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Magnetic moments of the 2_1^+ states in ^{146,148}Ce

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The g factors of the 2_1^+ states in ^{146,148}Ce have been measured using the time integral perturbed angular correlation technique. The levels were populated by the radioactive decay of mass-separated ^{146,148}La which was produced by thermal neutron fission of ^{235}U. The measured $g(2_1^+)$ values are 0.24 ± 0.05 and 0.37 ± 0.06 for ^{146}Ce and ^{148}Ce, respectively. The results are interpreted as a probe of the number of valence protons participating in the collective motion. Data for Ba, Ce, Nd, and Sm nuclei in the region of $N=90$ show a distinct change in the value of $g(2_1^+)$ as the number of neutrons increases from 86 to 90. This change is attributed to the effects of the strong interaction between the $\pi h_{11/2}$ and $\nu h_{9/2}$ orbits which causes a gradual dissipation of the $Z=64$ subshell gap.

I. INTRODUCTION

The fission process provides a large variety of neutron-rich nuclei, many of which cannot be reached by any other nuclear reaction. A considerable amount of experimental work has been devoted so far to the investigation of these exotic nuclei. In particular, isotopes at the onset of deformation in the regions of $A=100$ and $A=150$ have been extensively studied. The experimental methods have included ^{252}Cf sources,[1] fission product separators connected on-line to nuclear reactors,[2,3] and fast chemical separation.[4]

Recently, a program for the measurement of magnetic moments of excited states in neutron-rich nuclei has been initiated at the TRISTAN fission product on-line separator at Brookhaven National Laboratory. The first experiments were carried out using a conventional electromagnet.[5,6] In order to extend the measurements to nuclear half-lives shorter than 0.5 nsec, a superconducting magnet was installed on one of the five output beam lines of TRISTAN, and in this work, we report results of g-factor measurements of the 2_1^+ states in ^{146,148}Ce obtained using this facility.

The ^{146,148}Ce nuclei have $N=88$ and $N=90$, respectively, and thus are located at the onset of deformation of the mass 150 region. The measured g factors will be analyzed within the general framework of the interacting boson approximation,[7] in terms of the effective number of proton bosons N_π^{eff} which contribute to the collective motion in this region. In such a treatment, it is necessary to take into consideration the dissipation of the effects of the $Z=64$ subshell as the number of neutrons increases beyond $N=90$. This approach has been used previously,[5,8] and it will be shown that the present results support the previous[8] conclusion, namely that the value of N_π^{eff} for transitional nuclei in the region of $A=150$ changes significantly when N increases from 88 to 90. A preliminary result for ^{146}Ce and a lower limit for ^{148}Ce were reported in a previous publication.[8]

II. EXPERIMENTAL TECHNIQUES

A. The isotope separator and the ion sources

The TRISTAN mass separator facility[9] is installed at the exit port of a radial beam tube of the high flux beam reactor at Brookhaven National Laboratory. The facility consists of an integrated target-ion source system coupled to an on-line electromagnetic mass separator. The target contains about 5 g of 93% enriched ^{235}U on a graphite cloth backing. The neutron flux on the target is about 2×10^{10} neutrons/cm^2 sec. Fission products from thermal fission of ^{235}U diffuse through the target material and can be ionized by the ion source. The products that can be ionized and their yields are dependent on which of the six types of TRISTAN ion sources is being used for the experiment.[10–13] The ions produced in the source are subsequently extracted, mass separated by a 90° magnet, and routed by a switching magnet into one of five output beam ports.

For the study of ^{146}Ce, a beam containing ^{146}La with an intensity of 4×10^5 ions/sec was obtained using a surface ionization[10] ion source, while for ^{148}Ce a thermal ion source[11] was used. The latter source operates at about 2500 °C (i.e., about 400 °C higher than the surface ionization source), and provided a beam with an intensity of 4×10^4 ions/sec for ^{148}La, which represents about 20 times more than was available from the former source for this isotope. The radioactive beams of mass 146 and 148 were collected for a time T_c on an aluminized plastic tape, the beam was deflected, and the activity was transported within about 0.3—0.5 sec to a position inside the superconducting magnet, and then counted for T_c seconds. While the radioactive source was counted, the next sample was collected. T_c was set at 12.0 sec for ^{146}La and at 2.5 sec for ^{148}La.

