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SPECTROSCOPY IN A ROTATING DEFORMED NUCLEUS

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Abstract

Recent advances in the physics of nuclei at high spin are presented. In particular the new phenomena observed by the latest generation of γ-rays spectrometers are discussed. An overview of experimental and theoretical treatment of "backbending" effect, quasiparticle alignment and band crossing is described in more detail. The outlines of the Cranked Shell Model, which is a successfull framework for the interpretation of experimental data, are also reported.

* Presented by C.T. Papadopoulos

1. Introduction

In the past decade major advances have been achieved in the spectroscopic study of the nucleus due to the new generation of γ-ray spectrometers of high resolution[1] (4π-arrays of escape suppressed Ge-detectors) as well as to the high energy heavy ion beams to produce nuclei at high angular momentum by fusion-evaporation reactions. Thus the γ-ray spectroscopy has been extended to the study of nuclei in "extreme" conditions like the fast rotating nuclei, nuclei far from the β-stability line, nuclei at high-spin, super-deformed nuclei (a:b=2) and hyper-deformed nuclei (a:b=3).

The physics of a nucleus at high-spin is just ordinary nuclear physics. However, the nucleus under different conditions exhibits new interesting phenomena, as the "backbending" effect, the pair correlation, the band terminations etc. The Coriolis and centrifugal forces in these fast rotating and deformed nuclei play a decisive role in the derivation of these phenomena. Most of the experimental data on high spin spectroscopy refer to states near the yrast line, so in spite of the high energy of the nucleus the density of the levels is small and the nucleus is "cold".

2. Theoretical and experimental basis

The atomic nucleus is a many body quantum system with a finite number of strongly interacting fermions. The contribution of the pair correlation between the fermions, gives rise to the superfluid liquid drop behaviour of the nucleus. Gross properties of the nucleus, as mass and binding energy, are well reproduced by this liquid drop concept. The strong interaction between the nucleons is thus weak enough to allow them to behave as independent particles, but sufficiently strong to allow a finite number of valence nucleons to influence the nuclear shape. So, deformed nuclei can be generated by a few nucleons moving outside of closed shells and occupying anisotropic orbits.

Independent particle motion can be treated by a number of approximations to the nuclear potential. The most important of them are illustrated in Fig. 1 (taken from ref. 2). The spectrum of energy levels corresponding to independent particle motion, becomes increasingly complex by introducing more realistic approximations to the nuclear potential.

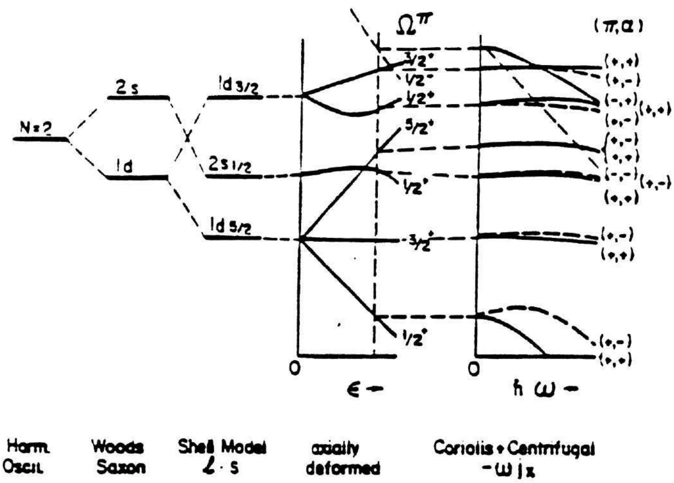

Fig. 1. *The spectrum of $N = 2$ (or s-d) shell independent particle states in a variety of potentials describing the nucleus.*

In the single-particle levels of the deformed harmonic oscillator large gaps appear causing extra stability as the quadrupole deformation ϵ of the nucleus gets bigger. In addition the Coriolis and centrifugal forces acting when a deformed nucleus is rotated, split the two-fold degeneracy of the Nilsson levels. The resulting energy levels are labeled by the conserved quantum numbers parity (π = + or -) and signature (α = +1/2 or -1/2).

According to the suggestions of ref. 3 a pair of nucleons in a high j - orbital can be broken and aligned along the axis of rotation, causing the well known "backbend" in the energy sequence of rotational γ-rays. This alignment occurs at rotational frequencies where the Coriolis force is sufficient to overcome the pairing force.

