Recoil Distance Transient Field Measurement in ^{87}Nb: A Novel Method to Measure Nuclear Magnetic Moments

A. Jungclaus, C. Teich, V. Fischer, D. Kast, K. P. Lieb, and C. Lingk
II. Physikalisches Institut, Universität Göttingen, D-37073 Göttingen, Germany

C. Ender, T. Härtlein, F. Köck, and D. Schwalm
Max-Planck Institut für Kernphysik, D-69029 Heidelberg, Germany

J. Billowes
Schuster Laboratory, University of Manchester, Manchester, M13 9PL, United Kingdom

J. Eberth and H. G. Thomas
Universität zu Köln, D-50937 Köln, Germany
(Received 6 October 1997)

The recoil distance transient field technique in coincidence mode has been used to measure the magnetic moments of the $21/2^+$ and $29/2^-$ yrast states in ^{87}Nb. This method in conjunction with the use of five highly efficient EUROBALL cluster detectors has for the first time allowed the direct determination of individual g factors of picosecond high-spin states populated in heavy-ion compound-nucleus reactions. The value $g(29/2^-) = +0.56(16)$ indicates that the five-quasiparticle band consists of both an aligned $g_{9/2}$ proton and a $g_{9/2}$ neutron pair besides the odd $p_{1/2}$ proton. [S0031-9007(98)05680-4]

PACS numbers: 21.10.Ky, 21.60.Cs, 24.70.+s, 27.50.+e

The understanding of the structure of transitional nuclei is still far from satisfactory. On the one hand, these nuclei have too many valence particles to allow full microscopic calculations, and on the other hand, they do not show sufficient collectivity to justify a description in the framework of deformed cranking models. In the mass 80–90 region, a dramatic transition from strongly deformed shapes around neutron and proton number $N \approx Z \approx 38$ to spherical multiparticle hole structures in $N = 48-50$ nuclei has been observed. Besides this change of structure with increasing neutron number, some of the transitional nuclei even exhibit a strong change in deformation with increasing spin. An intriguing example is the isobar pair ^{87}Nb and ^{87}Mo. In ^{87}Nb [1], collectivity seems to drop above the first backbending, whereas in ^{87}Mo [2] the particle alignment marks the onset of collectivity.

A special feature of this mass region is that both types of valence particles, protons and neutrons, are filling the same high-spin $g_{9/2}$ orbit. In the transitional $N = 46$ nuclei, the proton and neutron Fermi levels are very similar so that both types of quasiparticle excitations are very close in energy. It is therefore not possible to deduce the nature of the alignments from blocking or energy arguments or transition rates. However, since $g_{9/2}$ protons and neutrons have very different g factors ($g_\pi = +1.38, g_\nu = -0.24$), the measurement of magnetic moments provides unique information about the internal structure of these multiquasiparticle states. This has been demonstrated by the work of Mountford *et al.* [3], which indicates that in ^{86}Zr a neutron pair aligns first, followed by a proton alignment, while the four-quasiparticle states probably have mixed proton and neutron configurations. If the lifetimes of the states of interest are in the picosecond range, the strongest available magnetic fields, namely, the transient magnetic fields (TF), experienced by recoiling ions in a polarized ferromagnetic foil, have to be used in order to induce a measurable Larmor precession. Indeed, many TF g-factor measurements have been carried out, mainly after Coulomb excitation [4–7]. The main problem in applying the TF method to heavy-ion compound-nucleus reactions lies in the feeding delay in populating the states which may be comparable to the duration of the transient field. To overcome this difficulty a new technique, combining the standard transient field with the recoil-distance method (recoil distance transient field, RDTF) in a coincidence measurement, has been proposed [8,9], which eliminates the problems associated with the feeding delays. Only with the availability of the new generation of highly efficient Ge spectrometers can this method be fully exploited. In this Letter, we present the results of the first successful RDTF experiment using five EUROBALL cluster detectors [10] to determine g factors of three- and five-quasiparticle states in ^{87}Nb. The population of a particular high-spin state after a heavy-ion fusion reaction has a large time spread due to the statistical nature of the particle evaporation and γ-ray emission following the compound-nucleus formation. The interaction of the magnetic moment with the transient field is, however, restricted to a very short time

