First Evidence of Magnetic Rotation in the $A = 80$ Region

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Rotational bands with strong magnetic dipole transitions have been observed in the doubly odd nuclei ^{82}Rb and ^{84}Rb. These bands show the characteristic features of magnetic rotation. They are the first evidence of this new kind of nuclear excitation in the $A \approx 80$ region. The results are well reproduced within the framework of the tilted axis cranking model on the basis of four-quasiparticle configurations of the type $\pi(fp)$-$\pi(g_{9/2}^2)$-$\nu(g_{9/2})$. [S0031-9007(99)09279-0]

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The conventional concept of nuclear rotation is based on the existence of a deformed mass distribution of the nucleus. Regular rotational bands are formed by energy levels that depend on the spin I according to $E \propto I(I + 1)$ and are connected by electric quadrupole ($E2$) transitions [1].

Recently, a surprising phenomenon has been observed in nearly spherical Pb isotopes around $A = 200$. While the excited states at low spin show irregular multipletlike structures as expected for nearly spherical nuclei, regular sequences that follow the $I(I + 1)$ rule evolve at high spin, indicating a rotational mode. The levels of these sequences are linked by strong magnetic dipole ($M1$) transitions whereas crossover $E2$ transitions are very weak [2–5]. The ratios of the transition probabilities are typically in the order of $B(M1)/B(E2) \approx 20$–40 $(\mu_N/e\,\mathrm{b})^2$. These observations contradict the common understanding of nuclear physics that only well-deformed nuclei should exhibit rotational bands.

A solution of this apparent paradoxon has been given in the framework of the tilted axis cranking (TAC) model [6]. The coupling of angular momentum vectors of a few high-j nucleons is the basic mechanism for generating the total spin I of the nucleus. Few protons occupy orbitals with long spin vectors above a closed shell (high-j particlelike orbitals) while the neutrons fill up a shell except for a few holes (high-j holelike orbitals), or vice versa. A perpendicular coupling of their angular momenta is energetically favored because it maximizes the overlap of the spatial density distribution, which is toruslike for particle orbitals and dumbbell-like for hole orbitals. This coupling results in a substantial component of the magnetic dipole moment, which is transverse to the total spin and gives rise to large $M1$ transition probabilities of several μ_N^2. As the magnetic dipole rotates about the axis of the total angular momentum, this new mode has been called "Magnetic Rotation" [7]. The total angular momentum is increased by the gradual alignment of the individual particle and hole spins along the axis of the total angular momentum. Since this rearrangement of the particle and hole angular momentum vectors resembles the closing of the blades of a pair of shears, it has been called "shears mechanism" [3]. As a consequence of this alignment the transverse component of the magnetic dipole moment decreases and one expects smoothly decreasing $B(M1)$ transition probabilities with increasing spin. Recent results [5] confirm this trend of the $B(M1)$ values in the Pb region.

The TAC model predicts magnetic rotation in several regions of the nuclear chart [7,8]. These regions are characterized by nuclei of low deformation in the vicinity of shell closures. Recently, magnetic rotation has also been observed around the predicted regions $A = 110$ [9–11] and $A = 140$ [12]. Another mass region, where magnetic rotation is predicted to occur, is located around $A = 80$, where there are few particlelike protons in the high-j $g_{9/2}$ intruder orbital and few $g_{9/2}$ neutron holes in the $N = 50$ shell. Indications of $\Delta I = 1$ sequences with strong $M1$ transitions have been found in Br, Rb, and Kr isotopes of the $A = 80$ region (e.g., [13] and references therein). Since only a few levels and transition probabilities have been observed in those studies, no conclusions could be drawn about the predicted appearance of magnetic rotation in this mass region.

The phenomenon of magnetic rotation is expected only in a small range of nucleon numbers around $A = 80$. For example, the Rb isotopes below $N = 44$ are relatively well deformed [14–17] while the high-spin level sequences observed in the isotopes ^{85}Rb ($N = 48$) [18] and ^{86}Rb ($N = 49$) [19] display multipletlike structures. This raises the question whether there exists a region in between with neutron numbers of $N = 45, 46,$

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and 47, where, at a small deformation, regular $M1$ bands can be built from the $g_{9/2}$ proton and neutron orbitals. The identification in light and medium mass nuclei is of particular interest because the alternative description of the phenomenon of magnetic rotation by means of the shell model is well within the reach of modern computing.