The effect of Coriolis and centrifugal forces to the spectrum of energy levels is strongest on the highly-alignable high-j, low-Ω orbitals, lowering them to the Fermi-level from shells normally much higher in energy (intruder orbitals). The form of the nuclear potential can thus strongly influence the independent particle energy spectrum giving rise to new shells and new phenomena and driving the nucleus to extreme deformations where they can be stabilized by the nuclear rotation.

The aim of the high-spin spectroscopy is to provide information concerning the correlation between the macroscopic parameters (size, shape, surface diffuseness, pairing energy, moment of inertia, rotational frequency etc) and the microscopic configuration (proton and neutron numbers, fermi energy, particle configuration etc). This entails investigation of detailed properties of discrete energy levels of nuclei, such as excitation energy, spin, magnetic dipole moment, electric quadrupole moment etc.

3. Backbend and particle alignments

When a deformed nucleus with moment of inertia $\Im$, is rotated with a frequency ω (Fig. 2) the rotational energy is classically $E_R = 1/2\Im\omega^2$ and quantum mechanically $E_R = (\hbar^2/2J)\ I_R(I_R+1)$, as the rotational angular momentum is $I_R^2 = J^2\omega^2$. Hence E2 electric quadrupole transitions between two rotational states ($I_R \rightarrow I_R-2$) with $\Delta I_R = 2$ will have a photon energy $E_\gamma = (\hbar^2/J)\,(2I_R-1)$. Thus the energies of the γ-rays are approximatelly $E_\gamma \simeq (2\hbar/J)\ I_R \simeq 2\hbar\omega$ and will increase linearly with the rotational component of the angular momentum and with rotational frequency.

As an example, the spectrum of γ-rays from the yrast states in the nucleus ^{158}Er[1]) is shown in Fig. 3. It can be seen that initially E_γ increases with spin up to I=12$^+$. However, the energy of the γ-rays transitions starts to decrease up to spin 16$^+$ and then increases again, thus producing the well known "backbend". As suggested in ref. 3) the Coriolis force $\vec{F}_c \sim \vec{v} \times \vec{\omega}$

acting on a pair of nucleons in the highest j orbital tends to separate them (see Fig. 4).

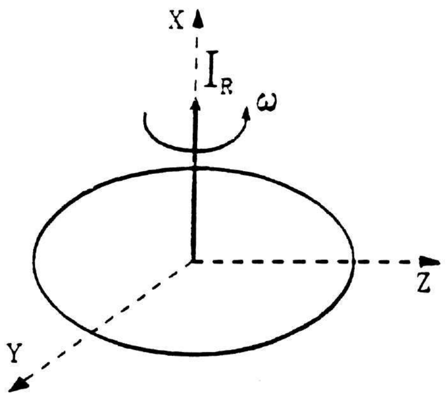

Fig. 2

As the nucleus rotates faster, the Coriolis force becomes sufficient (of the order of 0.5 MeV) to overcome the pairing correlation energy ($\Delta \sim$ 1MeV) and the pair is broken. The two nucleons align their angular momentum j_x with the axis x of rotation so that the total angular momentum $I = I_R + j_x$ and the rotational angular momentum I_R then decreases. This in turn lowers the γ-ray energy between states as well as the rotational frequency ω, producing the "backbend" in γ-ray spectra seen in Fig. 3. In ^{158}Er, at I = 12^+ an alignment of a pair of $i_{13/2}$ neutrons takes place. Then, as it can be seen from Fig. 3, another backbend is observed at about I = 28^+, which can be attributed to the alignment of a pair of $h_{11/2}$ protons. Between spins 38^+ and 40^+ the nucleus becomes energetically favourable to change its shape from prolate to oblate. There is another sudden decrease in the γ-ray energy at 40^+ as all the four valence protons align and finally all the valence nucleons are aligned at spin 46^+.