0031-9007/98/80(13)/2793(4)$15.00

interval, limited by the time of passage through the ferromagnetic host (typically below 1 ps). Consequently, the observed Larmor precession is a convolution of contributions from many states, populated at different times and different recoil velocities in the individual decays. It is therefore extremely difficult to assign the observed precession to the magnetic moment of a particular state. By separating the target layer from the ferromagnetic foil by a flight path, a delay time between the formation of the nucleus and its exposure to the transient field is introduced [11]. The flight distance has to be chosen such that the maximum population of the state of interest is reached when the recoiling nuclei enter the ferromagnet. The observation of the Doppler-shifted flight component of a γ-ray feeding this state, in coincidence with the unshifted component of a γ-ray depopulating it, then allows a unique determination of g factors of individual states. The ^{87}Nb nuclei were produced in the ^{58}Ni(^{32}S, $3p$) reaction with a 110 MeV ^{32}S beam (1.5 particle nA) from the Heidelberg MP-tandem accelerator. The target was a self-supporting metallic ^{58}Ni foil of 1 mg/cm^2 thickness. The ferromagnetic foil consisted of a 2.88 mg/cm^2 Gd layer which was pressed onto a thick gold backing with the help of a very thin In layer. The Gd thickness was chosen such that the recoiling nuclei came to rest only in the Au backing to avoid any contributions from the interaction of the stopped nuclei with the static hyperfine field. The two foils were stretched and mounted in a RDTF target chamber [12] with the distance between them adjusted to 25 μm by a micrometer. This distance corresponds to a delay time of 3.6 ps at a recoil velocity of $v/c = 2.3\%$. Two NdFeB permanent magnets provided a vertical polarizing magnetic field of 125 mT perpendicular to the beam axis whose direction was reversed every 30 min. The Gd/Au stopper foil was cooled by liquid nitrogen to well below the Curie temperature of Gd. During 80 h of beam time 1.2×10^9 $\gamma\gamma$ events were collected.

Five EUROBALL cluster detectors [10] were positioned in a horizontal plane, perpendicular to the magnetic field axis, at 0°, ±55° and ±125° with respect to the beam at a distance of 24 cm (25.4 cm for the 0° cluster) from the target. Each cluster detector consists of seven individual Ge crystals [10], leading to 15 groups of crystals at different angles Θ to the vertical plane containing the beam axis: 3 crystals at 0° ($\varphi = 0°$, ±13° out of the horizontal plane), 2 at ±12° (±7°), 2 at ±43° (±7°), 3 at ±55° (0°, ±14°), 2 at ±67° (±7°), 2 at ±113° (±7°), 3 at ±125° (0°, ±14°), and 2 at ±137° (±7°). For each of the 15 groups of crystals, four different $E_{\gamma_1} - E_{\gamma_2}$ matrices were produced containing coincidence events between a crystal of this group and one of the four remaining clusters. This gives a total of 60 $\gamma\gamma$ coincidence matrices for each direction of the polarizing field. Gates were first set on the strong low-lying transitions in order to identify the states which meet the requirements for the determination of their magnetic moments: Doppler-shifted feeding transition and unshifted depopulating transition. Figure 1 shows the relevant part of the level scheme of ^{87}Nb [1]. In the positive parity yrast sequence, all states above the $25/2^+$ state decay in flight. The 226, 729, and 955 keV transitions connecting the $25/2^+$ to the $21/2^+$ level show both shifted and unshifted components, the three $E2$ transitions below the $21/2^+$ 20(1) ps [1] state are emitted after the nuclei have come to rest. From this point of view, the $21/2^+$, $23/2^+$, and $25/2^+$ states are good candidates for g factor determinations. However, the 955 keV transition is a doublet with the much stronger 953 keV $17/2^+ \rightarrow 13/2^+$ transition and in the case of the 226 keV γ ray the shifted component is not completely separated from the unshifted, thus not allowing to produce clean flight peak gates. We will therefore discuss here only the 2491 keV $21/2^+$ state. In the negative parity, we will concentrate on the 5010 keV $29/2^-$ level [$\tau = 5.0(5)$ ps [1]], since all the γ rays above this state are emitted in flight and the depopulating 879 keV transition has only a small shifted component.

