High-Spin States in ^{167}Lu

C. Foin and D. Barnéoud
Institut des Sciences Nucléaires, Centre de Tri, 38044 Grenoble-Cedex, France
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We have studied the properties of two rotational bands in ^{167}Lu for high spin values. Backbending is observed in the $\frac{7}{2}^+[404]$ band, but not in the $\frac{1}{2}^+[541]$ band. These results are in agreement with the rotation-alignment model.

Study of high-spin levels in some even-even nuclei[1] has shown a sudden decrease of the rotational frequency with increasing spin and moment of inertia. Several hypotheses have been formulated to explain this process known as the "backbending effect." Thus, Mottelson and Valatin[2] predicted that at a sufficiently high angular velocity the nuclear pairing correlations should disappear (Coriolis antipairing effect), and they estimated that this effect occurs above a spin value $I_c = 12$ in the rare-earth region. Their hypothesis seems correct, since backbending is observed at a spin value of about 12–16 in many rare-earth even-even nuclei. More recently, Stephens and Simon[3] have proposed that backbending results from a crossing of two bands, one built on the ground state and the other on a two-quasiparticle state produced by a decoupling of two nucleons from the core (rotation-alignment model). Experiments have been performed on odd-A nuclei to test backbending models: Results obtained on odd-A Er nuclei[4] and odd-A Ho nuclei[5] are in good agreement with the rotation-alignment model.

In this Letter, we present results which show in an odd-A nucleus (^{167}Lu) the unlike behavior of two rotational bands at high spin values: only one exhibits backbending.

We have studied the γ-ray cascades following the reactions ^{169}Tm(^{3}He, 5n)^{167}Lu and ^{169}Tm(α, 6n)^{167}Lu, with Ge(Li) detectors. The beam was produced by the Grenoble isochronous cyclotron and the energy used was 45 MeV for the ^{3}He beam and 73 MeV for the α beam. The target was a metallic foil about 10 mg/cm^2 thick. The experimental arrangements for in-beam γ-ray spectroscopy measurements are described elsewhere.[6] The complete results obtained for the levels of ^{167}Lu will be the subject of a future publication.[7]

The rotational band built on the $\frac{7}{2}^+[404]$ ground state[8,9] is not perturbed by the Coriolis interaction, therefore all its levels are fed with regularity. Its components have been identified up to a spin value of $\frac{29}{2}$. As in the neighboring odd-A Lu nuclei,[10,11] the most strongly fed band is the $\frac{1}{2}^-[541]$ band, the levels of which are for $I \geq \frac{17}{2}$ the yrast levels. Because of the strong decoupling parameter ($a_{\text{exp}} \sim 3.7$) and the strong Coriolis interaction with the other $h_{9/2}$ bands, the odd-($I+\frac{1}{2}$) levels are strongly lowered with regard to the even-($I+\frac{1}{2}$) levels and therefore are the only levels fed in this band. This part of the band has been identified through the sequence of strong

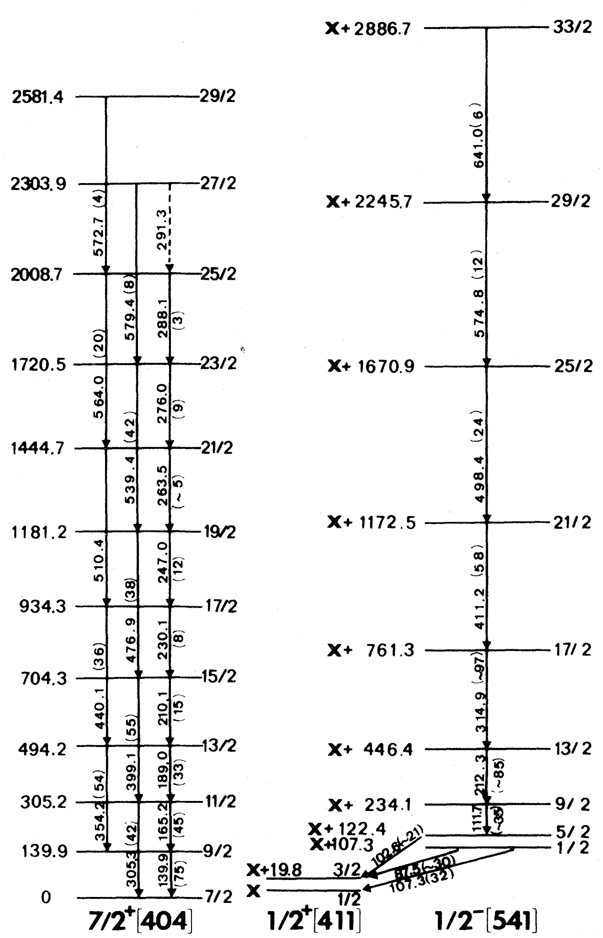

FIG. 1. Partial level scheme of ^{167}Lu. The values in parentheses are γ-ray intensities obtained with the ^{3}He beam. X has a value less than 60 keV.