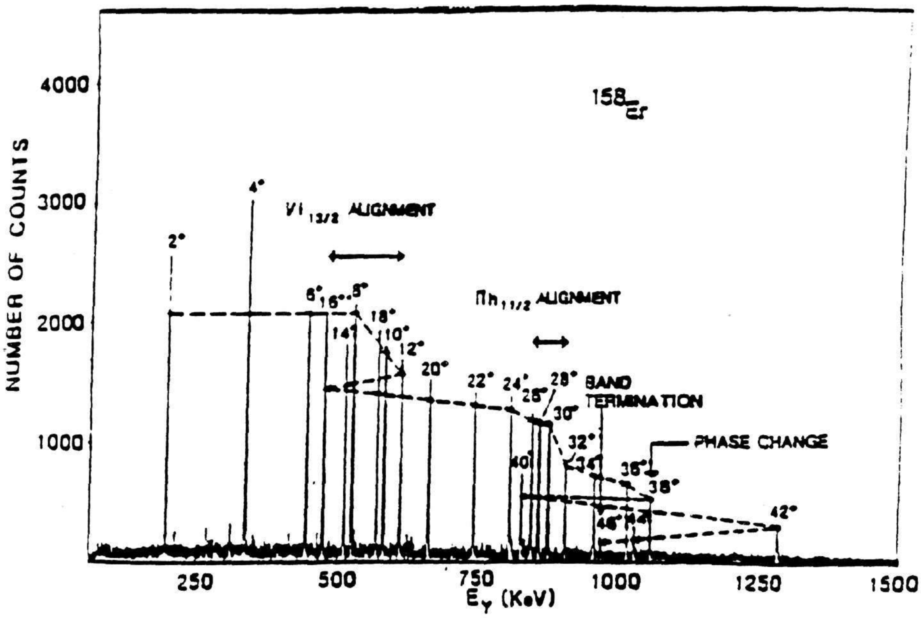

Fig. 3. *Spectrum of yrast γ-rays in ^{158}Er up to spin 46. The alignment of a pair of $i_{13/2}$ neutrons and of $h_{11/2}$ protons, the prolate to oblate phase change and the band termination are indicated. The figure is taken from ref.*[1]*).*

Appart from the γ-ray spectra, the backbending effect can also be illustrated in the plots of the total angular momentum I_z or the moment of inertia $\Im$ with respect to the rotational frequency ω.

It is apparent from the above discussion that the experimentally observed discontinuities in the rotating deformed nuclei are strongly related to excitations of intrinsic states of the nucleus.

4. The Cranked Shell Model

The theory of the alignment of quasiparticles in a deformed nucleus, as developed by Bengtsson and Frauendorf[4)], gave a particularly elegant and successful framework to interpret the experimental data. This, so called, Cranked

Sheil Model is based on the Hartree-Fock-Bogolyubov formalism which leads to the description of the rotating nucleus in terms of quasi-particles (which are mixtures of both particle and hole states) moving in a deformed uniformly rotating potential about the x-axis (z being the symmetry axis).

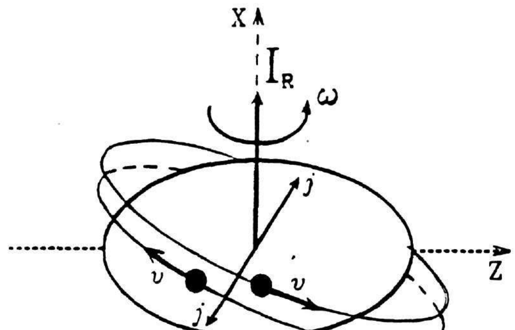

Fig. 4.

The properties of the nucleonic motion in a potential cranked about the intrinsic x-axis with a frequency of $\hbar\omega$ is obtained from the cranking hamiltonian, considered in the rotating frame $h' = h_{sp} - \omega j_x$, where h_{sp} is the single-particle hamiltonian in the laboratory frame and j_x is the component of the single particle angular momentum on the rotational x-axis. The term ωj_x represents the centrifugal and Coriolis forces acting on the nucleon. The eigen values $e' = e_{sp} - \omega j_x$ of h' are referred to as the single particle energies in the rotating system or the "routhians". The rotational alignment of a single particle is given by:

