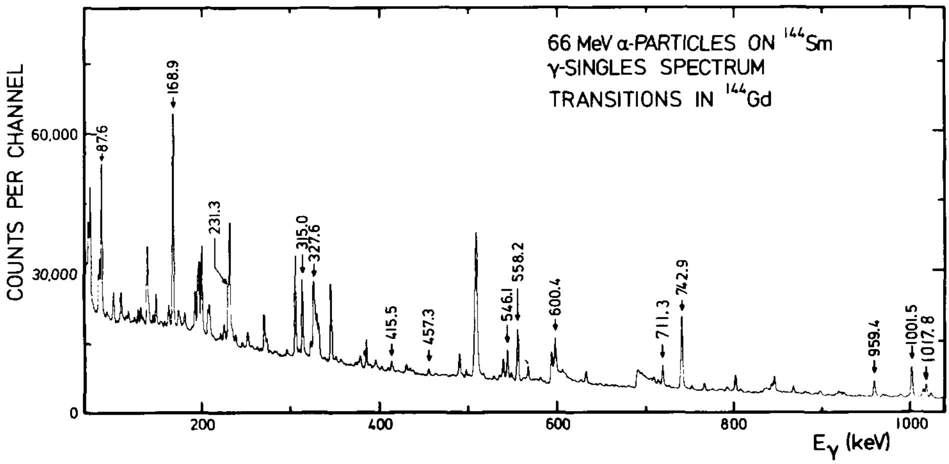

Fig. 1. γ-singles spectrum from the ^{144}Sm(α, xn) reaction at 66 MeV obtained with a 62 cm^3 Ge(Li) detector at 125°. Some of the transitions assigned to ^{144}Gd are indicated.

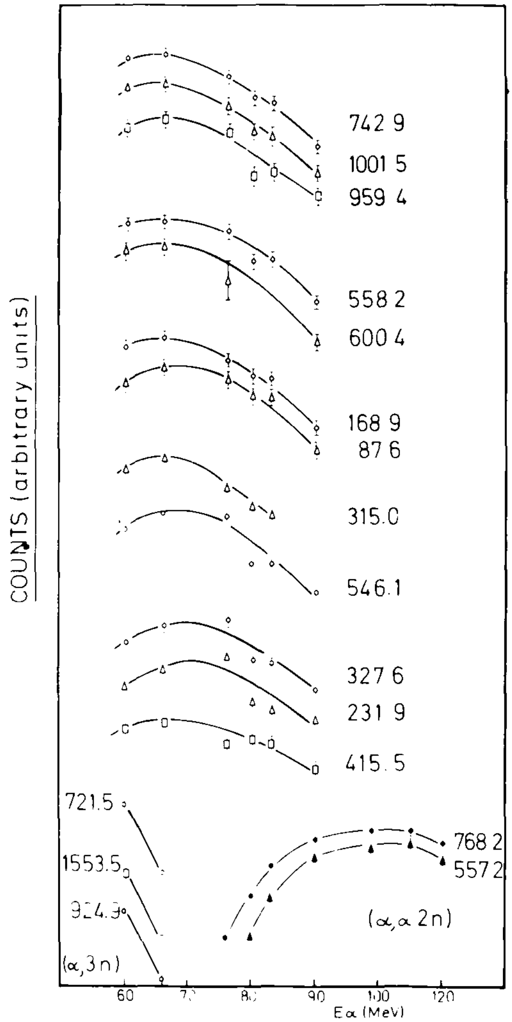

Fig. 2. Excitation functions of γ-rays assigned to ^{144}Gd and some representative γ-rays from the (α, 3n) and (α, α2n) reactions.

The results of the single γ-ray measurements at 66 MeV are given in tables 1 and 2. Table 1 contains the data corresponding to the delayed γ rays assigned to ^{144}Gd. Table 2 shows the relevant data for prompt γ-rays.

2.2. γ-γ COINCIDENCES

Two runs were carried out with the purpose of determining γ-γ coincidences. They had a duration of about 30 hours each and they were obtained at 66 MeV. The total coincidence rate was about 10^3 counts/s. In the first experiment the three

TABLE 1

Data on delayed γ-rays of ^{144}Gd

E_γ (keV) ±0.2	Intensity [a])		Ang. distribution coeff.		Internal conversion coefficients [b])						Adopted multi-polar. [c])	Transition assignments
	I_γ	I_T	A_2/A_0	A_4/A_0	α_K exp	α_K th	α_L exp	α_L th	α_M exp	α_M th		
87.4	37	53^{10}	-0.01^{2}	0.01^{3}			0.055	0.055 (E1)	0.013	0.013 (E1)	E1	$10^+ \rightarrow 9^-$
								0.38 (M1)		0.09 (M1)		
101.6	4		-0.23^{3}	-0.01^{4}								
168.9	61	86^{10}	0.15^{2}	-0.01^{3}	0.31	0.27 (E2)	0.13	0.1 (E2)	0.033	0.023 (E2)	E2	$7^- \rightarrow 5^-$
						0.42 (M1)		0.056 (M1)		0.012 (M1)		
231.3	26	31^{4}	-0.34^{2}	0.04^{3}	0.16	0.17 (M1)	(0.07)	0.024 (M1)			M1	$8^- \rightarrow 7^-$
						0.1 (E2)		0.03 (E2)				
315.0	37	39^{4}	0.17^{2}	0.00^{3}	0.088	0.075 (M1)	0.011	0.011 (M1)			M1	$7^- \rightarrow 7^-$
						0.042 (E2)		0.009 (E2)				
327.7	53	56^{5}	-0.25^{2}	0.02^{3}	0.075	0.066 (M1)	0.012	0.009 (M1)			M1	$9^- \rightarrow 8^-$
						0.036 (E2)		0.008 (E2)				
415.2	7	7^{2}	0.09^{5}	0.02^{6}	0.098	0.12 (M2)	0.034	0.02 (M2)			M2	$10^+ \rightarrow 8^-$
						0.05 (E3)		0.018 (E3)				
457.3	5		-0.09^{6}	0.03^{8}								
546.4	39	39^{4}	-0.25^{2}	0.08^{3}	0.012	0.017 (M1)					M1+E2	$8^- \rightarrow 7^-$
						0.009 (E2)						
558.1	57	57^{5}	-0.08^{2}	0.01^{3}	0.004	0.0035 (E1)					E1	$5^- \rightarrow 4^-$
						0.0086 (E2)						
600.3	34	34^{4}	0.13^{2}	-0.01^{3}								$5^- \rightarrow 3^-$
743.0	100	100^{8}	0.12^{2}	0.00^{3}	0.0045	0.0045 (E2)					E2	$2^+ \rightarrow 0^+$
959.3	36	36^{5}	-0.07^{2}	0.01^{3}								$3^- \rightarrow 2^+$
1001.1	61	61^{7}	0.16^{2}	-0.02^{3}								$4^+ \rightarrow 2^+$