TABLE I. Energies of the $\frac{7}{2}^+[404]$ and $\frac{1}{2}^-[541]$ rotational-band transitions observed in ^{167}Lu [^{169}Tm + α(73 MeV)].

	$\frac{7}{2}^+[404]$		$\frac{1}{2}^-[541]$
I	$E_I - E_{I-1}$ (keV)	I	$E_I - E_{I-2}$ (keV)
9/2	139.9 ± 0.2	9/2	111.7 ± 0.2
11/2	165.2 ± 0.2	13/2	212.3 ± 0.3
13/2	189.0 ± 0.3	17/2	314.9 ± 0.3
15/2	210.1 ± 0.3	21/2	411.2 ± 0.3
17/2	230.1 ± 0.3	25/2	498.4 ± 0.3
19/2	247.0 ± 0.4	29/2	574.8 ± 0.5
21/2	263.5 ± 0.4	33/2	641.0 ± 1
23/2	276.0 ± 0.4	37/2	(695.0 ± 1)[a]
25/2	288.1 ± 0.4		
27/2	291.3 ± 0.4		
29/2	281.4 ± 0.4		

[a]This transition is only observed in the coincidence spectrum.

quadrupole transitions and is constructed without ambiguity up to the level with spin $\frac{33}{2}$. A very weak 695-keV transition only observed in coincidence experiments suggests the existence of a $\frac{37}{2}$ state. The partial level scheme is shown in Fig. 1.

With the use of the formulas defined in Ref. 11 and by Klarma *et al.*,[12]

$$\overline{R}^2 = (I - j)^2$$

$$= I(I+1) - K^2 + (-1)^{I+1/2} a (I + \tfrac{1}{2}) \delta_{K,1/2}, \quad (1)$$

$$2J/\hbar^2 \approx \Delta R^2 / \Delta E, \quad (2)$$

$$(\hbar\omega)^2 \approx (\Delta E / \Delta R)^2, \quad (3)$$

and data of Table I, we have plotted (Fig. 2) the quantity $2\mathcal{J}/\hbar^2$ versus $(\hbar\omega)^2$ for the $\frac{7}{2}^+[404]$ and $\frac{1}{2}^-[541]$ bands of ^{167}Lu and also for the ground band of ^{166}Yb and ^{168}Hf.[13,14] In Fig. 2, we observe firstly that the $\frac{7}{2}^+[404]$ band backbends at about the same rotational frequency as in the even-even nuclei ($\hbar^2\omega^2 \simeq 0.08$), and secondly that the $\frac{1}{2}^-[541]$ band does not backbend, even for a $\hbar^2\omega^2$ much larger than 0.08. From this examination, we note that the unlike behavior of the two bands of ^{167}Lu is in disagreement with the pairing-collapse model. On the other hand, this difference is explained easily enough with the Stephens-Simon model.

As a matter of fact the result obtained for the $\frac{7}{2}^+[404]$ band is similar to that observed for the $\frac{7}{2}^-[523]$ band in Ho.[5] This result seems normal, all the more as the $\frac{7}{2}^+[404]$ band is not perturbed

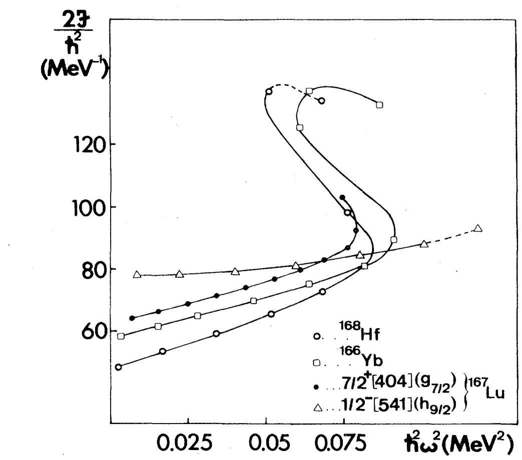

FIG. 2. $2\mathcal{J}/\hbar^2$ versus $\hbar^2\omega^2$ for ^{167}Lu and even-even ^{166}Yb and ^{168}Hf.

at all by the Coriolis interaction. Consequently, the protons of the $g_{7/2}$ shell which produce the $\frac{7}{2}^+[404]$ state are not involved in the mechanism of backbending.

On the other hand, the fact that the $\frac{1}{2}^-[541]$ band does not backbend means, according to Stephens and Simon,[3] that the $h_{9/2}$ protons are as strongly involved in the mechanism of backbending as the $i_{13/2}$ neutrons are in the case of Er.[4] As a matter of fact, if further we consider that backbending in neighboring even-even nuclei results from a crossing of the ground band with a two-quasiparticle band produced by a decoupling of two $h_{9/2}$ protons from the core, then, in the odd-A nucleus (^{167}Lu), if the extra particle is the $\frac{1}{2}^-[541]$, backbending cannot occur on account of blocking.

