High Energy Physics and Nuclear Physics

Volume 20, Number 2

Study of High Spin Isomer and Its Decay Level Scheme of Doubly Odd ^{144}Pm Nucleus

Zhang Yuhu[1,2], Y. Gono[2], A. Ferragut[2], K. Morita[2], C.B. Moon[2], A. Yoshida[2], T. Murakami[3], M. Nakajima[3], M. Ogawa[3], T. Morikawa[4], M. Oshima[4], H. Kusakari[5], M. Sugawara[6], K. Furono[7], T. Hayakawa[7], T. Komatsubara[7], J. Lu[7], S.J. Chae[8], J.C. Kim[8], and B.J. Min[8]

[1](Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China)
[2](RIKEN, Wako-shi, Saitama, 351-01, Japan)
[3](Department of Physics, Tokyo Institute of Technology, Oh-okayama, Megurao, Tokyo 152, Japan)
[4](Japan Atomic Energy Research Institute, Tokaii, Ibaraki 319-11, Japan)
[5](Chiba University, Chiba-shi, Chiba 260, Japan)
[6](Chiba Institute of Technology, Narashino-shi, Chiba 275, Japan)
[7](Tsukuba University, Tsukuba-shi, Ibaraki 305, Japan)
[8](Seoul National University, Seoul 151-742, Korea)

The high spin isomer (HSI) in ^{144}Pm was produced and separated by using the high spin isomer beam facility. Based on the measurements of γ-γ coincidence, γ-ray excitation functions, and isotropies, the decay level scheme of the HSI was established for the first time including 19 new high spin levels and 29 new γ-transitions assigned to ^{144}Pm by this work. The HSI-γ correlation measurement indicated that the half-life of the HSI is longer than 2 μs. From the systematic comparisons and the deformed independent particle model calculations for the N = 83 isotopes, the most possible particle configuration of $\pi(1h_{11/2}^2 d_{5/2})\nu(1i_{13/2}1h_{9/2}2f_{7/2})$ and the spin-parity of $J^\pi = 27^+$ were assigned to this HSI corresponding to an oblate deformation with $\beta = -0.18$.

Key words: high spin isomer, nuclear structure, γ-spectroscopy, decay level scheme.

Received on May 5, 1995. Supported by the Foundation of the Chinese Academy of Sciences.

1. INTRODUCTION

Bohr and Mottelson have once proposed that [1] some nuclei in high spin states could have a shape with oblate deformation; the angular momenta of such states are formed by the spin alignment of several individual particles along the symmetry axis instead of by the collective rotation. Consequently, the γ-transitions among the high spin states of single particle character lead to a change of particle configuration and therefore must follow the single particle selection roles. On the other hand, the transition energies are irregular along the yrast line, some low energy γ-rays could be involved during the deexcitation of the states. Both reasons often result in an occurrence of high spin isomers (HSI). An island of HSI in $64 \leq Z \leq 71$ and $82 \leq N \leq 88$ has been found by Pederson *et al.* [2] as a result of a systematic search for yrast traps across an extended region of nuclei. However, the structure of high spin states in such nuclei are very complex, and the spectroscopic data are determined usually by several experiments and different techniques, only the HSI in ^{147}Gd has been experimentally studied in detail [3-7] from which the particle configuration and an oblate deformation of $\beta = -0.18$ are assigned to this HSI, although many HSIs have been discovered in this mass region.

As a part of systematic investigation of HSI, this article reports the results of γ-spectroscopic studies for the newly observed HSI in ^{144}Pm. Preliminary reports can be found in Refs. 8-10.

