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1.2 Nuclei in Highly Excited States

1.2.1 High Spin States

Electromagnetic Properties of Nuclei at High Spins

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1. Introduction

A photon emitted by an excited state is likely to carry away, at most, 1 or 2$\hbar$ of angular momentum. Therefore, a profusion of photons is needed to deexcite the rapidly rotating states of nuclei formed by heavy-ion reactions. The study of electromagnetic properties has become the primary source of information on nuclear structure at high spins and, also, at the warm temperatures present in the initial stage of the electromagnetic cascade process. The purpose of this paper is a review of the E1, M1, and E2 properties of such highly excited states, in order to set the stage with theoretical props for the section on this topic in the present volume. This review does not aspire to completeness or a fair distribution of credit for past achievements, but does attempt to highlight the major current research topics in the field. A chart of these topics in the plane of energy versus angular momentum is given in Fig. 1. They involve both the properties of the rotating but "cold" states on or near the yrast line, which can be experimentally resolved as discrete states, and of the increasingly closely spaced levels at higher temperature. The former reveal the response of nuclear structure to rotation, and the latter provide unique insight into the transition of a quantum system from order to chaos.

2. Dipole Resonances.

2.1. E1 Giant Resonance

The vibration of protons against neutrons superposed on any nuclear state has a collective resonance, according to a famous hypothesis discovered by Axel in the thesis of BRINK [1]. Empirically the resonance on low-lying states occurs at $\hbar\omega \approx 78\ A^{-1/3}$ MeV, about 15 MeV in a medium heavy nucleus. Therefore, the resonances even on the ground-state and low-energy excited states occur in a region of high level density. The resonances become damped, or fragmented onto their many neighbors, and the E1 transition rates from all states at energies $U \gtrsim \hbar\omega$ are more or less enhanced by a share of the collectivity of the resonances.

The emission of gamma-rays at the energy of the E1 giant resonance in heavy-ion fusion-evaporation reactions is most likely to occur from the compound nucleus prior to any evaporation of particles. This follows from elementary statistical physics. Transition rates depend on the level density ρ at the initial and final states: $T \propto \rho\ (U_f)/\rho\ (U_i)$. According to the Fermi gas formula, ρ is the product of a relatively slowly varying factor with exp $(2\sqrt{aU})$, or equivalently exp $(2U/t)$ where the temperature $t = \sqrt{U/a}$. Inserting $U_i-U_f = 15$ MeV for the gamma ray and $U_i-U_f = 8 + 2t$ MeV for a neutron with binding energy 8 MeV, we get $T_\gamma/T_n \approx$ exp $(-14/t)$ which is a rapidly increasing function of temperature. Thus, when NEWTON et al. [2] observed a bump on the high-energy tail of the γ spectrum from ^{40}Ar induced fusion reactions, and were able to reproduce this bump in a statistical model calculation using the E1 strength function of the resonance on the ground state, they confirmed the Axel-Brink hypothesis for states of very high energy and angular momentum (Fig. 1).

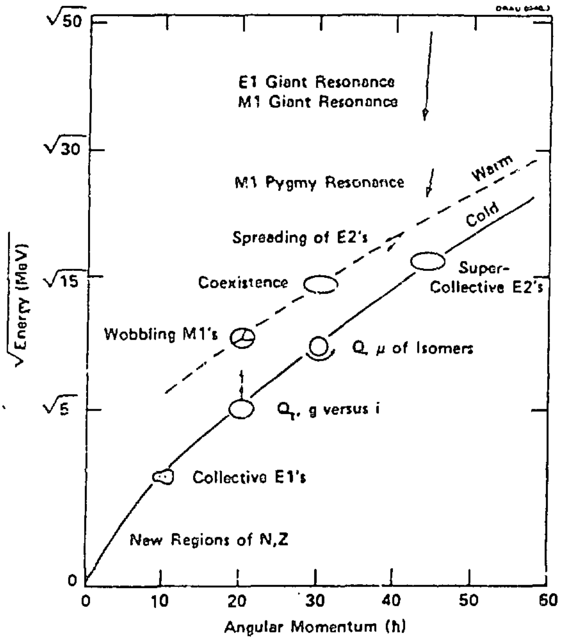

Fig. 1. Hot topics in warm and cold rotating nuclei

Continued interest in the E1 giant resonance rests on the fact that its shape is sensitive specifically to the shape of the nucleus. In a deformed nucleus there are several resonance frequencies, proportional to the reciprocal lengths along the principal axes. The angular momentum dependence has been investigated theoretically in the cranking model. It is found that at fixed shape there is little effect on either the centroid or the splitting of the resonance [3]. The inclusion of temperature in the calculations also has little effect. Even the damping width is unchanged at any rate on the RPA level of the theory [4]. Thus, there is the prospect of studying the shape of the giant E1 resonance to find out what happens to spherical and deformed shell structure at high spin and temperature [5]. A splitting into two peaks could be obtained for the "super-deformed" shapes that might occur at very high spins. Since the relative strength of the signal increases with temperature as discussed above, the E1 resonance might be used to probe the very existence of nuclei at extremely high temperatures. WONG [6] has suggested that rotating toroidal shapes might be favored under these conditions, and that the E1 resonance going around the torus would appear at an unmistakably low frequency.