B. The perturbed angular correlation system

The experimental technique used for the g-factor measurements is the integral perturbed angular correlation (PAC) method.[14] An external magnetic field was applied perpendicular to the γ-γ correlation plane, causing the correlation pattern to be shifted by an angle $\Delta\theta$ which is determined by the product $gBT_{1/2}$, where g is the g factor, $T_{1/2}$ the half-life of the state, and B the applied magnetic field. The g factor can be determined by measuring the full correlation with field up and field down and calculating the shift $\Delta\theta$, or by measuring the double ratio $R(\theta)$:

$$R(\theta)=\left[\frac{I(\theta,B)}{I(\theta,-B)}\Big/\frac{I(-\theta,B)}{I(-\theta,-B)}\right]^{1/2}, \tag{1}$$

where $I(\theta,B)$ is the correlation intensity at angle θ with magnetic field up.

As in previous experiments of this kind,[5,6] we measured $R(\theta)$ using a four-detector system, which was mounted around the superconducting magnet so that the correlation center coincided with the position inside the magnet to which the radioactive source was transported by the tape collector. The experimental system, which consisted of four high-resolution Ge detectors, has been described in detail elsewhere,[15] and it enables measurement of six angles simultaneously. This feature is crucial for PAC measurements at TRISTAN, as it saves a considerable amount of running time. Note that the double ratio $R(\theta)$ is independent of detector efficiency, geometry, beam intensity, and counting time with field up and down so that the corresponding systematic errors can be avoided.

At any given angle θ, $R(\theta)$ is determined by the angular correlation coefficients A_{22}, A_{44} and by the product $gBT_{1/2}$. Therefore, for short half-lives large values of B are needed. In the present work we used the $0_2^+\rightarrow 2_1^+\rightarrow 0_1^+$ cascades: 785-258 keV for ^{146}Ce and 612-158 keV for ^{148}Ce.[3] These are very anisotropic correlations (theoretical values $A_{22}=0.356$, $A_{44}=1.14$), and give quite large values of R, with a maximum in $R(\theta)$ near 150°. The four detectors were arranged in such a way as to give three angles of 150°, two of 120°, and one of 90°. This configuration gives maximum statistics at 150°, and the g factors were extraced from $R(150°)$. The results at 90°, 120° were used only as a consistency check since $R(90°)=1.00$ and $R(120°)$ is close to 1.00.

The data were accumulated on magnetic tape in event-by-event mode using a CAMAC system interfaced to a PDP 11/40 computer.[9]

The half-lives of the 2_1^+ states are[16]

$$\begin{aligned} T_{1/2}(2_1^+)&=(0.25\pm0.03)\text{ nsec for }^{146}\text{Ce},\\ T_{1/2}(2_1^+)&=(1.01\pm0.06)\text{ nsec for }^{148}\text{Ce}. \end{aligned} \tag{2}$$

These values are averages of the results of the two measurements described in Ref. 16.

In order to obtain a reasonable value $R(150°)\approx 1.10$ for ^{146}Ce, a field of the order of 5.0 T is needed due to the short half-life of the 2_1^+ state. For ^{148}Ce, a lower field is sufficient, but the rather poor statistics (of the order of 300—500 net counts per week per pair of detectors in the given cascade) require a large effect in order to attain a reasonable error bar on the g factor. Thus, in both cases the use of a superconducting magnet was found to be essential. The apparatus used in the current measurements was manufactured by Oxford Instruments. It consists of a split-pole Nb-Ti magnet housed in a ^{4}He cryostat, especially designed to permit four Ge detectors to be placed at about 10 cm from the center of the field. The activity is transported to the measuring point via the moving tape system running in a room temperature horizontal bore tube through the center of the magnet. The maximum field available is 6.25 T when the system is operated at 4.2 K, and 6.75 T when a λ point refrigerator is used to cool the magnet to 2.2 K. The field is homogeneous to better than 1% over a sphere of diameter 1 cm at the target position. In the current measurements, fields of 6.25 T and 4.5 T were used for ^{146}Ce and ^{148}Ce, respectively.