2. EXPERIMENT AND RESULTS

2.1. Experimental method

The experiment in search for HSI and γ-γ coincidence have been carried out by using the gas-filled recoil ion separator facility [11] at RINKE, Japan. This facility consists of 2 dipole deflection magnets and 4 quadrupole focussing lens. A primary ^{24}Mg target of 1 mg/cm^2 thick was bombarded by an E/u = 7.14 MeV ^{136}Xe beam, the reaction products were recoiled out of target downstream into the tube of the spectrograph and arrived at a catcher after 6 meters of flight. The catcher was a set of plastic scintillator through which the time of arrival of HSI's was detected. In order to increase the transportation efficiency of the line, the nitrogen gas with effective thickness of 2–3 mg/cm^2 were filled in the magnetic area, which allowed the charge equilibrium of reaction products after multi-colliding with gas molecules. 7 high purity Ge detectors with BGO anti-Compton shields were placed around the catcher for γ-ray measurement. During the experiments, a series of γ-rays were detected in the catcher position and identified as those coming from the deexcitation of HSI in ^{144}Pm. This HSI was produced through ^{14}N(^{136}Xe,6n)^{144}Pm reaction indicating that the filling gas served as a working gas for charge equilibrium and as a gas target for reactions with primary beam as well. By tuning carefully the magnetic strength of the spectrograph, the best transportation efficiency for the HSI in ^{144}Pm could be reached, and about 30 million γ-γ coincidence events have been accumulated.

The γ-rays belonging to ^{144}Pm were all from the deexcitation of the HSI in ^{144}Pm in this coincidence measurement, the intensity of any γ cascade should keep constant in principle; therefore, the transition sequence cannot be determined according to the differences of γ-ray intensities. Therefore, the measurements of γ-ray excitation functions and isotropies in ^{138}Ba(^{10}B,4nγ)^{144}Pm and ^{141}Pr(α,nγ)^{144}Pm reactions have been carried out in the Tandem Accelerator Research Center, Tsukuba University, Japan, in order to obtain some information about the transition sequences and the multipolarities of the cascade γ decays. In the reaction systems noted above, the maximum angular momentum for the evaporation residues was estimated to be about $25\hbar$, so the γ-ray deexcited directly from the HSI in ^{144}Pm (cf., 538 keV line in Fig. 2) has not been observed in ^{10}B + ^{138}Ba reaction. This result is helpful for building the decay scheme of the HSI; it also indicates indirectly that the spin value of the HSI in ^{144}Pm could be greater than $25\hbar$.

The energy and the efficiency calibrations have been made for the high purity Ge detectors used in our experiments, and the energy resolution are around 2.0–2.4 keV (FWHM) for the 1332 keV line