Coincidence gates were set on the shifted components of the 729, 583, and 447 keV lines in all 120 matrices. Just because the 583 keV γ ray shows *no* stopped part, the gates on 447 and 583 keV can be summed up to increase statistics. From these spectra, counting-rate ratios

$$R(\Theta_{\text{look}}, \Theta_{\text{gate}}) = \frac{N^{\uparrow}(\Theta_{\text{look}}, \Theta_{\text{gate}})}{N^{\downarrow}(\Theta_{\text{look}}, \Theta_{\text{gate}})} \qquad (1)$$

were calculated, where $N^{\uparrow,\downarrow}(\Theta_{\text{look}}, \Theta_{\text{gate}})$ is the intensity of the relevant depopulating γ ray observed in the Ge crystals at Θ_{look} in the coincidence spectrum with a gate set on the flight component of the feeding transition in the cluster at Θ_{gate} for the field directions "up" and "down."

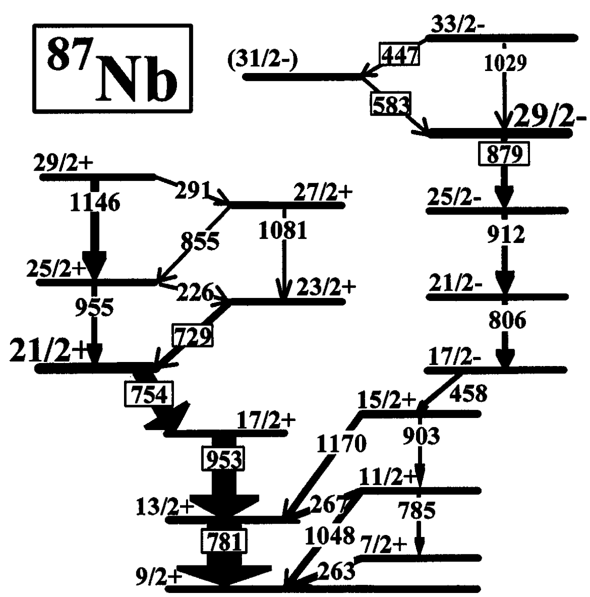

FIG. 1. Relevant part of the level scheme of ^{87}Nb [1].

Defining

$$I(\Theta_{\text{look}}) = \prod_{\substack{\Theta_{\text{gate}} \\ \Theta_{\text{gate}} \neq \Theta_{\text{look}}}} R(\Theta_{\text{look}}, \Theta_{\text{gate}}), \quad (2)$$

we can deduce the geometrical mean value

$$\rho_{55^\circ} = \left(\frac{I(+55^\circ) I(-125^\circ)}{I(-55^\circ) I(+125^\circ)} \right)^{1/16}, \quad (3)$$

and similar values ρ_{43° and ρ_{67° for the groups at $\{\pm 43^\circ, \pm 137^\circ\}$ and $\{\pm 67^\circ, \pm 113^\circ\}$, respectively. These values depend only on peak areas and are independent of other experimental factors such as detector efficiencies and integral beam currents for the two field directions. To check for systematic effects that might influence the observed precessions we also calculated the "check ratios"

$$\rho^c_{55^\circ} = \left(\frac{I(+55^\circ) I(-55^\circ)}{I(+125^\circ) I(-125^\circ)} \right)^{1/16} \quad (4)$$