[a]) Normalized to intensity 100 for 743.0 keV line. $I_T = I_\gamma(1+\alpha_T)$ where α_T is the total conversion coefficient.

[b]) Normalized to $\alpha_K(\text{exp}) = \alpha_K(\text{E2 th})$ for E_γ = 743.0 keV. Experimental errors are estimated to be less than 30%. The theoretical values shown are the closest to the experimental value.

[c]) Deduced from the internal conversion coefficients.

TABLE 2

Data on prompt γ-rays of ^{144}Gd

E_γ (keV) ± 0.2	I_γ [a])	A_2/A_0	A_4/A_0	Transition assignments
129.0	5^2	-0.29^4		
132.4	3^1	-0.20^3		
141.3	7^3	-0.20^3	0.04^4	
208.4	12^3	-0.20^2	-0.01^3	
226.8	7^2	-0.19^3	0.01^4	
235.8	8^2	-0.39^3	0.09^3	
352.6	7^2			
711.3	20^3	-1.02^2	0.09^{33}	$11^+ \rightarrow 10^+$
1017.8	25^4	0.39^2	-0.05^3	$12^+ \rightarrow 10^+$

[a]) Normalized to I_γ(743.0 keV) = 100 (see table 1).

variables E_{γ_1}, E_{γ_2} and $t_{\gamma_1\gamma_2}$ were recorded, while the second was a four-dimension experiment as $t_{\gamma\mathrm{R.F.}}$ was also recorded. The efficiency of the coincidence system was measured with the help of a ^{152}Eu source. The calibration obtained with this radioactive source was completed by using the γ-ray intensities observed in the ^{164}Dy(α, 2n)^{166}Er reaction in a parallel coincidence experiment carried out with the same arrangement. The ground state band transitions of ^{166}Er were utilized for this purpose since those following the gating transition have the same intensity in the corresponding coincidence spectrum (after correcting for internal conversion). Several sortings were made in order to study the different parameters as function of the others. This proved quite valuable for unraveling the position of the two isomeric states found in this work. Fig. 3 shows several coincidence spectra observed with the 77 cm^3 detector by gating on the 106 cm^3 detector and setting windows on the $t_{\gamma\gamma}$ and $t_{\gamma\mathrm{R.F.}}$ peaks (that is "prompt in-beam" coincidences). Fig. 4 shows two coincidence spectra, obtained by setting gates on delayed lines and a window on the "early" side of the $t_{\gamma\gamma}$ time spectrum. The resulting spectra show transitions which preceed the delayed transitions in time. Such spectra are not commonly reported in the literature. Therefore, a suitable name is lacking and they will be refered to as "reversed delayed" coincidence spectra. The first plot corresponds to the reversed delayed coincidence spectrum gated by the 168.9, 558.1, 600.3, 743.0, 959.3 and 1001.4 keV γ-rays while the second shows the reversed delayed coincidence spectrum gated by the 87.4 keV line. The lines seen in these spectra correspond to transitions which come earlier than the gates.

2.3. γ-RAY ANGULAR DISTRIBUTION

In these measurements the 62 cm^3 detector was placed at different angles with respect to the beam axis from 90° to 165° in steps of 15°. The details of the set-up and procedures are described in ref. [7]).