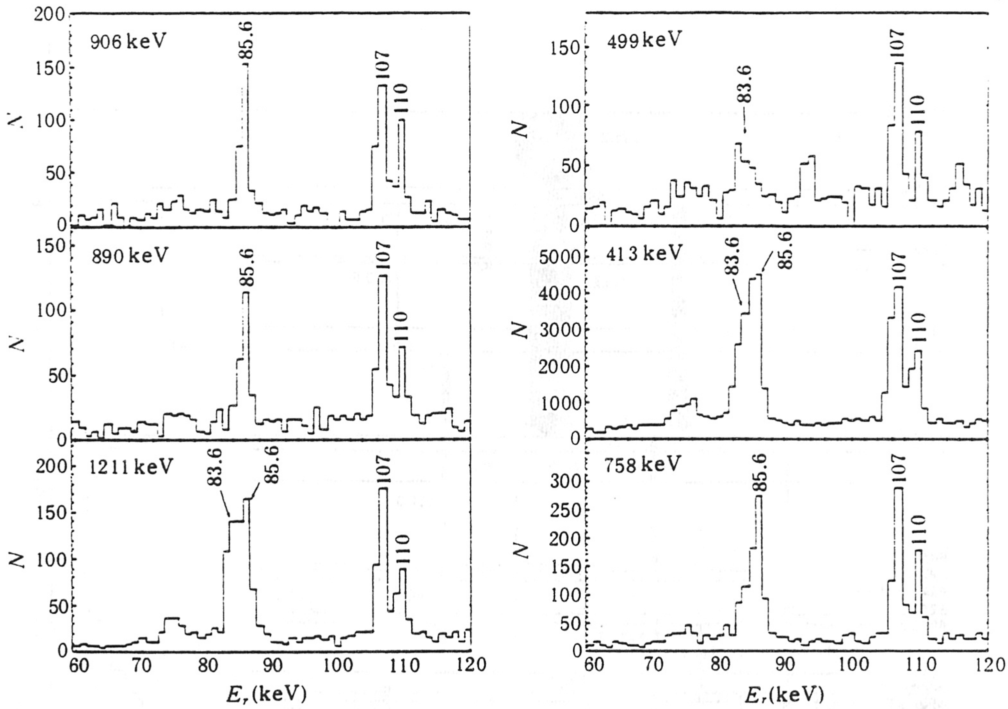

Fig. 1
Prompt coincidence spectra gated by the γ-rays indicated in the figure (only the low energy part is given).

of ^{60}Co source. Our experimental results about the structure of excited levels in ^{144}Pm are presented in the following based on the comprehensive analysis of our experimental data.

2.2. Level scheme

Prior to this work, Macphail *et al.* [12] has studied the low-lying excited states in ^{144}Pm using proton transfer reaction [^{143}Nd(^{3}He,d) and ^{143}Nd(α,t)] and using in-beam γ measurement in reactions [^{141}Pr(α,nγ) and ^{144}Nd(p,nγ)]; Y. Nagai measured their internal conversion electrons [13], the highest yrast state identified was an isomeric state ($J^\pi = 9^+$, $T_{1/2} = 0.78$ μs) at excitation energy $E_x = 0.841$ MeV. During the period of this investigation, a research group at the Florida State University reported their results of high spin states in ^{144}Pm by using ^{130}Te(^{19}F,5nγ)^{144}Pm reaction, the highest yrast state at $E_x = 5.85$ MeV, $J = 20\hbar$, has been reached. Comparing with the previous results, the higher excitation energy ($E_x = 8.6$ MeV) and higher spin ($J^\pi = 27^+$) have been reached in this work (see the level scheme given in Fig. 2). Up to about $E_x = 5.0$ MeV, our result is essentially in agreement with the former ones, but two points of difference exist:

1) In the lower lying excited region, a new γ-ray of 608.7 keV has been observed and assigned to the level scheme corresponding to $9^+ \rightarrow 6_2^-$ pure $E3$ transition.

2) At intermediate excited region, some transitions reported in Ref. 14 have not been distinctly observed such as γ840 keV ($15^- \rightarrow 14^+$), γ324 keV–γ364 keV ($16^- \rightarrow 15^- \rightarrow 14^-$), and γ499 keV–γ533 keV–γ262 keV ($20^- \rightarrow 19^- \rightarrow 18^- \rightarrow 17^+$); whereas a new γ cascade (γ177 keV–γ319 keV–γ634 keV) between the levels 3.905 MeV and 2.775 MeV (13^+) has been identified.