and correspondingly $\rho^c_{43^\circ}$ and $\rho^c_{67^\circ}$. The average value for all transitions is $\rho^c = 0.9992(17)$ in agreement with unity. The precession angle is given by

$$\Delta\Phi_\Theta = \left(\frac{\rho_\Theta - 1}{\rho_\Theta + 1} \right) \Big/ S(\Theta), \quad (5)$$

where $S(\Theta) = (dW/d\Theta)/W(\Theta)$ is the logarithmic slope of the unperturbed angular correlation function $W(\Theta)$ at the angle of observation $\Theta = 43^\circ, 55^\circ$, and 67°. (Strictly speaking, W and S are functions of both Θ and the out-of-plane angle φ. This leads, however, only to small corrections as demonstrated in [12], where a full account of the data treatment and analysis will be given.) The coefficients of these functions $W(\Theta)$ for the γ rays of interest were obtained by least-squares fits to the data. As an example, Fig. 2 shows the angular correlation function of the 754, 953, and 781 keV $E2$ transitions determined from the coincidence spectra with gate on the flight component of the 729 keV γ ray. The precession angles $\Delta\Phi_{43^\circ}$, $\Delta\Phi_{55^\circ}$, and $\Delta\Phi_{67^\circ}$ of these three transitions, deduced from the same coincidence spectra, are plotted in Fig. 3. The beauty of the RDTF technique is that the extraction of g factors from the observed rotations is extremely simple due to the fact that only one single state interacts with the field. The g factor of this state is then given by

$$g = -\frac{\hbar}{\mu_N} \frac{\Delta\Phi}{\int B_{\text{TF}}\, dt}, \quad (6)$$

where $\int B_{\text{TF}}\, dt$ is the integral strength of the velocity-dependent transient field experienced by the recoiling nuclei during the passage through the ferromagnetic foil. We adopted the TF parametrization of the Chalk River group [13], namely,

$$B_{\text{TF}}(v, Z) = aZ(v/v_0)e^{-\beta(v/v_0)} \quad (7)$$

with the Bohr velocity v_0, $a = 29(2)$ T, and $\beta = 0.135$ for Gd. We adjusted this parametrization to our experimental conditions by taking into account the known temperature dependence of the magnetization of Gd [14], leading to a reduction of the field strength by 24%. The results for the 2491 keV $21/2^+$ and 5010 keV $29/2^-$ states in ^{87}Nb are summarized in Table I. The g factor of the $21/2^+$ state agrees very well with the value $g(21/2^+) = +0.41(13)$ deduced from the time-integral precession in the static hyperfine field observed following the recoil implantation into a ferromagnetic iron host (IMPAD) [15]. This comparison is very informative since the two methods are susceptible to different sources of error. In an RDTF experiment, the only systematic uncertainty originates from the integral TF strength which has to be deduced from empirical parametrizations considering the lack of a full theoretical understanding of transient magnetic fields. In contrast to this, the static hyperfine

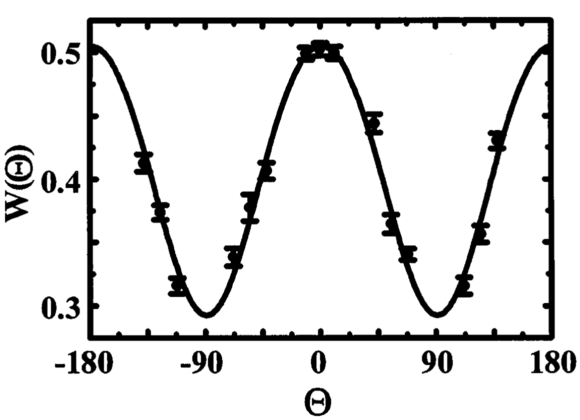

FIG. 2. Experimental angular correlation function of the $E2$ cascade below the $21/2^+$ state in ^{87}Nb determined in the coincidence spectra with gate on the flight component of the 729 keV feeding transition. The curve represents the fit to the data yielding a_2 and a_4 coefficients listed in Table I.