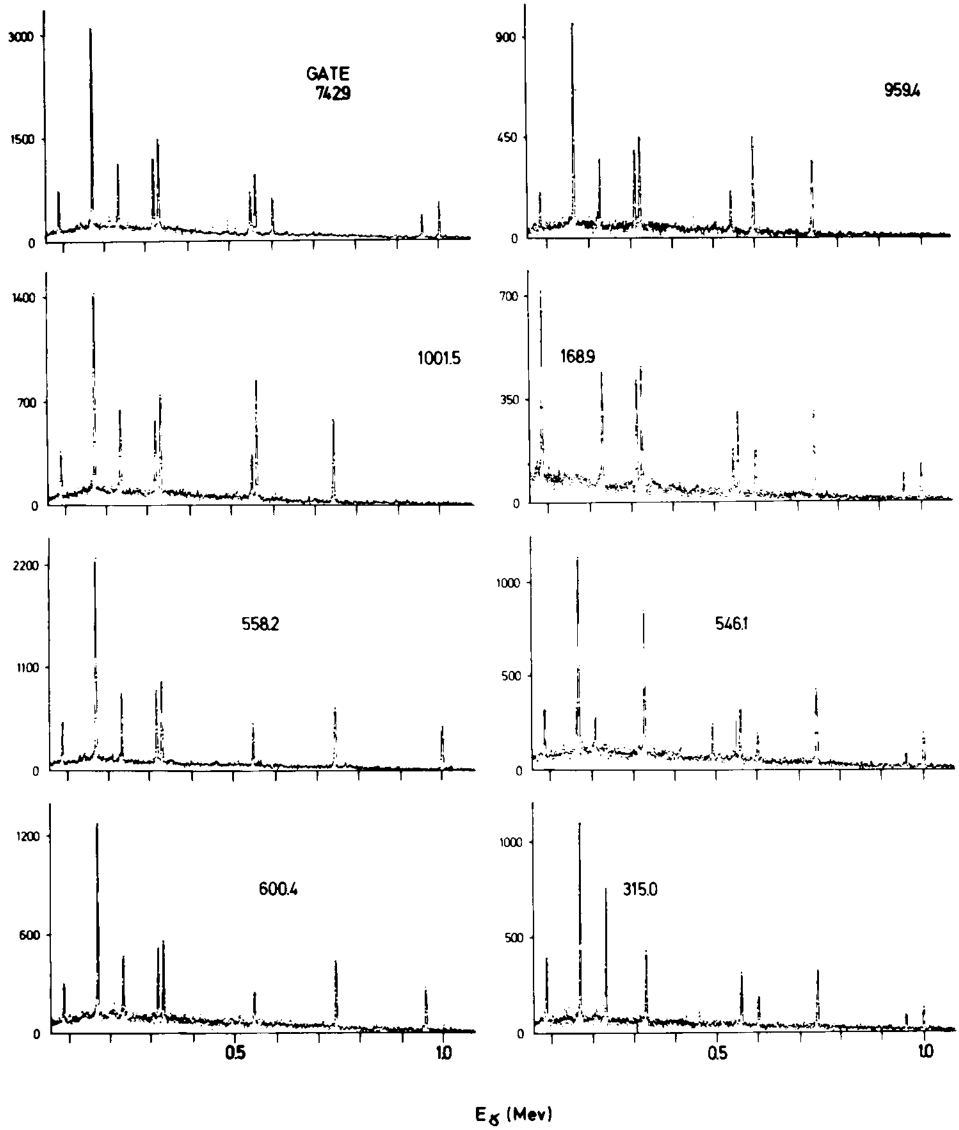

Fig. 3. Some prompt γ-γ coincidence spectra involving transitions in ^{144}Gd. The labels indicate the gating transition.

The results of the γ-ray angular distribution experiments are summarized in tables 1 and 2 and some of the fits are shown in fig. 5. Most lines exhibit negative anisotropies and small A_4 coefficients and these are interpreted as $\Delta I = 1$ transitions. There are a few lines which show positive A_2 coefficients. These are $\Delta I = 2$ transitions with the exception of the 315.0 keV line which corresponds to a $\Delta I = 0$ transition as will be discussed below.

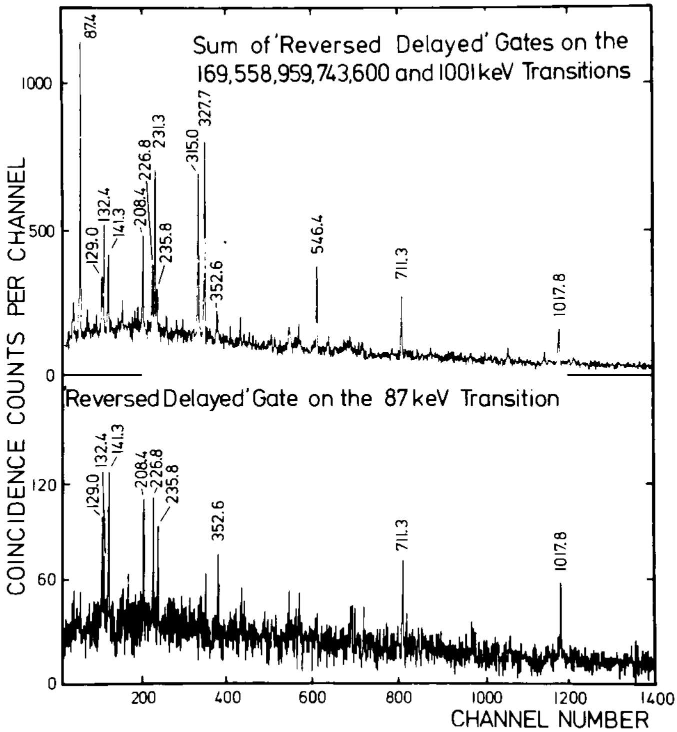

Fig. 4. "Reversed delayed" coincidence spectra gated on the 168.9, 558.1, 600.3, 743.0, 959.3 and 1001.4 keV peaks (plot (a)), and on the 87.4 keV peak (plot (b)). Only those transitions which have been shown to be on top of the 10^+ isomer by individual coincidences are labeled by their energies in the latter case.

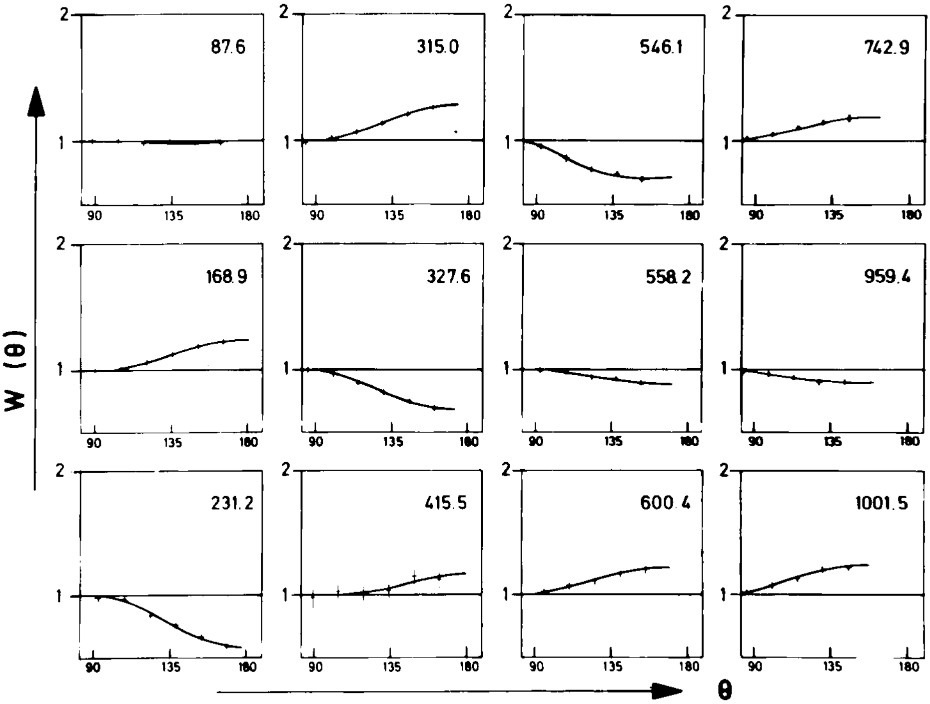

Fig. 5. Angular distributions for some γ-rays in ^{144}Gd.