2.2. M1 Resonances

It is not known whether M1 giant resonances play any role in the deexcitation of highly excited nuclei. It has been suggested, however, that a concentration of M1 transition strength in some energy interval can sometimes occur [7]. The resulting bump in the gamma spectrum should be observable when this energy lies above the energy of the yrast-like transitions. Such M1 pygmy resonances, to use the terminology of the corresponding phenomenon in β decay, are expected to arise when several of the strong M1 single-particle transitions near the Fermi level in the Nilsson scheme cluster around the same energy. In deformed nuclei this can happen for transitions of the type $[N\ n_Z\ \Lambda\ \Omega] \rightarrow [N\ n_Z{+}1\ \Lambda{-}1\ \Omega{-}1]$ or $[N\ n_Z\ \Lambda\ \Omega = \Lambda{-}1/2] \rightarrow [N\ n_Z\ \Lambda\ \Omega = \Lambda{+}1/2]$. Experimental evidence for dipole bumps at the appropriate energies have been obtained from a light-ion reaction leading to ^{161}Dy [8] and from a study of angular distributions following a (HI, xn) reaction leading to ^{158}Yb [9].

3. E2 Spreading Widths

When a nucleus formed by heavy-ion fusion has cooled down to a temperature of about 1/2 MeV, E2 transitions along collective rotational bands running roughly parallel to the yrast line are expected to become competitive with the dipole transitions [10,11]. Since there are many closely spaced interacting bands above the yrast line, the collective E2 strength from each initial state is probably spread over several final states, in analogy with the damping of the E1 giant resonance discussed above. The behavior of the spreading width will depend strongly on the nature of the mechanisms that contribute to it [12]. One estimate, based on the fluctuations of rotation-aligned particle angular momenta in the cranked harmonic oscillator model, gives a spreading width proportional to I^2/U [13], in other words, decreasing with increasing intrinsic excitation energy U contrary to what might be expected intuitively. An increase of the spreading width with increasing temperature, on the other hand, might result because the potential-energy-of-deformation surface generally becomes flatter with increasing temperature so that the interacting bands have a wider spread in moment of inertia [14].

Experimentally, it is clear that the upper limit on the E2 spreading width is about 1/2 MeV, since the spectra from rotational nuclei exhibit a quadrupole bump with a clear-cut edge that moves up in energy with increasing multiplicity and total energy of the cascades. The component of the average E2 strength function with a width less than some tens of keV must be rather small, of the order of 10%, because at best only weak ridge-valley structures are observed in E_γ-E_γ correlation plots [15]. Similar conclusions are obtained by looking at the change in the spectrum that comes from requiring a coincidence with some specified gamma ray energy E_γ [14,16]. The width of this narrow component is constant or slowly increasing with increasing E_γ, and its fraction of the total strength decreases, but both the width and the relative strength of the narrow component

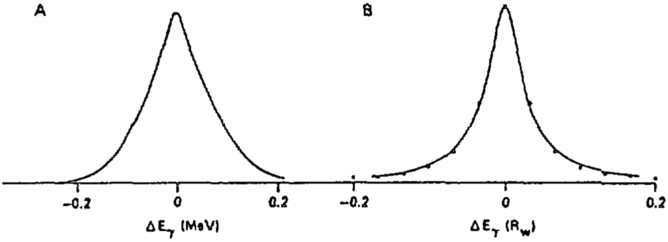

Fig. 2(A). A possible phenomenological E2 strength function obtained by superimposing a broad and a narrow Gaussian (see text). (B). An E2 strength function from the model of Ref. [12]. The dots show a Breit-Wigner line shape are insensitive to the total energy and multiplicity of the cascades. The evaluation of these experimental findings is still somewhat speculative. Figure 2A shows a phenomenological E2 strength function that might be suggested by the data. It consists of two Gaussians of width σ = 40 keV and 150 keV, respectively, with 10% of the strength in the narrow component. Figure 2B shows the strength function obtained from consecutive transitions using the model of interacting bands described in Ref. [12]. The distribution of B(E2; i → j) B(E2; j → k) is plotted versus the spread in energy, $(E_i - E_j) - (E_j - E_k)$. The result appears to follow a Breit-Wigner distribution, indicated by dots in Fig. 2A, which is the shape usually associated with damping. This result is obtained from the model even when the initial states i are constrained to be from the region where the level density increases rapidly with energy. The peaks of the distributions in Figs. 2A and B are quite similar, but the tails are radically different. Taking into account the factor E_γ^5 in transition rates, the bulk of all transitions would go deep into the low-energy tail of the Breit-Wigner like distribution, contrary to the empirical evidence. Before the aptness of any damping mechanism for the E2 spreading can be established, it will be necessary to resolve this difficulty.