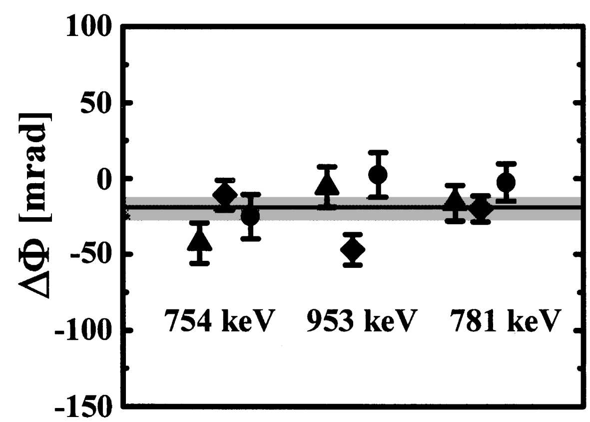

FIG. 3. Deduced precessions of the stopped components of the transitions below the $21/2^+$ state in coincidence with the flight component of the 729 keV feeding transition. Precessions determined at 43°, 55°, and 67° to the beam are marked by triangles, rhombs, and circles, respectively.

TABLE I. Experimental precession angles and deduced g factors for the $21/2^+$ and $29/2^-$ states in ^{87}Nb. The values g_{SM} are the results of our shell-model calculations within the $(g_{9/2}, p_{1/2})$ configuration space.

I^π	Gate transition(s)	Look transition(s)	a_2	a_4	$\overline{\Delta\Phi}$ (mrad)	g	g_{SM}
$21/2^+$	729	781 953 754	0.40(2)	−0.03(2)	−20.0(55)[a]	+0.36(11)	+0.38
$29/2^-$	447 583	879	0.39(2)	−0.02(2)	−30.9(82)	+0.56(16)	+0.58

[a]Average value obtained for the three look transitions.

field in the IMPAD measurement is well known, but here the lifetime of the state and the intensities of all the known feeding transitions have to be taken into account and assumptions about the unknown sidefeeding and the continuum g factor have to be made. In addition, the fraction of recoil nuclei coming to rest on substitutional, defect-free sites and the possible occurrence of defect-related hyperfine fields can cause problems in IMPAD experiments.

As already pointed out in [15], the $21/2^+$ g factor clearly indicates that this state is built from an aligned $g_{9/2}$ neutron pair coupled to the unpaired $g_{9/2}$ proton. The g factors of the two relevant seniority $v = 3$ configurations $[\pi(g_{9/2}) \otimes \nu^{-2}(g_{9/2})_{6,8}]$ are +0.45 and +0.25, in contrast to a large g factor of +1.38 expected for a pure $g_{9/2}$ proton configuration. Considering only configurations of the lowest possible seniority $v = 5$, there are three very different possibilities to build a state of spin $29/2^-$. In the first, an unpaired proton in the $p_{1/2}$ shell is coupled to both an aligned proton and neutron pair, $[\pi^2(g_{9/2})\pi(p_{1/2})] \otimes \nu^{-2}(g_{9/2})$, yielding g factors in the range from +0.43 to +0.65. Equally, the negative parity can be provided by a $p_{1/2}$ neutron, leading to either $\pi^3(g_{9/2}) \otimes [\nu(g_{9/2})\nu(p_{1/2})]$ or $\pi(g_{9/2}) \otimes [\nu^{-3}(g_{9/2})\nu(p_{1/2})]$ with g factors of +0.9 and +0.2, respectively. The experimental value $g(29/2^-) = +0.56(16)$ is a strong hint that the $29/2^-$ level in ^{87}Nb is indeed a mixed two-proton–two-neutron $g_{9/2}$ configuration coupled to the unpaired proton in the $p_{1/2}$ shell. This result definitely rules out pure $p_{1/2}$ neutron configurations.

