PHYSICAL REVIEW C VOLUME 58, NUMBER 5 NOVEMBER 1998

First direct measurements of g factors of the three superdeformed bands of ^{194}Hg

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(Received 2 June 1998)

The average g factors of the high-energy states of the three superdeformed bands in ^{194}Hg were determined *directly* in a transient field experiment. The reaction ^{150}Nd(^{48}Ca,4n)^{194}Hg at a beam energy of 203 MeV was used to provide recoiling reaction product nuclei with sufficient velocity to traverse a gadolinium ferromagnetic layer. The resulting g factors $g(\mathrm{SD1})=0.36(10)$, $g(\mathrm{SD2})=0.41(20)$, and $g(\mathrm{SD3})=0.71(26)$ are in agreement with cranked Hartree-Fock calculations as well as with the picture of a rigid rotation for which $g=Z/A$. [S0556-2813(98)50711-X]

PACS number(s): 21.10.Ky, 21.10.Re, 25.70.Gh, 27.80.+w

Superdeformation in the Hg isotopes and, in particular in ^{194}Hg, has been extensively studied in recent years. Three superdeformed (SD) bands have been identified, lifetimes of states have been measured, and the decays of the yrast (SD1) and one excited superdeformed (SD3) bands have been characterized [1–7].

The determination of magnetic moments of nuclear excited states can add an important element in the elucidation of the microscopic structure of these SD states because the corresponding operator reflects collective as well as single-particle degrees of freedom. In particular, the g factor of a rotational nuclear state in a band with good quantum number K, $g=g_R+(g_K-g_R)[K^2/I(I+1)]$, depends on g_R, the rotational g factor and the single-particle contributions g_K.

There exist only scant measurements of magnetic moments of short-lived, high spin states [8–11] and no *direct* measurement of magnetic moments of superdeformed states has been carried out so far. An indirect measurement determined from the observation of the $M1$ dipole transitions linking signature partner bands in ^{193}Hg [12] yielded a value $g_K=-0.65(14)$ consistent with a Woods-Saxon calculation of a $5/2^-[512]$ deformed neutron orbital. Similar determinations also exist for ^{193}Tl, ^{193}Pb, and ^{195}Tl [13–15].

Only the hyperfine interaction in an ion moving through a ferromagnetic layer (transient field) can create the necessary field strength to induce a measurable magnetic interaction. Therefore, only states that are populated while the ions traverse a ferromagnetic layer can be probed. In fusion-evaporation reactions, where nuclei are highly excited in a broad spin and energy range, the specific states of nuclei traversing this interaction zone are generally not known. Superdeformed bands are populated at very high excitation energies and a very short time after the initial nuclear fusion reaction takes place [16]. Thus, it is possible to design the kinematics of the reaction in such manner that specific ranges of excitation in the nucleus of interest can be probed [9]. The transient field method is, therefore, exceptionally well suited for measuring g factors in superdeformed nuclei.

The experiment was carried out at the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory using the Gammasphere array [17] which consisted, at the time, of 90 Compton-suppressed Ge detectors. The reaction ^{150}Nd(^{48}Ca,4n)^{194}Hg at 203 MeV was used to populate SD and high-spin normal-deformed states in the Hg isotopes. The target consisted of 1 mg/cm^2 ^{150}Nd evaporated on a 2.15 mg/cm^2 rolled and annealed gadolinium foil. A layer of 40 mg/cm^2 of gold was evaporated on the downstream side of the gadolinium layer to provide a perturbation free environment in which the Hg ions stop. The excited nuclei enter the ferromagnetic foil at an average time of 0.1 ps after production, with an average initial energy of 40 MeV and velocity $(v/v_0)_{\mathrm{in}}=2.9$ $(2.1\%c)$, and exit from the foil 0.5 ps later, with an average velocity $(v/v_0)_{\mathrm{out}}=2.0$ $(1.4\%c)$, where v_0 is the Bohr velocity.

During the experiment the beam intensity was kept at 2 particle nA. The target was cooled to 77 K by flowing liquid nitrogen. The gadolinium foil was polarized by an external field of 0.06 T produced in the gap of a small electromagnet mounted outside the vacuum chamber. The current in the electromagnet was reversed every five minutes. The magnetization of the gadolinium foil, measured independently as a function of temperature in an ac magnetometer, was $M=0.182(4)$ T.