III. RESULTS

The running time was one week for each isotope studied, during which about 10^8 events were accumulated for $A=146$ and 5×10^7 events for $A=148$. The direction of the magnetic field was reversed several times during each run. The data were sorted off-line using a PDP 11/34 computer. In addition to the $0^+\rightarrow2^+\rightarrow0^+$ cascade, the $3^-\rightarrow2^+\rightarrow0^+$ and $1^-\rightarrow2^+\rightarrow0^+$ cascades were also analyzed for each isotope. The theoretical values of $R(\theta)$ are close to 1.00 for all angles of the $3^-\rightarrow2^+\rightarrow0^+$ correlation, due to the rather weak anisotropy ($A_{22}=-0.07$) of this cascade. We therefore used it as a check against systematic errors.

The results at $\theta=150°$ for the $0^+\rightarrow2^+\rightarrow0^+$ cascades were used to obtain the g factors of the 2_1^+ states, using the half-lives from Eq. (2), and the solid angle corrections for the coefficients A_{22}, A_{44} as given by Camp and van Lehn.[17] The g factors and errors were extracted from a plot of $R(\theta)$ vs g factor, as shown in Fig. 1. The data and results are summarized in Table I. The final values are

$$\begin{aligned} g(2_1^+)&=(0.24\pm0.05)\text{ for }^{146}\text{Ce},\\ g(2_1^+)&=(0.37\pm0.06)\text{ for }^{148}\text{Ce}. \end{aligned} \tag{3}$$

As a consistency check, we used the above values of $g(2_1^+)$ to calculate the ratios $R(\theta)$ at $\theta=90°$ and 120° for all cascades, and these results are shown in Table II to-

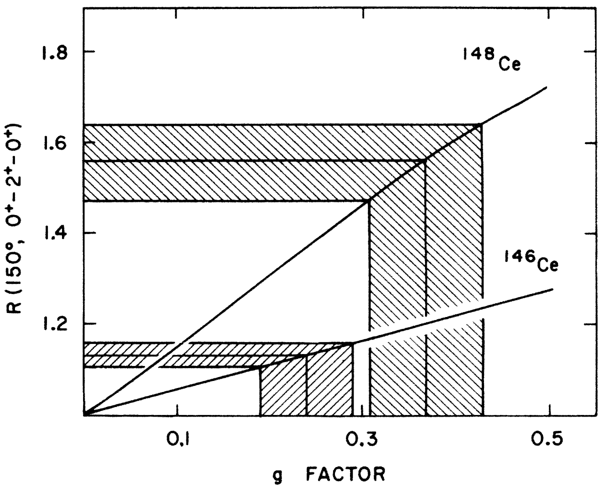

FIG. 1. Plot of g factor vs $R(\theta)$ for a 0^+-2^+-0^+ cascade with $\theta=150°$. Values for the applied magnetic fields and the half-lives are given in the text. The shaded regions show the experimental means and standard deviations for $R(150°)$.

gether with the experimental values. We see that all measured ratios are in very good agreement with the calculated values. Therefore, any systematic errors that are not canceled by the double ratio, if present, are smaller than the statistical errors.

The perturbed angular correlations $W(\theta,B)$ and $W(\theta,-B)$ were also determined for all the cascades measured in this work. In order to normalize the intensities of the different pairs of detectors, singles spectra gated by the constant fraction discriminators were taken for all detectors during the experiment, and these were used to calculate the relative efficiencies as described in detail in Ref. 15. The resulting correlations are given in Figs. 2 and 3. The solid lines in these figures were obtained by calculating $W(\theta,\pm B)$ with the g factors of Eq. (3). We see that all the experimental points are in agreement with the expected curves, which reflects the absence of significant systematic errors, as mentioned above.