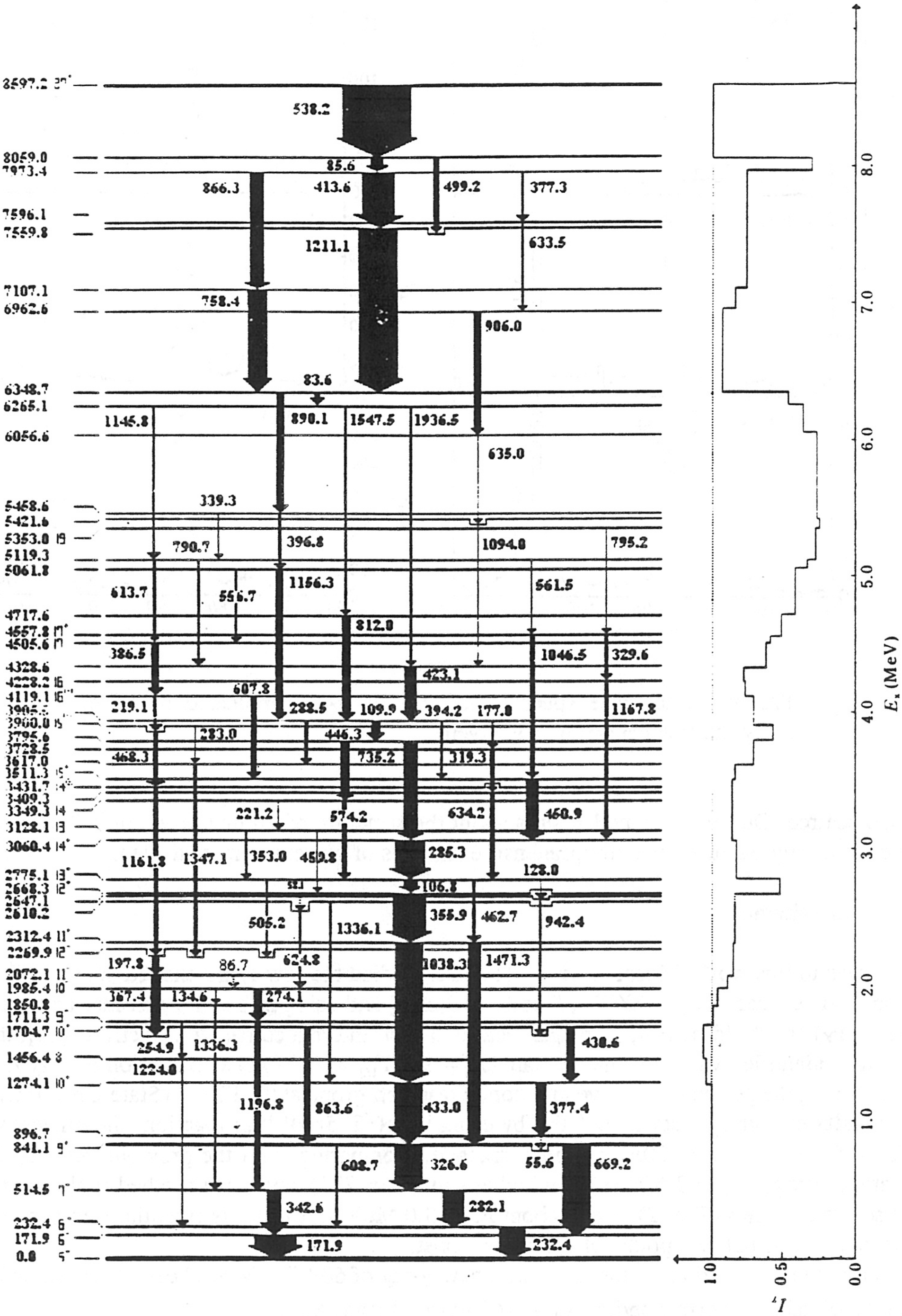

Fig. 2

γ decay scheme of the HSI in ^{144}Pm established by present work.

Energies are in keV, width of solid line represents the γ-ray intensity, the histogram at the right side gives the total γ-ray intensity as function of excitation energy.

Table 1

Relative intensities of the γ-rays deexcited from the HSI in ^{144}Pm.