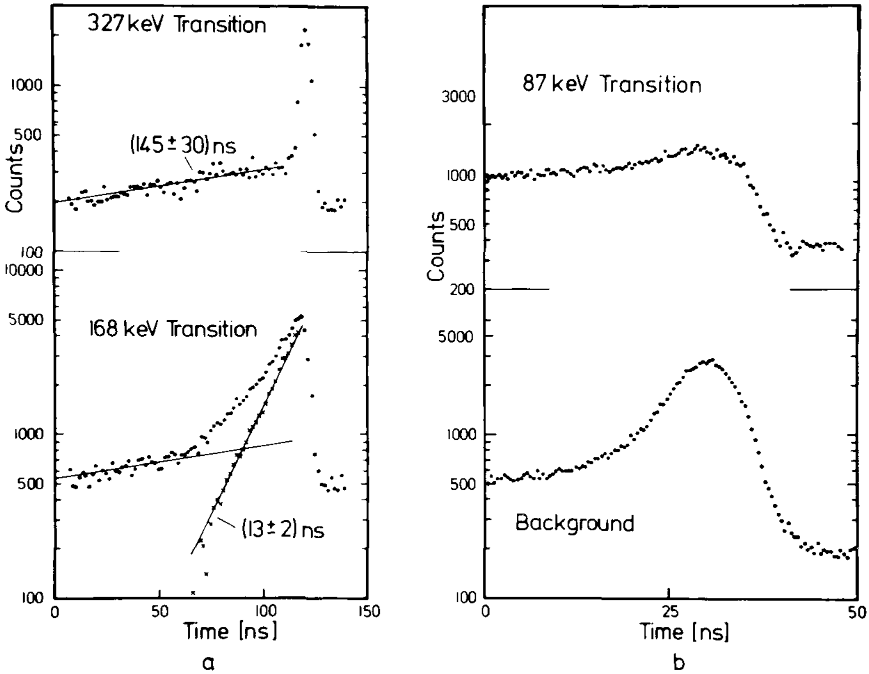

Fig. 6. Time distributions of γ-ray relative to the cyclotron beam burst: (a) For the 327.7 keV and the 168.9 keV transition using a 141 ns distance between the cyclotron beam pulses. (b) For the 87.4 keV transition and a gate on a neighboring background portion using the natural beam pulsing (47 ns) of the cyclotron.

2.4. TIMING MEASUREMENTS

All lines included in the level scheme (see below) with the exception of the 711.3 and 1017.8 keV lines, show a long time component. This corresponds to a half-life of 145 ± 30 ns. In addition the 168.9, 558.1, 600.3, 743.0, 959.3 and 1001.4 keV lines show a shorter half-life of 13 ± 2 ns. Fig. 6a shows how the two half-lives have been determined from $t_{\gamma \mathrm{R.F.}}$ timing experiments. The 168.9 keV transition is clearly seen to be the isomeric transition depopulating the 13 ns isomeric state since the time spectrum has no prompt component.

Out of four timing experiments only one with a small detector was good enough at low energies to prove that the 87.4 keV transition depopulates the long-lived isomeric state. This can be seen in fig. 6b. The upper spectrum for the 87.4 keV transition has no prompt component. For comparison the lower part shows the time spectrum for the background near the 87.4 keV line which should be mainly prompt. This experiment was done at an early stage of the study of ^{144}Gd when only the natural beam pulsing of the cyclotron (pulse distance 47 ns) was available. The half-life was later determined using a longer separation (141 ns) between beam bursts.

2.5. CONVERSION-ELECTRON MEASUREMENTS

Conversion-electron measurements were carried out at the Texas A & M Cyclotron. The measurements were limited to the delayed transitions. The delayed conversion-electron spectra from recoiling nuclei were obtained with a spectrometer consisting of a steering magnet and a cooled Si(Li) detector. The details of the set-up are described in ref. [8]). The results are summarized in table 1. The last column of table 1 gives the multipolarity deduced from these measurements. The conversion coefficients were normalized by assuming E2 multipolarity for the 743.0 keV transition. The theoretical values of the conversion coefficients given in table 1 correspond to the two closest to the experimental value. One M2 transition has been observed (the 415.2 keV transition), and the 546.4 keV γ-ray appears to have an important E2/M1 admixture. The errors of the conversion coefficients are assumed to be of the order of 30–50 % mainly because of the uncertainty in evaluating the delayed γ-ray intensities and the efficiency of the β-spectrometer which has been taken as constant within the range of interest.

3. The level scheme

Until now only the first 2^+ and 4^+ states in ^{144}Gd were known [3]). Our data confirm the results of Habs *et al.* [3]) regarding these levels. In addition several new levels were found. On the basis of the data presented in the preceding section the level scheme shown in fig. 7 was constructed.

An unusual lack of side feeding is observed. This fact made it necessary in some cases to perform a detailed analysis of the γ-coincidence intensities in order to establish the order of the γ-ray transitions. Also the observation of two isomeric states, firmly established as a result of the "reversed delayed" γ-γ coincidence spectra and the analysis of the time spectra (see figs. 4 and 6), helped to remove possible ambiguities in the placement of transitions. In this way all uncertainties, but one, could be overcome. We discuss this exception in the next paragraph.

Spins and parities, on the other hand, were, in most cases readily deduced from the angular distribution and electron-conversion measurements.