4. Shape Coexistence

The coexistence of different nuclear shapes at high spins has long been predicted by theory; see, for example, the summary of the cranked Nilsson-Strutinsky model calculations by the Lund group during the years 1975-1980 in Ref. [17]. At the highest spins the increase of the bulk 'liquid drop' energy with increasing deformation is counteracted by a decrease of the bulk rotational energy; the potential energy surface becomes flatter, and shape-dependent shell closures over a wide region of deformation space come into play. It is becoming increasingly evident from experiment that a richness of structure stemming from coexisting shapes and symmetries of the nucleus does indeed occur and can be studied in the gamma-ray spectrum (e.g., the contributions of Sharpey-Schafer, Khoo and de Voigt to this volume).

With the existence of coexistence well established, new questions arise. Most importantly, what is the degree of order, as opposed to chaos, in the

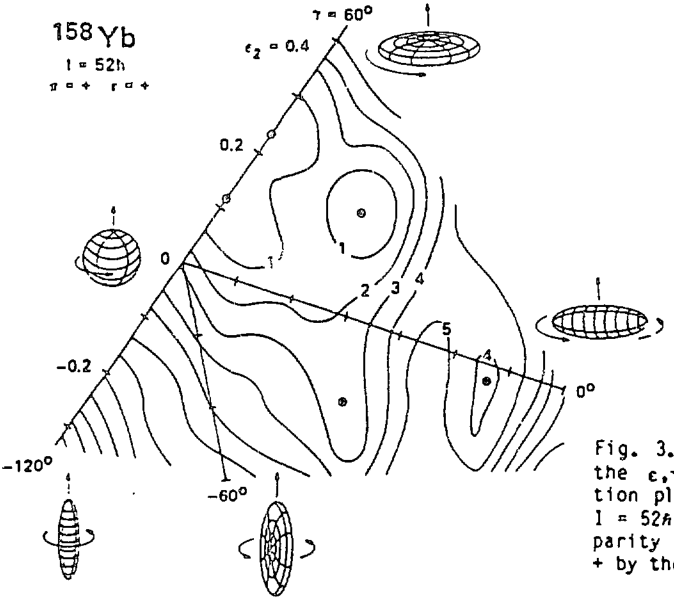

Fig. 3. Potential energy in the ϵ,γ quadrupole deformation plane for ^{158}Yb at spin I = 52ħ, calculated for total parity and signature π, r = +, + by the method of Ref. [19]

structure of the coexisting configurations? There is a hierarchy of quantum numbers which are present in the theoretical models, or at any rate imposed on them, which can be used to classify configurations and to calculate potential energy surfaces for the classes. At the extreme of internal chaos, there are the traditional potential-energy surfaces [17] and their extensions to finite temperature [18]. Various degrees of order were introduced in the calculations by T. BENGTSSON and RAGNARSSON [19]. For example, in Fig. 3 the total parity π and total signature r are conserved. The minima then tend to become more distinct, with higher potential barriers between them, than without these requirements. Slightly different surfaces are obtained for other combinations of π and r. The highest degree of order used by Bengtsson and Ragnarsson is conservation of the number of particles with each combination of π, r, N_r, τ, where π and r now refer to the single-particle parity and signature, N_r is the major oscillator quantum number in the rotating basis, and τ is isospin. Then, for example, superdeformed and weakly deformed minima do not appear in the same potential energy surfaces. At low spins the onset of pairing certainly scatters pairs of particles between the π, r, N_r groups, however, and allows different classes of bands to interact. Data like those recently obtained for the superdeformed band in ^{152}Dy and the onset of its electromagnetic decay into the weakly oblate configurations [20] are highly interesting in this context.

Some types of coexisting bands which should exist according to Fig. 3 have not yet been positively identified at high spins, namely, the well-deformed triaxial and oblate bands. Wobbling bands associated with triaxial configurations might be characterized by the M1 and E2 transitions "leaking" between such bands [21,22]. High-K bands associated with well-deformed oblate configurations could be characterized by $\Delta I = 1$ transitions.