The nuclear spin precession is obtained from the observed rotation of the angular distribution of γ rays emitted by the decaying nuclei. This rotation about the direction of the transient magnetic field, which is the same as that of the external field direction, causes, for each field flip, a small change in the counting rate in most detectors. Even with a large detec-

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tor array such as Gammasphere, such measurements depend essentially on the quality of spectra observed in a *single* detector, albeit gated by all the other detectors in the array.

Double-gated and triple-gated coincidence spectra were sorted separately for events recorded with the external magnetic field in either the ''up'' or ''down'' direction and for individual detectors in the array. For the extraction of double-gated spectra, the events were ''unpacked'' [18–20] and the resulting spectra were incremented if at least two SD coincidence conditions were satisfied by the remaining detectors. As expected, the lowest members of the SD bands were found to decay while fully stopped. The γ rays from states that decayed while in flight were seen to be increasingly Doppler shifted and an energy-dependent Doppler-shift correction was applied when gating on these transitions. While the SD transitions in the SD1 spectra were well established, the double-gated coincidence spectra for the SD2 and SD3 bands had low peak to background ratios.

The data were also analyzed by applying triple-gating conditions. In a direct event-by-event sort, one-dimensional spectra for each of the 90 detectors were generated as outlined in [18]. Because of the energy dependent Doppler shift for the higher SD transitions, individual gating lists containing up to 15 transitions in the SD bands were used for each detector. The background was determined from double-gated spectra generated by the same gate lists [21]. As expected, triple gating reduces the overall intensities in the SD bands, but improves the peak to background ratio. The relative errors in the peak sums of double-gated and triple-gated spectra are roughly the same, as they are dominated by the respective background subtraction. For the SD1 band, double-gated and triple-gated spectra yielded the same precessions.

Figure 1 shows sample spectra of the three superdeformed bands in ^{194}Hg obtained in a *single* backward detector under the triple-gate conditions described above.

In order to verify the angular distributions of the observed transitions, spectra for detectors with the same azimuthal angle with respect to the beam axis were added and efficiency corrected. The relative efficiencies, including the specific absorption caused by the geometry of the angular correlation chamber and magnet, were measured it *in situ* using the activity of the target immediately after the run. These angular distributions yielded A_2 and A_4 coefficients in qualitative agreement with data obtained by Hackman *et al.* [22], where angular distributions were measured more precisely with single element targets. For the analysis of the current data, the coefficients of Hackman *et al.* for all quadrupole transitions in the SD bands $A_2=0.352(3)$ and $A_4=-0.103(3)$ were adopted.

For the precession measurements, the z axis is defined by the direction of the external magnetizing field. The angular distribution for γ rays from detectors whose position is characterized by the two Euler angles θ and ϕ is given by

$$W(\theta,\phi)=1+A_2Q_2P_2(\cos\theta\cos\phi)+A_4Q_4P_4(\cos\theta\cos\phi),$$

where $Q_{2,4}$ are the geometrical attenuation coefficients.

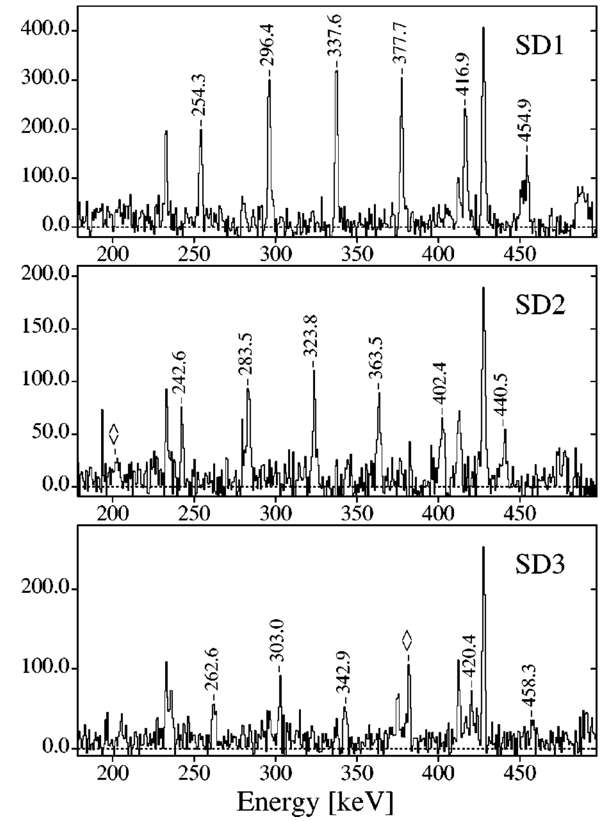

FIG. 1. Spectra of the lower energy regions of the ^{194}Hg SD bands observed in a single backward detector. The lines that are labeled by their energy were analyzed for precession. The diamonds indicate SD transitions that were not analyzed because of contamination.