3.1. THE 13 ns ISOMER AND LEVELS BELOW IT

The timing and coincidence measurements show that the 168.9, 558.1, 600.3, 743.0, 959.3 and 1001.4 keV lines are delayed by a half-life of 13 ± 2 ns. The 168.9 keV γ-ray is identified with the isomeric transition. The 743.0 and 1001.4 keV lines correspond to the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions previously reported by Habs *et al.* [3]). The 558.1 keV γ-ray is in cascade with the 1001.4 keV γ-ray adding up to the same energy as the 600.3–959.3 keV cascade. These two parallel sequences, as clearly borne out by the coincidence spectra, define the 2302.5 keV level. However, the order of the 600.3–959.3 keV cascade could not be established solely on the basis

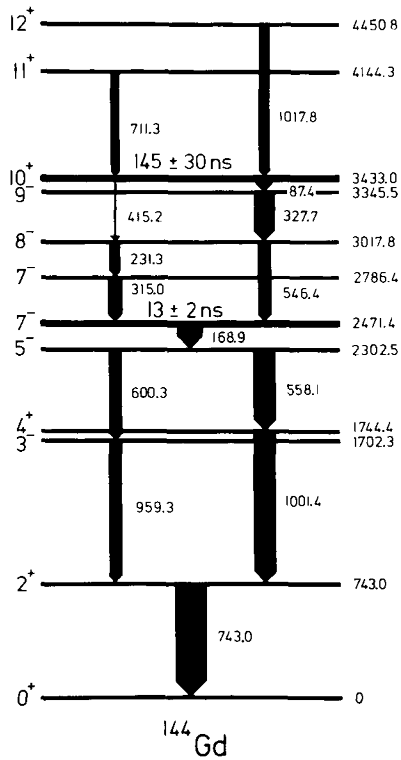

Fig. 7. Level scheme proposed for ^{144}Gd.

of our experimental data as the intensity of the two lines is the same within the experimental uncertainty and no other crossover transition was detected. For this reason we have resorted to the systematics of first excited levels in this region of the periodic table in order to determine the sequence of these transitions. The conversion coefficient and angular distribution of the 558.1 keV γ-ray, which feeds the 4^+ state at 1744.4 keV, indicate that this is a $\Delta I = 1$ transition of E1 character. This together with the fact that a crossover transition to the 2^+ state is not observed, lead us to assign $I^\pi = 5^-$ to the 2302.5 keV state. Hence if the 600.3 keV γ-ray depopulates this state we obtain the intermediate state at 1702.3 keV. This state must have $I^\pi = 3^-$ because: (a) The angular distribution of the 600.3 keV line indicates either $\Delta I = 2$ or 0. The latter would not be consistent with the prompt decay into the 2^+ state via the 959.3 keV line which exhibits $\Delta I = 1$ character. Therefore $\Delta I = 2$ for the 600.3 keV γ-ray (b) The branching ratio I_γ (600.3)/I_γ (558.1) clearly indicates that the 600.3 keV line is electric rather than magnetic. Conversely if the 959.3 keV line, instead of the 600.3 keV line, depopulated the 5^-, 2302.5 keV state, an intermediate $I = 4$ level at 1343.3 keV would be obtained. The reasonably well established systematics of 3^- and 4 states in neighboring nuclei clearly favours the former choice, taking into account that the expected 4^+ state is seen at 1744.4 keV.

The 7^- assignment for the 13 ns isomer is inferred from the stretched E2 character of the 168.9 keV γ-ray as indicated by its angular distribution and conversion coefficient.

The lifetime of this states implies an E2 transition rate which is about 3 times faster than the Weiskopff estimate [9]). We shall come back to this point in the next section.

3.2. THE 145 ns ISOMER AND ITS DECAY

On top of the 13 ns isomer one can easily identify a group of lines with a long-lived component. Since a prompt distribution is missing in the case of the 87.4 keV line this is interpreted to be the isomeric transition. The other lines have energies of 231.3, 315.0, 327.7, 415.2 and 546.4 keV. Because of its low intensity it is difficult to ascertain whether the 415.2 keV line has a prompt component. However the following arguments allow us to establish that this line also depopulates the 145 ns isomer: (a) the "prompt off-beam" coincidence spectrum gated on this line shows all the lines placed in the level scheme (fig. 7) below the long-lived isomer except the 87.4 and 327.7 keV lines. (b) An analysis of the coincidence intensities in the energy interval $168.9 < E_\gamma < 1001.5$ keV obtained by gating on the 231.3, 315.0, 327.7, 546.1 and 743.0 keV lines, shows that the 327.7 keV γ-ray precedes the 231.3, 315.0 and 546.4 keV transitions. Hence the 415.2 is the crossover transition in the 87.4–327.7 keV cascade, (c) In addition an M2 transition of 415 keV is expected to have a lifetime in the ns region.

The decay of the 145 ns isomer can be seen in fig. 7. The arguments for spin-parity assignments are as follows. Both the 231.3 and 546.4 keV transitions have a large negative A_2 and small but positive A_4. Thus $\Delta I = 1$ in both cases. In addition the conversion coefficients indicate no parity change. The 315.0 keV line has positive A_2, hence $\Delta I = 0$, 1 or 2. Since the conversion coefficient gives M1, $\Delta I = 2$ is ruled out. These results lead to the conclusion that the 2786.4 and 3017.8 keV level have $I^\pi = 7^-$ and 8^-.

Similar arguments yield the assignments $I^\pi = 9^-$ for the 3345.5 keV state and $I^\pi = 10^+$ for the 3433.0 keV isomer since, the 87.4, 327.7 and 415.2 keV lines are E1, M1 and M2, respectively.

3.3. LEVELS ABOVE THE 145 ns ISOMER

The 145 ns state is fed by two transitions of 711.3 and 1017.8 keV. These lines are clearly seen in fig. 4 which shows the "reversed delayed" coincidence spectrum gated with the 87.4 isomeric transition. This spectrum also shows several other lines which are listed in table 2 but have not been placed in the level scheme.