E_γ (keV)[a]	E_x (keV)[a]	I_γ[b]	E_γ (keV)[a]	E_x (keV)[a]	I_γ[b]
55.6	896.7	(d)	499.2	8059.0	93
58.1	2668.3	(d)	505.2	2775.1	40
83.6	6348.7	104	538.2	8597.2	1000
85.6	8059.0	199	556.7	5061.8	38
86.7	2072.1	(d)	561.5	5119.3	23
106.8	2775.1	210	574.2	3349.3	72
109.9	3905.5	128	607.8	4119.1	72[c]
128.0	2775.1	22	608.7	841.1	34[c]
134.6	1985.4	25	613.7	5119.3	57
171.9	171.9	608	624.8	2610.2	52
177.0	3905.5	50	633.5	6962.6	36[c]
197.8	2269.0	120	634.2	3409.3	78[c]
219.1	4119.1	70	635.0	6056.6	28[c]
221.2	3349.3	27	669.2	841.1	401
232.4	232.4	392	735.2	3795.6	226
254.9	1911.2	48	758.4	7107.1	289
274.1	1985.4	133	790.7	5119.3	39
282.1	514.4	336	795.2	5353.0	30
283.0	3900.0	20[c]	812.1	4717.6	145
285.3	3060.4	450	863.6	1704.7	100
288.5	3905.5	56	866.3	7973.4	216
319.3	3728.5	78	890.1	6348.7	114
326.6	841.1	412	906.0	6962.6	129
329.6	4557.8	58	942.4	2647.1	42
339.3	5458.6	32	1038.3	2312.4	400
342.6	514.5	207	1046.5	4557.8	70
353.0	3128.1	44	1094.0	5421.6	28
355.9	2668.3	473	1145.6	6265.1	25
367.4	2072.1	160	1156.3	5061.8	135
377.3	7973.4	36[c]	1161.8	3431.7	81
377.4	1274.1	153[c]	1167.8	4228.2	55
386.5	4505.6	113	1196.8	1711.3	99
394.2	3905.5	41	1211.1	7559.8	512
396.8	5458.6	66	1224.0	1456.4	22
413.6	7973.4	416	1336.1	2610.2	31[c]
423.1	4328.6	181	1336.3	1850.8	31[c]
430.6	1704.7	121	1347.1	3617.0	60
433.0	1274.1	391	1471.3	2312.4	200
446.3	3795.6	143	1547.5	6265.1	45
450.9	3511.3	201	1936.5	6265.1	33
459.8	3128.1	29			
462.7	2775.1	54			
468.3	3900.0	84			

(a) Energy errors are in the range of 0.1 keV–0.3 keV.
(b) Relative intensities are normalized to 538.2 keV line, errors are within 10%–30% depending on its intensity.
(c) Intensities are determined through coincidences.
(d) Intensities are too small to be determined.

The level scheme above 5 MeV excitation energy is established by the present work. Five parallel γ-ray cascades with lower intensities and higher transition energies connect the two parts of the level scheme situated at high and middle excitation energies. At the intermediate excitation region, the level structure might be very complicated, many γ-rays with higher energies and lower intensities may be involved during the deexcitation of the levels, and could be not detected; that is probably the reason why the level scheme was built up to an excitation energy of about 5.5 MeV in the work of Ref. 14. In our case, however, the γ-γ coincidence measurement was performed in an off-beam condition, the contaminations from background and other in-beam radioactive sources were thus greatly reduced, and it was therefore possible to observed the strong coincidence relations between some weak γ-rays and their lower lying sequential decays (for example, γ1146 keV–γ614 keV, γ890 keV–γ397 keV–γ1156 keV, γ1547 keV–γ812 keV, and γ1937 keV–γ423 keV).

The 538 keV line is assigned to deexcite directly from the HSI since it coincides with all the observed γ-rays. For the γ-transitions between E_x = 8.059 and E_x = 6.265 MeV levels, there exist two low energy γ-rays (γ85.6 keV and γ83.6 keV) which are essential for the establishment of present level scheme, Fig. 1 shows some important gated spectra from which one can see clearly that the γ-rays of 906 keV and 890 keV coincide with 85.6 keV line but not with 83.6 keV peak; γ499 keV coincides with γ83.6 keV but not with γ85.6 keV. In the coincidence spectra gated by γ1211 keV and γ413 keV, the intensities of both γ83.6 keV and γ85.6 keV are comparable. All the coincidence relations mentioned above determine the positions of γ83.6 keV and γ85.6 keV in the level scheme.

The arrival time of HSI at the catcher position was detected by the catcher itself (i.e., plastic scintillator). The time signals obtained by catcher (for HSI) and those by high purity Ge (for γ-rays) give the information about time correlations between the HSI and the emitting γ-rays. By gating the γ transitions above the 9^+ state in off-line data analysis, one gets the time spectrum of γ-decay from HSI, a least square fit to the time spectrum gave a half-life of the HSI around 2.7 μs. However, the statistics were not high enough in our data, and the dynamic range of TDC was set too small (2 μs), and a large error bar is proposed for the value given here.