IV. DISCUSSION

The even-even cerium isotopes are known[18] to undergo a transition from vibrational to rotational-like structure as the number of neutrons changes from $N=86$ to $N=92$. For example, the ratio $E_{4_1^+}/E_{2_1^+}$ changes from 2.4 to 3.2, and $E_{2_1^+}$ drops from 397 to 98 keV between ^{144}Ce and ^{150}Ce. This transition has been attributed[18] to the strong neutron-proton interaction between spin-orbit partner states, which causes protons to occupy the $h_{11/2}$ orbit when the $h_{9/2}$ neutron orbit begins to be filled near $N=90$. The resulting $\pi h_{11/2}$-$\nu h_{9/2}$ interaction induces a rapid onset of deformation, similar to the situation in the $A=100$ region,[19] and also has the effect of essentially eradicating the $Z=64$ subshell closure. The isotopes studied in this work have $N=88,90$, and thus are exactly where the above transition takes place.

We now proceed to analyze the values of $g(2_1^+)$ obtained in the present experiment in view of the vibrational-rotational transition in the $A=150$ region. The analysis is essentially similar to the one we used previously[5,8] for $g(2_1^+)$ values of Ba, Ce, Nd, and Sm isotopes.

Following Sambataro et al.[20] we write the expression for the g factor of a 2_1^+ state which is fully symmetric in the neutron and proton degrees of freedom as

$$g(2_1^+)=g_\pi\frac{N_\pi}{N_t}+g_\nu\frac{N_\nu}{N_t}\ , \tag{4}$$

where N_π and N_ν are the number of proton bosons and neutron bosons, respectively, and $N_t=N_\pi+N_\nu$. g_π and g_ν are the g factors of a proton boson and a neutron boson, respectively. In a previous study[8] we found that one can use constant values of g_π and g_ν for a large number of nuclei around $A=150$. In fact, a best fit procedure in which experimental $g(2_1^+)$ values for 12 nuclei were used yielded[8]

$$\begin{aligned} g_\pi&=0.63\pm0.04\ ,\\ g_\nu&=0.05\pm0.05\ . \end{aligned} \tag{5}$$

Now we use the measured values $g(2_1^+)$ for ^{146}Ce and ^{148}Ce and Eqs. (4) and (5) in order to extract N_π^{eff}, the effective number of proton bosons. We assume $N_\nu=3$ and 4 for ^{146}Ce and ^{148}Ce, respectively, and obtain

$$\begin{aligned} N_\pi^{\text{eff}}&=1.5\pm0.6 \text{ for } ^{146}\text{Ce}\ ,\\ N_\pi^{\text{eff}}&=4.9\pm2.1 \text{ for } ^{148}\text{Ce}\ . \end{aligned} \tag{6}$$

These values of N_π^{eff} indicate that when N increases from 88 to 90 the number of valence proton bosons in the Ce nuclei changes by

$$\Delta N_\pi^{\text{eff}}=3.4\pm2.2\ . \tag{7}$$

The above conclusion is consistent with the ideas discussed above concerning the dissipation of the $Z=64$

TABLE I. Experimentally determined values of $R(\theta)$ at 150° for the $0^+\rightarrow2^+\rightarrow0^+$ cascades in ^{146,148}Ce.

Isotope	Applied field (T)	$T_{1/2}$ (nsec)	$R(150°)$	Derived g factor
^{146}Ce	6.25	0.25±0.03	1.13±0.02	0.24±0.05
^{148}Ce	4.50	1.01±0.06	1.56±0.08	0.37±0.06

subshell when N increases beyond $N=88$. As mentioned in previous publications,[5,21] the simplest considerations, which neglect the effects of pairing correlations, suggest that N_π should be counted in the $Z=50$–64 shell for $N \leq 88$, and in the major 50–82 shell for $N \geq 90$. According to this counting procedure, one expects $N_\pi=3$ for ^{146}Ce and $N_\pi=4$ for ^{148}Ce; i.e., a change $\Delta N_\pi=1$ in the number of proton bosons takes place simultaneously with the onset of deformation. More generally, the total change might be expected to be spread over a broader range of N values. However, the experimental results given in Eqs. (6) and (7) are consistent with the full change, although the absolute value for ^{146}Ce is significantly smaller than expected.