Symmetric combinations of groups of four detectors at the same $\pm\theta$ and $\pm\phi$ angles, two forward (2,3) and two backward (1,4), were used to form double ratios [9], $\rho_{ij}=(N(\theta_i)\uparrow\cdot N(\theta_j)\downarrow/N(\theta_i)\downarrow\cdot N(\theta_j)\uparrow)^{1/2}$, where $N(\theta_i)\uparrow$, $N(\theta_i)\downarrow$ are the γ-ray rates in detectors $i,j=1$, 2, 3, 4 with the external field in the ''up'' and ''down'' direction, respectively. Such double ratios do not depend on the detector efficiency or on beam intensity fluctuations. The average double ratio $\rho=(\rho_{23}/\rho_{14})^{1/2}$ yields an effect $\epsilon=\rho-1/\rho+1$ from which the angular precession $\Delta\theta=\epsilon/S$ is calculated. The logarithmic slopes at the selected angles $S=1/W(\theta,\phi)\times dW(\theta,\phi)/d\theta$ ranged from 0.113–0.594. The double ratios ρ_{13} and ρ_{24} are expected to be close to unity and the value $\epsilon_{\rm check}=\rho-1/\rho+1$ with $\rho_{\rm check}=(\rho_{13}/\rho_{24})^{1/2}$ serves as a consistency check. Similar double ratios were used for the combinations of three and two detectors. In total 62 detectors were chosen such that $100°\leqslant\theta\leqslant160°$ or $20°\leqslant\theta\leqslant80°$ and $0.5°\leqslant\phi\leqslant53°$. The peak sums for the lowest six (SD1 and SD2) or five (SD3) band transitions were used to sample the average effects $\langle\epsilon\rangle$ for the 15 detector groups and in turn to calculate the average precession angle $\langle\Delta\theta\rangle$. It should be emphasized again that these angles correspond to the precessions of states populated while the nuclei traverse the gadolinium layer.

Finally, the average $\langle g\rangle$ factors were derived from the formula relating measured precessions to the transient magnetic field

$$\Delta\theta = -g\frac{\mu_N}{\hbar}\int_{t_{in}}^{t_{out}} B(v(t),Z)e^{-t/\tau}dt,$$

in which the Ziegler stopping powers [23] and the Chalk River parametrization of the transient field $B(v,Z)=154.7 \times Z \times (v/v_0) \times e^{-0.135 v/v_0} \times M$ T obtained from data on heavy nuclei [24] were used.

This experiment determines the average magnetic moments of the high-energy states of the three SD bands in ^{194}Hg. The ^{194}Hg nuclei are populated at an average excitation energy of 24 MeV. The energy of the first observed superdeformed state in SD1 at spin $\sim 50^+$ lies at 18.6 MeV [1,2]. The decay from the entry states into the superdeformed well is very fast and occurs mostly while the excited nuclei are still in the ^{150}Nd target. Subsequently, the γ flux remains in the corresponding SD bands until the decay-out towards the normal-deformed states occurs at the bottom of the band. The nuclei traverse the gadolinium foil during a time window of 0.5 ps, during which the average g factor of the higher members of the SD band are probed. These states lie at an approximate excitation energy $12.2 \gtrsim E_{\rm exc} \gtrsim 9.8$ MeV which corresponds to $34\hbar \gtrsim I \gtrsim 28\hbar$ for SD1 and SD2 and $33\hbar \gtrsim I \gtrsim 25\hbar$ for SD3.

The resulting average g factors are

$$\langle g(SD1)\rangle = 0.36(10),$$

$$\langle g(SD2)\rangle = 0.41(20),$$

$$\langle g(SD3)\rangle = 0.72(26).$$

The quoted errors reflect the counting statistics in the relevant detectors and a 5% uncertainty in the calibration of the transient field.