Figure 2 shows the γ-decay level scheme of the HSI in ^{144}Pm, and the histogram at right side of the figure presents the total γ-ray intensity as function of excitation energy. Normalized to 538 keV line, Table 1 gives the relative intensities of all the γ-rays deexcited from the HSI.

3. DISCUSSIONS

The nuclear structure at low excitation has been discussed in a framework of the shell model [15], it was pointed out that the excited states below 600 keV are mainly constructed by $\pi 2d_{5/2}\nu 2f_{7/2}$ and $\pi 1g_{7/2}\nu 2f_{7/2}$ particle configurations. For the high spin states below $E_x \le 5.8$ MeV and $J \le 20$, the structure was discussed and interpreted using the empirical shell model [16]. In this paper, however, it is difficult to discuss the microscopic structure of the newly observed high spin states because of the lack of detailed spectroscopic data. Yet considering the doubly closed character of ^{146}Gd and the systematic appearance of HSI for N = 83 isotopes in this mass region, not to mention that the excitation energies of these HSI show a regular trend as function of nuclear mass number, a gross discussion to the HSI in ^{144}Pm follows.

For the N = 83 isotopes, a HSI in ^{147}Gd has been investigated in detail [4,5], the g-factor of 0.446 [6] and the electric quadrupole moment of $|Q|$ = 3.14(b) [7] have been measured for this HSI of $J^\pi = 49/2^+$, $T_{1/2}$ = 560 ns at E_x = 8.7 MeV. The calculations by using the deformed independent particle model (DIPM) [17] show that a state with $[\pi(1h^2_{11/2})\nu(1i_{13/2}1h_{9/2}2f_{7/2})]_{J^\pi=49/2^-}$ particle configuration forms the HSI with a deformation parameter of $\beta = -0.18$ at the yrast line. Furthermore, the calculated g-factor and the Q-value are consistent with the measured ones.

A similar calculation based on DIPM has been performed for the yrast bands in ^{147}Gd, ^{145}Sm [18], and ^{144}Pm, and it is found that the oblate deformations are small (around $\beta = -0.05$) for the states at intermediate excitation energy (and spin) region. At higher excitation (and spin), the states with similar particle configurations as those in ^{147}Gd are of the oblate deformations around $\beta = -0.18$. Comparing the total γ-ray intensities as a function of excitation energy shown at the right side of Fig. 2, one may find a peculiar behavior for both ^{147}Gd and ^{144}Pm, i.e., the γ-ray intensity balance has lost at the excitation energy region of 6.5–7.9 MeV for ^{147}Gd, that it becomes more apparent for ^{144}Pm at E_x = 5.0–6.3 MeV excitation region where the γ-ray intensity is only one-fourth of the total one (see the histogram at the right side of Fig. 2). The authors of Ref. 5 analyzed this phenomenon and pointed out that the γ-decays originating from the HSI do not follow the yrast line but along a path 2 MeV above the yrast levels. In the plot of E_x versus $J(J+1)$, there are two slopes corresponding to two effective moments of inertia [5]. This result indicates the existence of states with different deformations at higher and lower excitation regions. The fact that the nuclear shape becomes more deformed with increasing the excitation energy (spin) may be caused by breeding a neutron pair and exciting it to the Nilsson orbitals up across the $N = 82$ closed shell. Taking into account the calculated results based on DIPM and the regularity of the HSIs' excitation energy in $N = 83$ isotopes, together with the similarity of γ-decay properties of the HSIs in both ^{147}Gd and ^{144}Pm as discussed above, it is therefore reasonable to conclude that the HIS in ^{144}Pm has the most probable particle configuration of $\pi(1h^2_{11/2}2d_{5/2})\nu(1i_{13/2}1h_{9/2}2f_{7/2})$ and the higher excited levels above E_x = 6.0 MeV may correspond to a larger oblate deformations. Of course, these conclusions are extracted from the systematic comparisons and the theoretical calculations, and therefore could be not definitely correct. At this point, the measurements and determinations of spectroscopic data for the high spin levels (for example, the measurements of g-factors, Q values, and the spin-parity assignments to the highly excited states) are absolutely necessary and important.