Significant changes ΔN_π were also inferred[8] from g-factor data for Nd and Sm isotopes[22] as N increases from 86 to 92. The values for N_π^{eff} deduced for isotopes of Ba, Ce, Nd, and Sm are summarized in Fig. 4. The values assigned to N_π corresponding to the extreme assumptions of a shell closure at $Z=50$–82 and $Z=50$–64 are also indicated. The figure shows not only the distinct change in N_π, but also the tendency of the N_π change to begin at lower neutron number and become more gradual as Z increases. This effects can be understood in terms of the proton occupation of the $h_{11/2}$ orbital beginning at lower neutron numbers[18,21] for nuclei with higher Z. In other words, the effectiveness of the $\pi h_{11/2}$-$\nu h_{9/2}$ interaction will depend on the energy gap between the Fermi surface and the relevant orbit, for both neutrons and protons. Thus as this gap becomes smaller in the proton space, the effects of the interaction will become apparent at a lower neutron number.

It is interesting to mention two more points. First, one expects $\Delta N_\pi=0$ for the Ba isotopes around $N=90$, which was indeed confirmed by experimental results[5] for ^{144}Ba and ^{146}Ba. Second, a recent parametrization[23] of en-

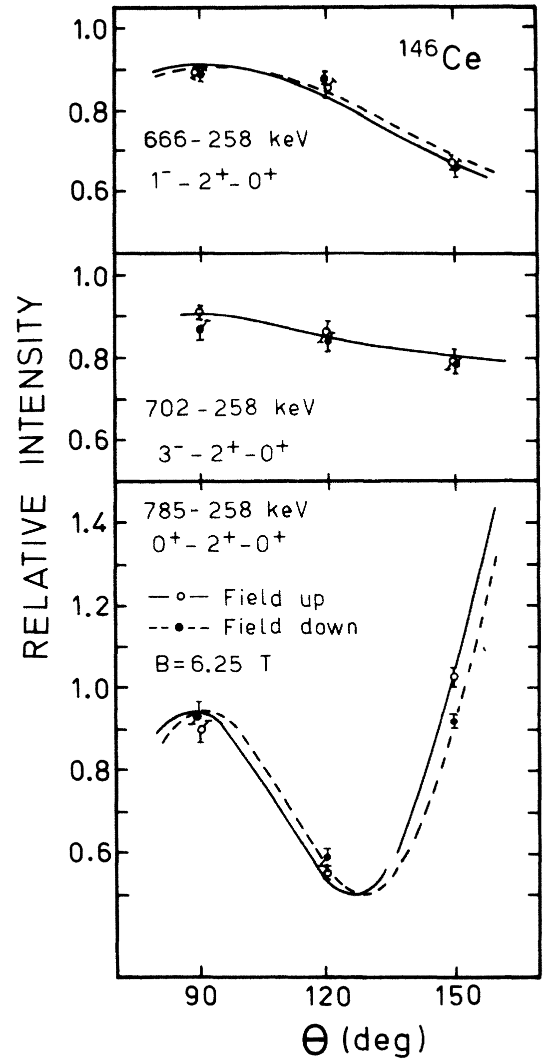

FIG. 2. Angular correlations obtained for ^{146}Ce for the indicated cascades with field up and field down.