These results can be contrasted with the results obtained in the same experiment on the g factors of six normal-deformed bands in ^{193,194}Hg. In this latter situation, g factors considerably lower than the nominal Z/A were obtained [25], indicating significant single-neutron contribution to the g factor of the levels studied, and confirming the validity of the general analytical approach to obtaining g factors from this type of data.

Several models have been used to estimate the magnetic moments of SD bands in ^{194}Hg. As a first approximation, g_R can be assumed to take on the rigid body value, $g^{RB}=Z/A=0.412$. Calculations in the projected Hartree-Fock framework yield g factors very close to g^{RB} [26,27]. Perries *et al.* [28] determined the collective gyromagnetic ratio g_R^{IC} from the Inglis cranking approach applied to the static Hartree-Fock plus BCS and the SkM* force. These authors predict $g^{IC}=0.363$ for the yrast SD band in ^{194}Hg. Sun *et al.* [29] have calculated electromagnetic properties and pairing correlations of SD bands on the basis of the projected shell model. They predict g factors whose neutron contribution remains constant as a function of spin at –0.06, but whose proton contribution increases slowly with spin in the range $24\hbar \lesssim I \lesssim 44\hbar$, reaching a maximum at 0.47, yielding $g=0.41$ for the high-spin states in the yrast SD band in ^{194}Hg. However, the suggestion of Ref. [29] that the distinction between Coriolis antipairing and gradual high-j orbital alignment disappears at very large deformation is contradicted by the experimental data [30] on even-even, odd-even, and odd-odd nuclei. These experiments confirm the modified total Routhian surface (TRS) calculations which attribute the observed rise of $\mathcal{J}^{(2)}$ with $\hbar\omega$ to successive alignments of neutrons and protons occupying high-N intruder orbitals, with an additional contribution resulting from the response of the mean field to the alignment process.

The present experimental g factor for the yrast band is in good agreement with g_R^{IC} [28] but lacks the accuracy to exclude the rigid body value g^{RB} or the projected shell model result [29] and there do not yet exist TRS calculations of magnetic moments.

There are no theoretical predictions for g(SD2) or g(SD3). However, if the experimental g_R is taken from the measurement of g(SD1), the experimental g(SD2) and g(SD3) can be used to extract g_K. Nakatsuka *et al.* [31] have suggested, on the basis of the latest data on SD3 [2], that SD2 and SD3 represent octupole excitations built on a SD minimum with $K=2^-$. Other possible explanations in terms of aligned quasiparticle excitations [5] might lead to different predictions. However, unless $K\sim I$, a determination of g_K for SD2 and SD3 is difficult to extract from the present measurements at very high spin because the term $I(I+1)$ strongly attenuates the term $(g_K - g_R)$ in the expression for the g factor.

This paper presents the first measurement of g factors in the SD well, a quest which has had to await the completion of large γ arrays like Gammasphere. The present results should be considered as a demonstration of the potential of future studies. In this respect, two improvements in the experimental procedure will lead to more accurate measurements of the g factors of SD bands. First, it is clear that the g factors of the lower spin states in the band are critical for detailed interpretation. Such an experiment using a target with a gap between the ^{150}Nd target and the gadolinium ferromagnetic layer is in progress. Second, it is also important to achieve a higher statistical accuracy. Thus, a combination of a better detector coverage such as will be available with the future segmented detectors and longer counting periods will improve the statistical accuracy obtainable in such experiments.

In summary, the average g factors of the high-energy states of the three SD bands in ^{194}Hg have been measured. The $\langle g\rangle$ factor of the yrast band SD1 is smaller than the rigid body value and agrees with the prediction from an Inglis cranking approach. The $\langle g\rangle$ of the SD2 and SD3 bands are not accurate enough to distinguish among theoretical calculations.

The authors wish to express their gratitude to Leo Sapir and John Greene for target preparation, to Boris Elkonin for the design of the cooling system, to Randy McLeod for assistance with the data acquisition system and to the staff of the 88-Inch Cyclotron for their help during the experiment. This work was supported in part by the U.S. National Science Foundation, the Israel-U.S. Binational Science Foundation, and the U.S. Department of Energy W-31-109-ENG-38.

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