$$i = -\frac{d\epsilon'}{d\omega} \qquad (1)$$

For heavier nuclei, where the pairing correlation energy Δ is larger than

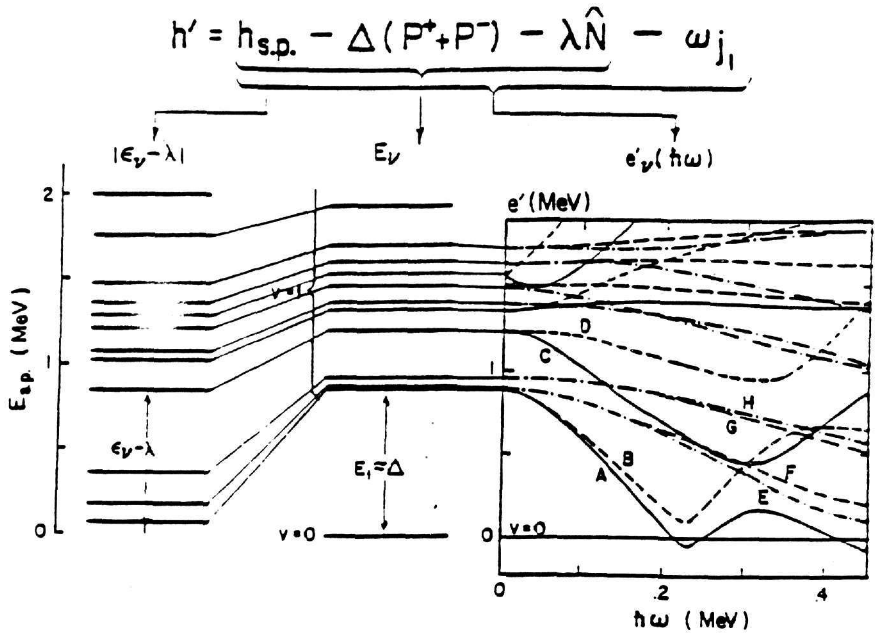

Fig. 5. *Spectra of Nilsson states (left), quasiparticle energies, $E\nu$, for the Nilsson model plus pairing (center), and routhians, e', as a function of $\hbar\omega$ (right) indicating the effects of pairing and rotation on independent-particle motion in a deformed potential. The hamiltonian for independent-particle motion in a rotating deformed potential is given at the top of the figure, and the various terms associated with each predicted spectrum are indicated. These spectra were calculated assuming $e_2 = 0.242$, $e_4 = \gamma = 0.0$ and $\Delta_n = 0.87$ MeV and are appropriate for the $\nu = 1$ quasineutron spectra of ^{165}Yb. The figure is taken from ref. 2.*

the average spacing of the independent particle states, it is necessary to include the effects of pairing expiicity in the hamiltonian

$$h' = hsp - \lambda N - \Delta(p^{+} + p^{-}) - \omega j_z \ , \qquad (2)$$

where p^+ and p^- are the two particle creation and annihilation operators, N' is the particle number operator (eigenvalue N for particle states and -N for hole states) and λ is the chemical potential (represents the average Fermi level corresponding to the appropriate particle number).

Fig. 5 illustrates the effects of pairing and rotation on independent-particle motion in a deformed potential. The right part of the figure demonstrates the routhians e', eigen values of the cranked hamiltonian h' of eq. (2), as a function of $\hbar\omega$. The style of lines and the letter labels indicate the parity and signature of the quasi-particle trajectories as described in Table I

Table I

Letter labels and corresponding Parity-Signature labels used to identify the one-quasiparticle routhians

Letter label	Parity - signature label neutrons	protons
A	(+, +1/2)	(-, -1/2)
B	(+, -1/2)	(-, +1/2)
C	(+, +1/2)	(-, -1/2)
D	(+, -1/2)	(-, +1/2)
E	(-, +1/2)	(+, -1/2)
F	(-, -1/2)	(+, +1/2)

Only positive eigenvalues are plotted, since the information is repeated for negative e' due to the symmetry of HFB equations. Every configuration corresponding to a certain distribution of quasiparticles over the trajectories is associated with a rotational band. The ground-state band or g-band of the system corresponds to zero quasiparticle configuration (referred to as a quasiparticle vacuum state). Excitations of the system above the quasiparticle vacuum-state energy in the rotating coordinate frame are constructed by placing one or more quasiparticles into unoccupied states of positive eigenvalues leaving the conjugate state free. Different bands can cross at certain rotational frequencies called crossing frequencies. The band crossing is strongly related to the characteristic multivalued behaviour exhibited by the angular momentum and the moment of inertia, the so called "backbending effect". The first excited rotational band crossed with the ground state band is called the "Stockholm" or S band.

It is apparent from fig. 5 that the levels with the highest slopes, such as levels A and B, play an important role in the behaviour of the rotating system, as they are easiest to align (see eq. (1)). The abrupt change in the slope corresponds to a rapid increase in nuclear alignment and therefore to a backbending.