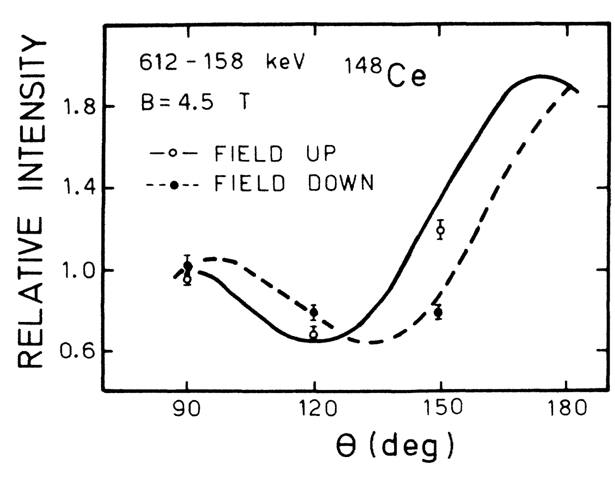

FIG. 3. Angular correlations obtained for the ^{148}Ce 0$^+$-2$^+$-0$^+$ cascade with field up and field down.

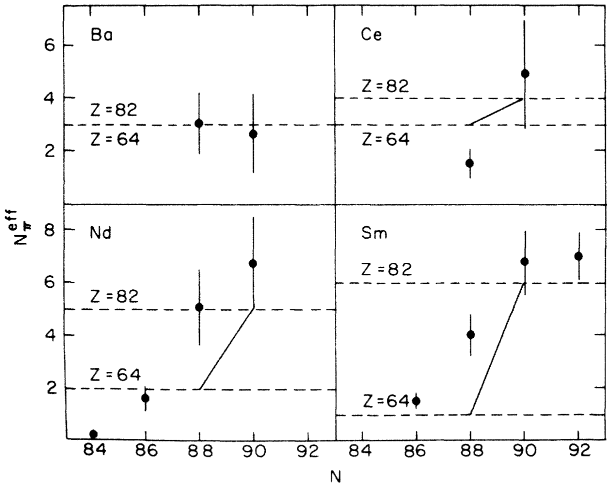

FIG. 4. N_π^{eff} deduced for isotones of Ba, Ce, Nd, and Sm. The values of N_π expected for major shell closure at $Z=50$–82 and $Z=50$–64 are indicated by the dashed lines. The solid line indicates the region of transition between shells (Refs. 5 and 21). The Ce data are from this paper; the Ba, Nd, and Sm data are from Ref. 5 and references therein.

TABLE II. Experimental and calculated values of $R(\theta)$ at 90°, 120°, and 150° for all cascades measured in this work. We used a magnetic field of 6.25 T for ^{146}Ce and 4.5 T for ^{148}Ce.

Isotope	Cascade	θ	$R(\theta)$ Experimental	Calculated[a]
^{146}Ce	0^+-2^+-0^+	90	0.96 ± 0.04	1.00
		120	0.94 ± 0.04	0.93
	1^--2^+-0^+	90	1.01 ± 0.03	1.00
		120	0.97 ± 0.02	0.98
		150	1.02 ± 0.02	0.98
	3^--2^+-0^+	90	1.03 ± 0.04	1.00
		120	1.04 ± 0.03	1.00
		150	1.01 ± 0.03	1.00
^{148}Ce	0^+-2^+-0^+	90	0.98 ± 0.07	1.00
		120	0.85 ± 0.05	0.83
	1^--2^+-0^+	90	1.12 ± 0.07	1.00
		120	0.91 ± 0.04	0.93
		150	0.90 ± 0.05	0.92
	3^--2^+-0^+	90	0.96 ± 0.06	1.00
		120	1.01 ± 0.04	0.98
		150	1.02 ± 0.05	0.98

[a] The calculated values were obtained using the g factors [Eq. (3)] which were extracted from the experimental ratios $R(150°)$ of the 0^+-2^+-0^+ cascades.

ergies $E_{2_1^+}$ and ratios $E_{4_1^+}/E_{2_1^+}$ for transitional nuclei in terms of the product $N_\pi \cdot N_\nu$ was found to imply similar changes of N_π around $N=90$ as those observed from g-factor data.

In summary, we have shown that g factors of 2_1^+ states can help us follow the change in the number of active protons as the $Z=64$ subshell is dissipated with the onset of deformation. This conclusion becomes more and more evident as new experimental data are accumulated. More generally, it is now clear that this type of data can serve in the future as a sensitive probe for identifying the existence and role of proton subshells in new regions far from stability.

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