To approach this problem we have investigated the isotopes ${}^{82}_{37}\mathrm{Rb}_{45}$ and ${}^{84}_{37}\mathrm{Rb}_{47}$, which have nine proton particles above the $Z = 28$ shell and five or three neutron holes in the $N = 50$ shell, respectively. Excited states in ^{82}Rb and ^{84}Rb were populated using the fusion-evaporation reaction ^{76}Ge(^{11}B,xn) at a beam energy of 50 MeV, delivered by the XTU tandem of the Laboratori Nazionali di Legnaro (Italy). The target consisted of a stack of two thin self-supporting ^{76}Ge foils with a thickness of about 0.2 mg/cm^2 each. Emitted γ rays were detected with the GASP spectrometer [20] consisting of 40 Compton-suppressed HPGe detectors and an inner ball with 80 Bismuth germanate elements. Approximately 1.5×10^8 highfold ($F \geq 3$) events were collected and sorted off-line into $E_\gamma - E_\gamma$ matrices as well as an $E_\gamma - E_\gamma - E_\gamma$ cube.

The low-lying excited states in ^{82}Rb and ^{84}Rb up to an excitation energy of $E_x \approx 2$ MeV and a spin of $I \approx 10\hbar$ have been known from previous work [21,22]. Compared to these earlier measurements, the present coincidence experiment has led to a substantial extension of spectroscopic information for both nuclei, with excited levels observed up to an excitation energy of $E_x \approx 7$ MeV and a spin of $I \approx 17\hbar$. Spin and parity assignments are based on $\gamma - \gamma$ directional correlations of oriented states (DCO) [23] and deexcitation modes. In both nuclei, several new level sequences have been found. In this Letter we concentrate on the most interesting feature, the sudden development of regular magnetic dipole bands at excitation energies around 3 MeV. Partial level schemes of ^{82}Rb and ^{84}Rb including the $M1$ bands and their deexcitation to low-lying states are shown in Figs. 1 and 2, respectively.

The analysis of ^{82}Rb has revealed a cascade of five strong $M1$ transitions on top of the $I^\pi = 11^{(-)}$ level at $E_x = 2.616$ MeV. Weak crossover $E2$ transitions up to the highest spin are observed as well. In ^{84}Rb a similar band with six $M1$ transitions develops above the $I^\pi = 11^{(-)}$ level at $E_x = 3.393$ MeV. The dipole character of the transitions has been proven by the DCO ratios and multipolarity $M1$ is suggested by the analogy to multiparticle excitations in neighboring nuclei [13,17–19]. Multipolarity $E1$ can be ruled out, since regular $E1$ bands are connected with a static octupole deformation. There is no indication for that in this mass region. Negative parity has tentatively been assigned to the states of the $M1$ bands in both ^{82}Rb and ^{84}Rb. If the $M1$ band in ^{82}Rb had positive parity, then the 773 and 885 keV γ rays would have $M2$ character. These $M2$ transitions are associated with level lifetimes in the order of μs and would not be observable in our coincidence experiment. On the other hand, if the levels at 1732 and 1843 were also assumed to have positive parity, then it is the 601 keV γ ray which would be an $M2$ transition. These arguments support our assumption of negative parity for the $M1$ band in ^{82}Rb. Furthermore, the similarity of the $M1$ bands in ^{82}Rb and ^{84}Rb suggests equal parity for both bands.

A striking feature of the $M1$ bands is the regularity of the level spacings $[I \propto \hbar\omega, \hbar\omega = E_\gamma(\Delta I = 1)]$ which can be seen in the upper panels of Figs. 3 and 4, respectively, indicating the rotational character. Nevertheless, the emission of $M1$ radiation is strongly favored over the emission of $E2$ radiation. This magnetic character of the rotation is demonstrated by the ratios of transition probability $B(M1)/B(E2)$ for each level in the band. These ratios are shown in the lower panels of Figs. 3 and 4 for ^{82}Rb and ^{84}Rb, respectively. They reach values up to about 20 $(\mu_N/e\,\mathrm{b})^2$, which are comparable with the ratios in other regions of magnetic rotation. The $B(M1)/B(E2)$ ratios decrease smoothly with increasing rotational frequency $\hbar\omega$ in a range of $\hbar\omega \approx 0.4$–0.7 MeV, manifesting the shears mechanism. Hence, we have found the main characteristics of magnetic rotation.