4. CONCLUSIONS

The high spin states in ^{144}Pm have been experimentally investigated, the γ-decay level scheme of the HSI was established for the first time by the present studies, the excitation energy and the half-life of the HSI are given to be E_x = 8.597 MeV and $T_{1/2} = -2\ \mu$s, respectively. Through the systematic comparisons in the γ-decay properties and the excitation energies of HSIs for $N = 83$ nuclei, and through the DIMP calculations, the most probable particle configuration of $\pi(1h^2_{11/2}2d_{5/2})\nu(1i_{13/2}1h_{9/2}2f_{7/2})$ and the oblate deformation with $\beta = -0.18$ have been assigned to the HSI in ^{144}Pm. With this configuration, the full spin alignment of individual particles along the symmetry axis forms the HSI with a spin-parity of $J^\pi = 27^+$. The loss of intensity balance occurs around E_x = 6.0 MeV for the γ-decay of the HSI in ^{144}Pm which also existed in the decay of the HSI in ^{147}Gd. The spins and parities of the newly observed high spin levels have not been determined in this work, so it is therefore not possible to analyze the variation trends of E_x versus $J(J + 1)$. However, because of the similar particle configuration of two HSIs in ^{144}Pm and ^{147}Gd, and the similar γ-decay properties, it can be qualitatively assumed that the high spin states at lower and higher excitations correspond to the different deformations, although a definite conclusion is awaiting confirmation.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the staffs in the Ring Cyclotron Division of RIKEN for providing a highly qualified ^{136}Xe beam. One of us, Zhang Yuhu, acknowledges the financial support from RIKEN during his stay in Japan.

REFERENCES

[1] A. Bohn and B.R. Motteson, *Nuclear Structure*, **2**, Benjamin, New York, 1975.
[2] J. Pederson *et al.*, *Phys. Rev. Lett.*, **V39**(1977), p. 990.
[3] R. Broda *et al.*, *Z. Phys.*, **A285**(1978), p. 423.
[4] R. Broda *et al.*, *Z. Phys.*, **A305**(1982), p. 281.
[5] O. Bakander *et al.*, *Nucl. Phys.*, **A389**(1982), p. 93.
[6] O. Hausser *et al.*, *Phys. Rev. Lett.*, **V42**(1979), p. 1451.
[7] O. Hausser *et al.*, *Phys. Rev. Lett.*, **V44**(1980), p. 132.
[8] Y.H. Zhang *et al.*, *IMP Annual Report* (1992), p. 83.
[9] Y.H. Zhang *et al.*, *UTTAC Annual Report*, **59**(1992), p. 41.
[10] T. Murakami *et al.*, *Z. Phys.*, **A345**(1993), p. 123.
[11] Y. Gono *et al.*, *Nucl. Phys.*, **A557**(1993), p. c341.
[12] M.R. Macphail and R.G. Summers-Gill, *Nucl. Phys.*, **A237**(1975), p. 285.
[13] Y. Nagai *et al.*, *Nucl. Phys.*, **A282**(1977), p. 29.
[14] T. Glasmacher *et al.*, *Phys. Rev.*, **C47**(1993), p. 2586.
[15] M.R. Macphail and R.G. Summers-Gill, *Nucl. Phys.*, **A263**(1976), p. 12.
[16] I. Talmi, *Rev. Mod. Phys.*, **34**(1962), p. 704.
[17] T. Dossing *et al.*, *Phys. Sci.*, **24**(1981), p. 258.
[18] A. Odahara *et al.*, *Z. Phys.*, **A350**(1994), p. 185.