The 711.3 keV γ-ray has an unusually large negative anisotropy and has been identified with a $\Delta I = 1$ transition depopulating an $I^{\pi} = 11^{+}$ state at 4144.3 keV. This large anisotropy implies a high degree of alignment (which is clearly not preserved for the following transitions below the long-lived isomer) as well as a significant E2/M1 admixture. Another evidence of the high degree of alignment above the isomer is provided by the angular distribution of the 1017.8 keV line. Since this is an stretched $\Delta I = 2$ transition we can readily compute the attenuation coefficient $\alpha_2 = A_2^{\text{exp}}/A_s^{\text{max}} = 0.96 \pm 0.04$. This value should be compared with $\alpha_2 \sim 0.2-0.3$ for the E2 transitions below the isomer (i.e. 168.9, 743.0 and 1001.4 keV γ-rays). If we assume that the 11^{+} state has the same alignment as the 12^{+} state the E2/M1 admixture of the 711.3 keV γ-ray can be estimated. Using the tabulated values [10]) of the α_2 and α_4 coefficients and the mixing ratios we obtain $-0.6 < \delta(711.3$ keV$) < -0.5$. This δ-value implies about 20 % of E2 admixture.

4. Discussion of the results and conclusions

The measurements and results described in the preceding sections contribute new information on the level properties of ^{144}Gd and enlarge our knowledge of some systematic features of $N = 80$ nuclei. The nucleus ^{144}Gd is the heaviest isotone for which data are presently available. The proposed level scheme follows the general pattern discernible in the lighter isotones. It is interesting to discuss some aspects of it.

Below the 10^{+} isomer only two excited states have positive parity, i.e., the 2^{+} and the 4^{+} states. Between the 4^{+} and 10^{+} states negative-parity states are the yrast states in ^{144}Gd. The 7^{-} isomer at 2471.4 keV has a similar excitation energy as the 7^{-} isomers in ^{142}Sm (2372.0 keV) [1]), ^{140}Nd (2221 keV) [4]) and ^{138}Ce (2128 keV) [4]) displaying a slight tendency of increasing excitation energy with mass number. The 7^{-} isomer in ^{142}Sm has been interpreted [1]) as a $\{\nu d_{\frac{3}{2}}^{-1} \times \nu h_{\frac{11}{2}}^{-1}\}$ two-neutron-hole state based on the large logft value of the β-decay from the ^{142}Eu 7^{-} isomer which is supposed to have a dominant configuration $\{\pi d_{\frac{5}{2}} \times \nu h_{\frac{11}{2}}^{-1}\}_{7^-}$. The 7^{-} isomer in ^{144}Gd decays via the E2 168.9 keV transition to the 5^{-} state at 2302.5 keV. This state has also been found in the other $N = 80$ isotones. In ^{138}Ce, the 5^{-} state is about 90 keV above, in ^{140}Nd about 50 keV above and in ^{142}Sm about 25 keV below the 7^{-} state. Kennedy *et al.* [1]) have pointed out that since the $3s_{\frac{1}{2}}$ orbit lies close to the $2d_{\frac{3}{2}}$ orbit such state could have both terms $\{\nu d_{\frac{3}{2}}^{-1} \times \nu h_{\frac{11}{2}}^{-1}\}_{5^-}$ and $\{\nu s_{\frac{1}{2}}^{-1} \times \nu h_{\frac{11}{2}}^{-1}\}_{5^-}$ as dominant configurations. This hypothesis can be tested by computing the expected lifetime between the 7^{-} and 5^{-} state. It is found [1]) that the experimental half-life in ^{142}Sm is considerably shorter than the predicted one. A similar result is obtained in our case. Using the same B(E2) values as used in ref. [1]), the calculated half-lives for the 2471.4 keV 7^{-} isomer are up to ten times larger than the measured value. These results are summarized in table 3. It is therefore apparent that although the ^{142}Eu decay provides us with a valuable probe to deduce the wave function of the 7^{-} isomer,

TABLE 3

Strength of the $7^- \to 5^-$ isomeric transition in the $N = 80$ isotones ^{144}Gd and ^{142}Sm

	E_γ (keV)	$T_{1/2}$ (ns)	B_{exp}(E2) ($e^2 \cdot fm^4$)	B_{exp}(E2)/$B_{s.p.}$(E2) [a]	B_{exp}(E2)/B_{th_1}(E2) [b]	B_{exp}(E2)/B_{th_2}(E2) [c]
^{144}Gd	168.9	13^{2}	275^{50}	3.1^{5}	5.9^{8}	11.4^{18}
^{142}Sm [d]	24.1	170^{2}	364.2^{30}	3.30^{3}	6.40^{6}	12.2^{1}

[a]) Using Weisskopf estimate for $B_{s.p.}$(E2).

[b]) B_{th_1}(E2) is obtained assuming the wave functions $\{\nu d_{3/2}^{-1} \times \nu h_{11/2}^{-1}\}_7$ and $\{\nu s_{1/2}^{-1} \times \nu h_{11/2}^{-1}\}_{5^-}$ for the $7^- \to 5^-$ transition [from ref. [1])].

[c]) B_{th_2}(E2) is obtained assuming the wave function $\{\nu d_{3/2}^{-1} \times \nu h_{11/2}^{-1}\}$ coupled to $I^\pi = 7^-$ and 5^-, for the $7^- \to 5^-$ transition [from ref. [1])].

[d]) From ref. [1]).

the transition rates show that other terms also contribute to the structure of this state making it more collective.

The 3^- state probably corresponds to the octupole vibrational mode and has collective character. Some evidence that this state has contributions from proton, rather than neutron states stems from the fact that the energy of the 3^- states is seen to change little up to neutron number $N = 82$ [$E_{3^-} = 1579$ keV, ref. [11])] and decreases above $N = 82$ because there the $f_{\frac{7}{2}}$ and $h_{\frac{9}{2}}$ neutrons can contribute. The same situation occurs in the Pb isotopes. Furthermore there is evidence that the energy of the 3^- states in the $N = 80$ isotones increases as Z diminishes.