We have interpreted the $M1$ bands in ^{82}Rb and ^{84}Rb in the framework of the TAC model. The parameter κ of the QQ interaction is adjusted such that in a calculation for

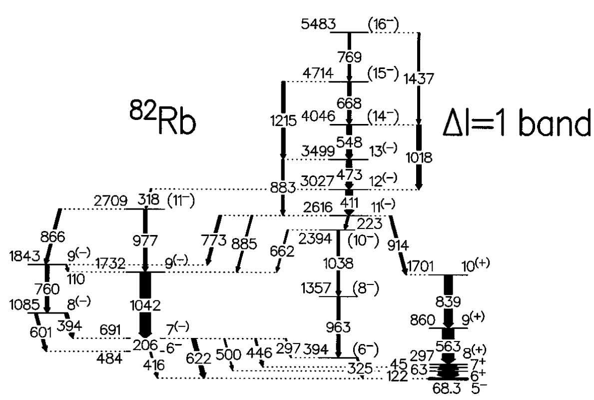

FIG. 1. Partial level scheme of ^{82}Rb with the width of the γ transitions proportional to their measured intensities.

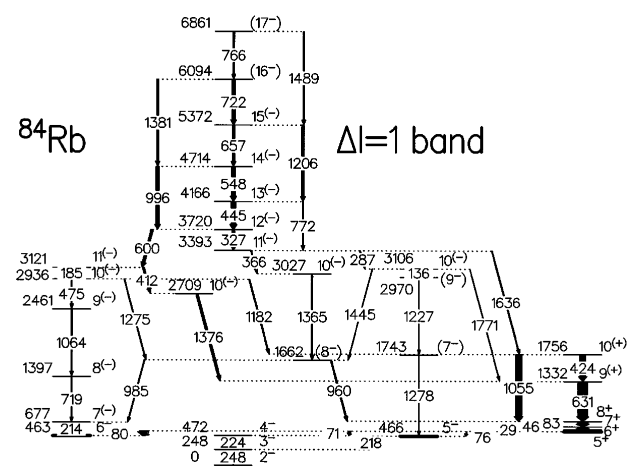

FIG. 2. Partial level scheme of ^{84}Rb with the width of the γ transitions proportional to their measured intensities.

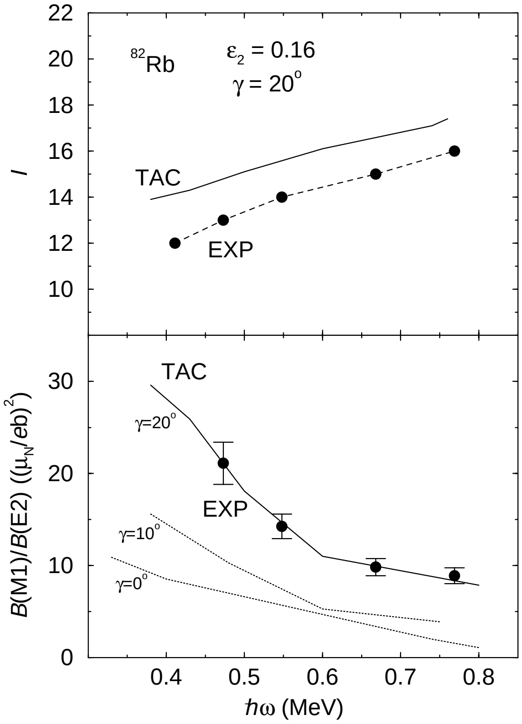

FIG. 3. Comparison of experimental spins (upper panel) and $B(M1)/B(E2)$ ratios (lower panel) in ^{82}Rb with TAC model predictions as a function of rotational frequency. The lower panel includes TAC calculations for different values of the triaxiality parameter γ.