A systematic study of level energies and decay properties of $N = 46-49$ nuclei [16] suggests that above the first $g_{9/2}$ alignment ^{87}Nb can be well described within the spherical shell model using the $(g_{9/2}, p_{1/2})$ single-particle basis and the residual interaction deduced by Gross and Frenkel [17]. We extended these calculations using the code RITSSCHIL [18] and found that the largest components of the yrast and yrare $29/2^-$ states are indeed $[\pi^2(g_{9/2})\pi(p_{1/2})]_{17/2} \otimes \nu^{-2}(g_{9/2})_6$ and $[\pi^2(g_{9/2})\pi(p_{1/2})]_{17/2} \otimes \nu^{-2}(g_{9/2})_8$, respectively, leading to g factors of +0.58 and +0.52. Only the third $29/2^-$ level with $g(29/2_3^-) = +0.29$ is predicted to be dominated by the $\pi(g_{9/2}) \otimes [\nu^{-3}(g_{9/2})\nu(p_{1/2})]$ configuration. It is important to notice that this interpretation does *not* depend on the choice of the TF parametrization, e.g., Chalk River, Rutgers [3], or linear parametrization [19].

In conclusion, we reported on the first successful *direct* measurement of the g factor of a high-spin state with a lifetime as short as 5 ps populated in a heavy-ion fusion reaction, using the RDTF technique in coincidence mode in conjunction with highly efficient EUROBALL cluster detectors. The result demonstrates the unique power of magnetic moments for the clarification of the complex structure of multiquasiparticle states. The experiment proves that with the new generation of γ spectrometer such as EUROBALL and Gammasphere, the RDTF method can now be used to determine magnetic moments of a large variety of excited nuclear states which were not accessible to such measurements before.

We are most grateful to Dr. Repnow and the crew of the Heidelberg tandem accelerator for their friendly and efficient cooperation. The EUROBALL project is funded by Deutsches Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF).

[1] A. Jungclaus *et al.*, Z. Phys. A **340**, 125 (1991).
[2] Ch. Winter *et al.*, Phys. Lett. B **258**, 289 (1991); Ch. Winter *et al.*, Nucl. Phys. **A535**, 137 (1991).
[3] A. W. Mountford *et al.*, Phys. Rev. C **51**, 513 (1995).
[4] N. Benczer-Koller, M. Hass, and J. Sak, Annu. Rev. Nucl. Part. Sci. **30**, 53 (1980).
[5] K. H. Speidel *et al.*, Z. Phys. A **342**, 17 (1992).
[6] O. Häusser *et al.*, Nucl. Phys. **A406**, 339 (1983).
[7] A. Stuchbery *et al.*, Nucl. Phys. **A528**, 447 (1991).
[8] E. Lubkiewicz *et al.*, Z. Phys. A **335**, 369 (1990).
[9] U. Birkental *et al.*, Nucl. Phys. **A555**, 643 (1993).
[10] J. Eberth *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **369**, 135 (1996).
[11] C. G. Ryan, Ph.D. thesis, University of Melbourne, 1985.
[12] C. Teich, A. Jungclaus, and K. P. Lieb (to be published).
[13] O. Häusser *et al.*, Phys. Lett. **144B**, 341 (1984).
[14] N. Benczer-Koller *et al.*, Hyperfine Interact. **33**, 37 (1987).
[15] M. Weiszflog *et al.*, Nucl. Phys. **A584**, 133 (1995).
[16] D. Rudolph *et al.*, Nucl. Phys. **A597**, 298 (1996).
[17] R. Gross and A. Frenkel, Nucl. Phys. **A267**, 85 (1976).
[18] D. Zwarts, Comput. Phys. Commun. **38**, 365 (1985).
[19] J. L. Eberhardt and K. Dybdal, Hyperfine Interact. **7**, 387 (1979).