The $h_{9/2}$ protons, as well as the $i_{13/2}$ neutrons, satisfy all the conditions necessary to give a two-quasiparticle band: (a) the angular momentum j has a high value, $j = \frac{9}{2}$; (b) the matrix element $\langle \Omega \pm 1 | j^{\pm} | \Omega \rangle$ has a mean value of 4.1 for $\beta = 0.3$; (c) only the low-Ω states are filled, i.e., the difference in energy between states near the Fermi surface connected by Coriolis matrix elements will be weak, and on the other hand these low-Ω states are the most important in the Coriolis interaction.

We therefore see that for the region studied the $h_{9/2}$ proton shell seems to play a role similar to that played by the $i_{13/2}$ neutron shell and thus actively participates in producing backbending.

[1]D. Ward, in Proceedings of the International Con-

ference on Reactions between Complex Nuclei, Nashville, Tennessee, 10–14 June 1974 (to be published).
[2]B. R. Mottelson and J. G. Valatin, Phys. Rev. Lett. 5, 511 (1960).
[3]F. S. Stephens and R. S. Simon, Nucl. Phys. A183, 257 (1972).
[4]E. Grosse, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. 31, 840 (1973).
[5]E. Grosse, F. S. Stephens, and R. M. Diamond, Phys. Rev. Lett. 32, 74 (1974).
[6]D. Barnéoud, C. Foin, A. Baudry, A. Gizon, and J. Valentin, Nucl. Phys. A154, 653 (1970).
[7]D. Barnéoud and C. Foin, to be published.
[8]C. Ekström, S. Ingelman, B. Wannberg, and I. L. Lamm, Phys. Lett. 39B, 199 (1972).
[9]B. J. Meijer, F. W. N. De Boer, and P. F. A. Goudsmit, Nucl. Phys. A204, 636 (1973).
[10]D. Barnéoud, C. Foin, A. Baudry, J. Gizon, A. Gizon, and J. Valentin, J. Phys. (Paris) 33, 15 (1972).
[11]C. Foin, D. Barnéoud, S. A. Hjorth, and R. Bethoux, Nucl. Phys. A199, 129 (1973).
[12]W. Klamra, S. A. Hjorth, J. Boutet, S. André, and D. Barnéoud, Nucl. Phys. A199, 81 (1973).
[13]H. Beuscher, W. F. Davidson, R. M. Lieder, and C. Mayer-Böricke, Phys. Lett. 40B, 449 (1972).
[14]R. M. Lieder, H. Beuscher, W. F. Davidson, A. Neskakis, and C. Mayer-Böricke, in *Proceedings of the International Conference on Nuclear Physics, Munich, Germany, 1973*, edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam, 1973), p. 188.

Proton-Proton Total Cross Section above 10^4 GeV: Can Cosmic Rays Give the Answer?

V. Barger* and F. Halzen*
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

and

T. K. Gaisser† and C. J. Noble
Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania 19081

and

G. B. Yodh†
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 24 June 1974)

From Glauber calculations of the absorption cross section of nucleons on air (σ_{abs}) we find that present extensive-air-shower data cannot resolve the question of the asymptotic energy behavior of the nucleon-nucleon total cross section [$\sigma_t(NN)$]. Relative differences between various asymptotic extrapolations for $\sigma_t(NN)$ are reduced by about a factor of 3 in σ_{abs} through the Glauber conversion. Novel techniques or conventional experiments with a better determination of electron and muon numbers in extensive air showers will be required in order to obtain useful information on proton-proton cross sections in the asymptotic region.

The discovery[1] of a rising proton-proton total cross section at the CERN intersecting storage rings generated a great deal of interest in the eventual asymptotic behavior. Although the CERN data may provide clues as to the asymptotic regime, measurements at higher energies are necessary to determine the ultimate trend. A wide range of theoretical speculations accounting for the CERN data give very different asymptotic extrapolations. The proposals for the rise of $\sigma_t(NN)$ include (i) a $\ln^2 s$ growth inferred from studies of massive quantum electrodynamics,[2] (ii) an empirical $\ln s$ growth from geometrical scaling with a logarithmically growing radius,[3] (iii) an asymptotic constant behavior from Regge-cut models,[4] (iv) a threshold behavior from particle production,[5] (v) an oscillating behavior from complex Regge poles associated with dynamical thresholds,[6] and (vi) asymptotically growing cross sections from s-[7] and t-channel[8] unitarity arguments. The wide divergence of high-energy expectations of $\sigma_t(NN)$ is illustrated in Fig. 1.

Until a new generation of accelerators is constructed the only hope of resolving the question of asymptotic growth lies with cosmic-ray experiments. Whereas new generations of accelerators and cosmic-ray techniques might eventually compete between 10^4 and 10^6 GeV, the 10^6–10^9 GeV energy range is exclusively accessible to extensive-air-shower (EAS) techniques. We address the