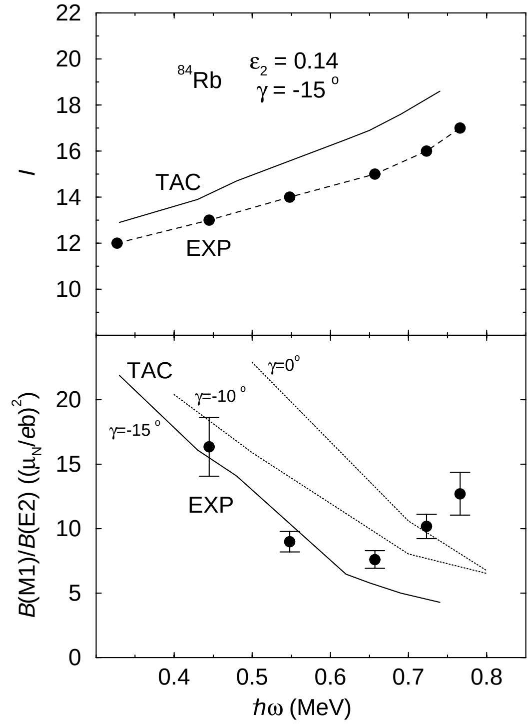

FIG. 4. Comparison of experimental spins (upper panel) and $B(M1)/B(E2)$ ratios (lower panel) in ^{84}Rb with TAC model predictions as a function of rotational frequency. The lower panel includes TAC calculations for different values of the triaxiality parameter γ.

the even-even neighbor ^{82}Kr the experimental $B(E2, 2^+ \rightarrow 0^+)$ [24] value is reproduced. In the case of ^{84}Rb this value is scaled according to $\kappa \propto A^{-5/3}$. Pairing is taken into account by using values of $\Delta_\pi = 1.08, \Delta_\nu = 0.94$ and $\Delta_\pi = 0.86, \Delta_\nu = 0.79$ for ^{82}Rb and ^{84}Rb, respectively, calculated in MeV according to Ref. [25]. The chemical potentials (in MeV) were chosen to reproduce the appropriate particle number in each nucleus (^{82}Rb: $\lambda_\pi = 45.45, \lambda_\nu = 47.70$; ^{84}Rb: $\lambda_\pi = 45.10, \lambda_\nu = 48.00$). In the calculations, the lowest-lying four-quasiparticle $(4qp)$ configuration for $Z = 37$ and $N = 45$, 47 turns out to be $\pi(fp)$-$\pi(g_{9/2}^2)$-$\nu(g_{9/2})$, which has been adopted. This configuration has negative parity which is consistent with our experimental findings. The "shears" mechanism is generated by two protons in the $g_{9/2}$ orbital and one unpaired $g_{9/2}$ neutron. An equilibrium deformation of $\epsilon_2 = 0.16$ and $\epsilon_2 = 0.14$ is obtained in ^{82}Rb and ^{84}Rb, respectively. Total Routhian surface calculations performed with the ultimate cranker code [26] confirm these minima in the potential energy surface. As illustrated by Fig. 5, both nuclei turn out to be very soft with respect to γ deformation. Assuming a typical value of 300 keV for the zero point energy of the γ degree of freedom the wave function is expected to extend far to both sides of the minimum of the potential energy. Since the potential curves are very asymmetric, one expects the mean value of γ to be different from the position of the minimum of the potential energy, being more positive for ^{82}Rb and more negative for ^{84}Rb. Hence, we have carried out TAC calculations for different γ values, which are included in the lower panels of Figs. 3 and 4. As can be seen in the figures, the best approximation to the experimental data is obtained by choosing $\gamma = 20°$ and $\gamma = -15°$ for ^{82}Rb and ^{84}Rb, respectively. These values were finally adopted in the following discussion.

The experimental and calculated dependence of the spin on the rotational frequency for the $M1$ bands in ^{82}Rb and ^{84}Rb is shown in the upper panels of Figs. 3 and 4, respectively. The calculated curve follows well the experimental behavior although lying about one spin unit above the experimental curve. Table I summarizes the absolute transition probabilities $B(M1)$ and $B(E2)$ calculated within the TAC model. The $B(M1)$ values decrease from values of more than 1 μ_N^2 to about 0.3 μ_N^2 in the considered frequency range while the $B(E2)$ values increase by some 20%. Because of the different values of γ deformation used for ^{82}Rb and ^{84}Rb, the $B(E2)$ values in these nuclei differ by almost a factor of 2. In the lower panels of Figs. 3 and 4 calculated $B(M1)/B(E2)$ ratios are compared to the observed ones. The calculated $B(M1)/B(E2)$ ratios for the proposed configuration in ^{82}Rb are in excellent agreement with the experimental values. In ^{84}Rb the behavior of the experimental $B(M1)/B(E2)$ ratios is fairly well described in the calculation up to $\hbar\omega = 0.7$ MeV. The upbend in the experimental $B(M1)/B(E2)$ ratios above $\hbar\omega = 0.7$ MeV cannot be described with the