There are several two-particle configurations which may contribute to the higher-lying negative-parity 7^-, 8^- and 9^- states at 2786.3, 3017.8 and 3345.5 keV, such as the $\{\nu d_{\frac{3}{2}}^{-1} \times \nu h_{\frac{11}{2}}^{-1}\}$, the $\{\pi g_{\frac{7}{2}} \times \pi h_{\frac{11}{2}}\}$ and the $\{\pi d_{\frac{5}{2}} \times \pi h_{\frac{11}{2}}^{-1}\}$ configurations. It is not very probable that these states are part of a collective negative parity band such as that observed for instance in the $Z = 80$ Hg isotopes [12]). The well-developed negative-parity bands in these nuclei mainly consist of stretched quadrupole transitions; that is not the case in ^{144}Gd. On the other hand the dipole transitions depopulating these states in ^{144}Gd, particularly the 327.7, 231.3 and 546.4 keV lines have considerable E2 admixtures. This has been deduced from the rather large negative anisotropies of these γ-rays, especially if one takes into account the typical attenuation factors for transitions following the long-lived isomeric decay, deduced from the $\Delta I = 2$ transition values (see subsect. 3.5). These large anisotropies imply a non-negligible amount of E2/M1 admixture (possibly more than 10 %). This observation is further confirmed by the conversion-electron measurement of the 546.4 keV transition which also revals a considerable E2 mixing. Consequently, even though a well-developed odd-parity band is not observed for ^{144}Gd, the states involved seem to show some degree of collectivity. In this regard it would be valuable to search for these states in neighboring nuclei and study their behavior as function of N and Z. No such information is available yet with the required certainty. An odd-parity band has been recently observed [2]) in ^{136}Ce, which separates in an odd-spin and an even-spin sequence showing similar features as the $\Delta I = 2$ collective bands of the Hg isotopes. It is worth noting that a 5^-, 7^-, 9^-, 11^- sequence of levels, connected by stretched transitions, has been recently proposed [13]) in the $N = 84$ ^{148}Gd isotope. This structure is similar to a known sequence built on the 3^- octupole state in ^{144}Nd [ref. [14])].

The 10^+ isomeric state at 3433 keV has a similar excitation energy as the proposed 10^+ isomer in ^{138}Ce at 3538 keV [ref. [2])] and can be interpreted as a $\{\nu h_{\frac{11}{2}}^{-2}\}$ two-neutron-hole state. This is the highest spin possible from a two-particle configuration in this region. In principle also a $\{\pi h_{\frac{11}{2}}^{2}\}$ configuration is possible. A simple argument against this latter interpretation however is that a 10^+ state has not been observed in the closed neutron shell nucleus ^{146}Gd at a similar excitation energy [6, 15]).

The 11^+ and 12^+ states at 4144.3 and 4450.8 keV respectively, cannot be two-particle states since the $h_{\frac{11}{2}}$ orbit is that with the highest j in this shell. These states must include 4-particle configurations or they have to be of collective nature. In this connection, it should be remembered that from the angular distributions of the 711.3 and 1017.8 keV transitions it was deduced (see preceding section) that the 711.3 keV line has an E2 admixture of the order of 20 %. This supports the idea that some collectivity is present in these states. The fact that some of the low-lying states in ^{144}Gd can be described as relatively pure two-neutron-hole states suggests that the proton states are at higher excitation energies. This is consistent with the notion that the spherical Gd isotopes have an extra stability associated with the filling of the $g_{\frac{7}{2}}$ and $d_{\frac{5}{2}}$ proton orbitals at $Z = 64$. Other evidence for this "shell closure" has been observed in the systematics of α-decay energies [16]) and of levels in 86-neutron isotopes [17]). More recently this has been supported by the result that in ^{146}Gd the lowest excited state is a 3^- and not a 2^+ state [ref. [11])], which probably occurs at a higher excitation energy.

It is interesting to seek a clue as to where the next member of the ground state band, i.e. the 6^+ state, should be expected to lie. This can best be done by plotting together all the available data on 6^+ states in the vicinity of ^{144}Gd. In fig. 8 the energy ratio E_{6^+}/E_{2^+} is plotted against mass number A for nuclei in this region of the periodic table (in this particular case it is found more convenient to plot E_{6^+}/E_{2^+} rather than E_{6^+} as in ref. [3]). Solid and dashed lines correspond to the isotopic and isotonic families respectively. The intersection of the $Z = 64$ and $N = 80$ curves with the abscissa $A = 144$ determines the extrapolated value of $E_{6^+}/E_{2^+} = 3.19 \pm 0.02$ for ^{144}Gd. Thus the 6^+ state in ^{144}Gd should be expected to lie at about 2.37 MeV or approximately 100 keV below the 7^- isomeric state. A limit to the intensity with which this level is fed can be estimated from the coincidence spectrum gated by the 4^+ to 2^+, 1001.4 keV transition by assuming that the 6^+ state should decay predominantly to the 4^+ state. Examining the data one finds $I_\gamma(6^+ \text{ to } 4^+)/I_\gamma(5^- \text{ to } 4^+) < 6 \times 10^{-2}$. The 6^+ state should be fed by the 7^- isomeric state since the 7^- to 6^+ E1 transition should compete with the 7^- to 5^- E2 transition. Hence from the above ratio one

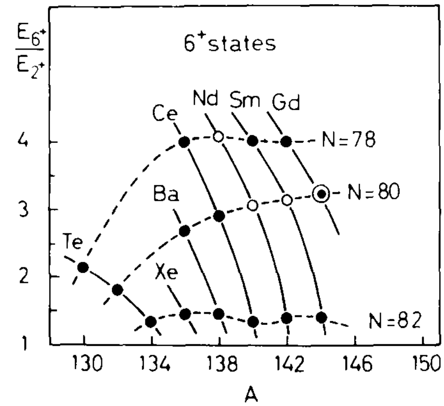

Fig. 8. Systematics of E_{6^+}/E_{2^+} ratios in nuclei with N = 78, 80 and 82. The estimated value for ^{144}Gd, indicated with an encircled dot, is E_{6^+}/E_{2^+} = 3.19±0.02 so that E_{6^+} ≈ 2.37 MeV. The open circles denote tentative assignments. The data are taken from refs. [1,2,4,18,21]).