For example, the slopes of curves A and B change sign at a rotational frequency $\omega \simeq 0.23$ MeV and the vacuum contribution to the total angular momentum increases by the amount given by the change in slope according to eq. (1). Moreover the total excitation of the S-Band (defined by levels A and B occupied by quasiparticles) equals $e_A^{'\omega_c} + e_B^{'\omega_c} \simeq 0$ and thus the S-band crosses the ground-state band at ω_c, becoming yrast (AB crossing). For an odd-nucleon system the odd particle occupies the lowest level, for example level A in fig. 5, while level B is empty. It then follows from the properties of HFB solutions that the conjugate state (which is not shown in fig. 5) -A is empty, while -B is occupied. Thus the gain of alignment coming from the change in slope of -B is compensated exactly by the loss in level A, producing no jump in angular momentum and consequently no backbending. This effect is referred to as "blocking" of the backbending on the yrast line by the odd nucleon.

5. Analysis of experimental data

In order to study the single-particle motion in a rotating system it is necessary to separate the energies associated with the single particle motion and the collective rotation. Further, in order to compare the experimental data with the cranked shell model, the experimentally observed excitation energies E and angular momentum I must be transformed into the equivalent quantities in the rotating frame, the routians E' and the angular frequency ω.

The angular frequency of a rotation about the x-axis at the discrete intermediate spin value I is obtained from the observed energy difference between two adjacent members of the rotational band by means of the relationship:

$$\omega(I) = \frac{E(I+1) - E(I-1)}{I_x(I+1) - I_x(I-1)} \simeq E_\gamma/2$$

where $I_x(I)$ represents the projection of the total angular momentum on the rotational axis and can be obtained from the total angular momentum I and its projection on the symmetry axis K according to the expression:

$$I_x = \sqrt{(I+\hbar/2)^2 - K^2}$$

The energy in the rotating frame, i.e. the routhian $E'(I)$, is defined for the transition $I+1 \rightarrow I-1$ as follows:

$$E'(I) = \frac{1}{2}[E(I+1) + E(I-1)] - \omega(I)I_x(I)$$

The routhians $E'(I)$ contain the energy associated with both the collective rotation and the quasiparticle excitation. Further, the angular momentum I_x also contains both the rotational and quasiparticle contributions. However, in the analysis by means of the independent quasiparticles only the excitation spectra rather than the absolute energies are of interest. So it is necessary to isolate the quasiparticle routhians e' and the quasiparticle alignment i from those associated with the collective rotation. This is achieved by referring the experimental routhians and alignments to a reference configuration. Usually the ground state of the even-even nucleus is chosen as such a reference since it contains no quasiparticle excitations. The moment of inertia of the reference configuration is often parametrized according to the Harris formula [5]:

$$J = J_0 + J_1\omega^2$$

The reference energy E_g and the reference projection of the angular momentum on the rotation axis I_{xg} are given by:

$$E_g(\omega) = -\frac{1}{2}\omega^2\Im_0 - \frac{1}{4}\omega^4\Im_1 + \frac{1}{8}\frac{\hbar^2}{\Im_0}$$

and

$$I_{xg}(\omega) = (\Im_0 + \omega^2\Im_1)\omega$$

The quasiparticle routhians and alignments are therefore given by:

$$e' = E' - E_g \; ,$$

$$i = I_x - I_{xg} \; .$$

This article reviews some of the new physics that has been revealed in the structure of nuclei by the latest generation of γ-ray spectrometer arrays. The subjects presented here are closely related to the experimental work undertaken at Daresbury Laboratory in an extented scientific collaboration between 9 European laboratories financially supported by the EEC (ESSA-30 collaboration). The aim of this collaboration was the systematic study of fast rotating rare earth nuclei in the region of $A \sim 170$ at high spins. The Athens group, consisted of C.A. Kalfas, S. Kossionides and the authors, in collaboration with the Stockholm group undertook the study of the region of Re and Os isotopes[6,7]. A part of this work, the study of ^{173}Os will be presented in the next contribution by R. Vlastou. Our group has now been enlarged by including two more members, Dr. S. Harissopulos and Mr. N. Fotiades, and is still heavily involved in the high-spin γ-spectroscopy.

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