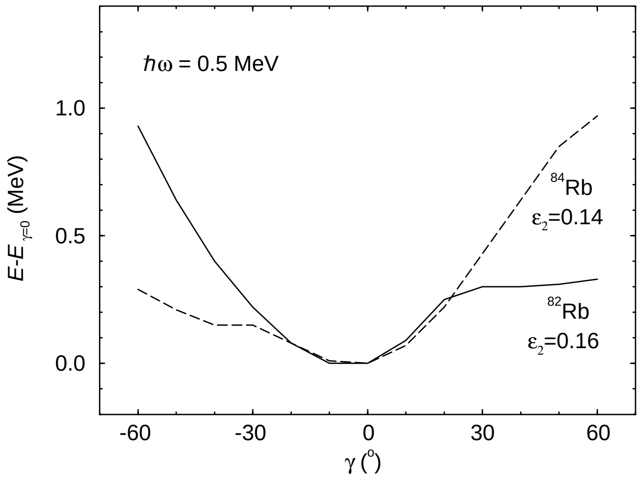

FIG. 5. Total energy $E(\gamma)$ relative to $E(\gamma = 0)$ of the configuration $\pi(fp)$-$\pi(g_{9/2}^2)$-$\nu(g_{9/2})$ as a function of γ deformation for the nuclei ^{82}Rb and ^{84}Rb, calculated within the TAC model.

chosen $4qp$ configuration. It may indicate a change of the configuration caused by a breakup of an additional pair of protons or neutrons, which is consistent with the slight upbend of the experimental function $I(\hbar\omega)$ in the upper panel of Fig. 4. Quasiparticle Routhians deduced from our TAC calculations predict a crossing for neutron $g_{9/2}$ orbitals at $\hbar\omega \approx 0.6$ MeV.

In conclusion, we have observed regular magnetic dipole bands in the nuclei ^{82}Rb and ^{84}Rb. These bands are the first examples of magnetic rotation in the $A \approx 80$ region. They show the typical characteristics: (i) the regularity of the bands ($I \propto \hbar\omega$), (ii) the observation of strong $M1$ and weak crossover $E2$ transitions with ratios of the transition probabilities $B(M1)/B(E2)$ of up to about 20 $(\mu_N/e\,\mathrm{b})^2$, and (iii) a smooth decrease of the $B(M1)/B(E2)$ ratios with increasing frequency up to $\hbar\omega = 0.7$ MeV, which is evidence for the shears mechanism. These characteristics are well reproduced by TAC calculations on the basis of the lowest-lying $4qp$ configuration: $\pi(fp)$-$\pi(g_{9/2}^2)$-$\nu(g_{9/2})$. The agreement between experiment and calculations proves the applicability of the concept of magnetic rotation to these bands. We present the first evidence of this novel rotational mode in the mass region around $A = 80$, confirming the predictions of the TAC model. It seems, the shears mechanism resulting in regular $M1$ bands can evolve despite the relatively short spin vectors of the $g_{9/2}$ orbitals, as compared to those of the $h_{11/2}$ and $i_{13/2}$ orbitals generating the shears bands in heavier nuclei. Magnetic rotation may be limited to a small range, because small variations of the proton and neutron numbers lead to drastic changes of the nuclear deformation in the mass 80 region.

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TABLE I. Reduced transition probabilities $B(M1)$ and $B(E2)$ predicted by TAC model calculations for the configuration $\pi(fp)$-$\pi(g_{9/2}^2)$-$\nu(g_{9/2})$ in ^{82}Rb and ^{84}Rb.

	$\hbar\omega$ (MeV)	$B(M1, \Delta I = 1)$ (μ_N^2)	$B(E2, \Delta I = 2)$ ($e^2\,\mathrm{b}^2$)
^{82}Rb:	0.20	1.06	0.026
$\epsilon_2 = 0.16$	0.30	0.91	0.026
$\gamma = 20°$	0.38	0.80	0.027
	0.50	0.53	0.029
	0.60	0.33	0.030
	0.72	0.28	0.031
	0.77	0.20	0.031
^{84}Rb:	0.20	1.19	0.040
$\epsilon_2 = 0.14$	0.33	0.93	0.043
$\gamma = -15°$	0.43	0.74	0.046
	0.48	0.67	0.048
	0.62	0.34	0.052
	0.69	0.26	0.052
	0.74	0.22	0.051

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