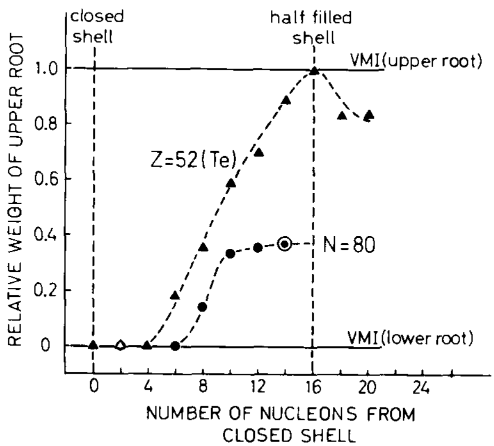

Fig. 9. Description of 6⁺ level energies in nuclei with two neutrons (or protons) away from closed shell, in terms of VMI solutions. The experimental data are taken from refs. [1,2,4,21]). The extrapolated value for ^{144}Gd deduced form the systematics shown in fig. 8 is indicated with an encircled dot.

obtains a limit for the branching $I(7^-$ to 6^+ E1$)/I_\gamma(7^-$ to 5^- E2$) \lesssim 4\times10^{-2}$. Taking into account the measured half-life of the 2471.4 keV state this value implies a hindrance factor for the unobserved E1 transition of about 10^6. A similar value ($\sim 0.5\times10^6$) is found for the E1 transition depopulating the long-lived 10^+ isomer at 3433.0 keV so that the estimated value for E_{6^+} appears consistent with our data.

It is known that the 6^+ state energies of medium-A nuclei with two particles or holes outside closed shells such as ^{144}Gd, are not well reproduced by the VMI model [19]) but instead appear to lie between the normal VMI root yielding the larger value and a lower root which fits the even-parity yrast states of magic nuclei [20]). The estimated E_{6^+} value for ^{144}Gd follows this rule as well as the 6^+ energies of ^{142}Sm, ^{140}Nd and ^{138}Ce. It has been suggested [21]) that these deviations from either of the predicted values can be viewed as reflecting a transition from one VMI solution to the other. Such an interpretation is supported by the observation [21]) that for the Te isotopes the deviation takes place as a smooth function of the neutron number N. In this case the 6^+ level energies of the heavier Te isotopes (those nearest $N = 82$) agree with the lower VMI value while a gradual transition towards the normal VMI root develops as N decreases.

Until recently no other data were available to further check this effect. The information we now have on 6^+ states in the $N = 80$ isotones (although in some cases tentative) can serve as a new test of the occurrence of this transition, in this case, as a function of Z. As in the earlier analysis we express the measured E_{6^+} energies as a linear combination of the two VMI solutions, and study the contribution of the upper root as function of Z. The results for the $N = 80$ isotones are shown in fig. 9 and are compared to the Te data. In order to facilitate the comparison the x-axis represents the number of nucleons away from closed shell. The tentative extrapolated value for ^{144}Gd obtained above has been included in fig. 9 and it is indicated with a encircled dot. It is seen that the behavior of the $N = 80$ isotones is as smooth as for the Te isotopes although the transition to the upper solution does not fully develop. This gradual variation is in sharp contrast to the erratic behavior observed in a plot of E_{6^+}/E_{2^+} *versus* E_{4^+}/E_{2^+} for these nuclei. The lighter isotones ^{132}Te and ^{136}Ba have 6^+ state energies which agree with the lower VMI solution. These nuclei are closest to the doubly magic pair $Z = 50$, $N = 82$. On the other hand the tendency towards the normal VMI solution as one approaches the middle of the shell is apparent in the case of the Te isotopes. The fact that the curve for $N = 80$ flattens off at an intermediate value may be related to the possible existence of a subshell closure at $Z = 64$ as indicated earlier.

5. Summary

This paper presents a new level scheme for ^{144}Gd obtained through the ^{144}Sm (α, 4n) reaction. The previously reported first 2^+ and 4^+ states are confirmed. The most salient aspects of ^{144}Gd found in this work are:

(i) Two isomeric states, analogous to isomeric states known in lighter $N = 80$ isotones have been identified. The 7^- state at 2471.4 keV has a half-life of 13 ± 2 ns and decays into the 5^- 2302.5 keV state. Previous results suggest that the wave functions of the isomer and the 5^- state predominantly contain the $\{\nu d_{\frac{3}{2}}^{-1} \times \nu h_{\frac{11}{2}}^{-1}\}$ and $\{\nu s_{\frac{1}{2}}^{-1} \times \nu h_{\frac{11}{2}}^{-1}\}$ terms but the transition rate is larger than that expected from these configurations. The 10^+ isomer lies at 3433.0 keV and has a half-life of 145 ± 30 ns. This state most probably arises from the coupling of two neutron holes in the $h_{\frac{11}{2}}$ orbit to the maximum allowed angular angular momentum.

(ii) The observed odd-parity states do not form a collective $\Delta I = 2$ band of the type found in other even-mass nuclei in this region or in heavier even-mass nuclei. Nevertheless the transitions connecting these states show significant E2 admixture indicating some degree of collectivity.

(iii) The 6^+ and 8^+ members of the ground state band are not observed, but the systematics yields $E_{6^+} \sim 2.37$ MeV for ^{144}Gd. At this energy it is possible to understand that this state is not populated in the decay of the 7^- isomer if an E1 hindrance factor of $\sim 10^6$ is assumed. This seems to be a plausible assumption as a similar hindrance is obtained for the E1 isomeric transition from the 145 ns isomer.

(iv) An analysis of the 6^+ energies in the $N = 80$ isotones shows that the departure from the VMI predictions, which characterize nuclei two particles away from closed shell, takes place as a smooth function of Z in a way resembling the previously noted behavior of the Te isotopes as a function of N.

(v) An unusual lack of side feeding to the state below the 10^+ isomer has been observed in this reaction. It is possible that the 10^+ isomer plays an important role in this respect as it may act as a "trap" in the decay of the residual nucleus.

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