5. Electromagnetic Moments of Discrete States

Structure theories of the more strongly populated yrast states can be tested by measuring their electromagnetic moments.

5.1. E2 Moments

One of the early predictions of the cranking model was the occurrence of high-spin isomers, with a shape made oblate by the ring-shaped orbits of the aligned high-j particles, in the regions of nuclei around A ~ 150 and ^{212}Po [23]. Measured electric quadrupole moments of the high-spin isomers in ^{147}Gd support this picture [24,25]. In the lead region, however, the issue has been clouded by a recent measurement for the 63/2$^-$ isomer of ^{211}Rn which gave no evidence for deformation [26]. In collectively rotating nuclei, the ring shaped orbits of aligned high-j particles in the S-band are expected to polarize the nuclear shape toward positive γ (c.f. Fig. 3), thereby reducing the collectivity of the rotation [27,28]. Evidence for this has been found in the in-band E2 transition moments, which are reduced above the backbend in nuclei around ^{158}Er [29]. The rotation-aligned high-j quasiparticles obtained when the Fermi level is nearer the middle of a high-j shell are expected to have other orbital shapes, however, and may even drive the γ deformation in the opposite direction so as to enhance the collectivity of the rotation [27,30]. Evidence for this has not yet been found. The nucleus ^{172}W would seem to be a relevant test case: the Fermi level lies higher in the neutron $i_{13/2}$ shell than for ^{160}Yb, and a cranking calculation predicts roughly constant E2 transition moments along the yrast line (the dashed curve in Fig. 4). A recent experiment on ^{172}W did give information about the high spin structure, but of an unexpected kind which has not yet been fully understood [31]. Namely, the measured E2 transition moments in Fig. 4 reveal a drop which is surprisingly sharp considering the smoothness of the upbend in ^{172}W, and closer analysis of the data establishes that the yrast upbend is due to a three-band crossing (cf. the inset in Fig. 4). Energy level systematics appear to link the mysterious third band to the proton $h_{9/2}$ shell, which would indeed have ring shaped aligned orbitals.

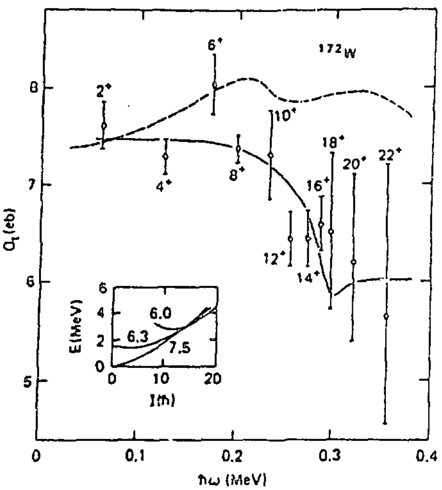

Fig. 4. Measured Q_t values [31] for yrast levels of ^{172}W. Mixing of the three unperturbed bands shown in the inset can reproduce the yrast energies. The unperturbed intrinsic quadrupole moments indicated (in eb) in the inset were obtained from the calculated change in γ deformation assuming first $(\pi h_{9/2})^2$ and then $(\nu i_{13/2})^2$ rotational alignment. The Q_t values that result from the mixing are shown by the solid curve

Overall, whereas earlier studies of deformed nuclei by Coulomb excitation had shown that rotor-like E2 moments could persist up to high spins (e.g. Ref. [32]), the recent lifetime measurements on neutron-deficient nuclei from Ce to W indicate a more consistent trend towards reduction of the E2 transition moments in the S-band than is expected from theory.

5.2. M1 Moments

Magnetic moments probe the microscopy of nuclear rotations. The magnetic g-factors in collective bands can indicate whether backbending phenomena are due to neutrons or protons [33]. Direct measurements on collective states have so far been carried out only for a couple of actinides [34], the quasicontinuum in a few rare-earth nuclei [35], and the nucleus ^{168}W which has a retarded yrast transition due to weak interaction at the backbend [36]. In $\Delta I = 1$ bands, indirect information on the M1 transition moments is more readily available from branching and mixing ratios. The signature splitting of the M1 transitions rates in such bands is highly sensitive to the triaxiality of the nuclear shape ([37] and references therein). The magnetic moments of high-spin isomers can put some constraints on their configurations. One interesting experiment that has not yet been made is to measure an M1 moment of a very high spin isomer together with the M1 transition moment of a rotational band built on that isomer.

5.3. E1 Transition Moments

In recent years, it has been established that some nuclei are characterized by reflection asymmetric intrinsic shapes [38]. With the reflection symmetry broken, the nucleus can sustain a collective intrinsic E1 moment. This E1 moment cannot be observed as a static moment in the laboratory frame due to parity conservation, but the E1 transition moment leads to enhanced E1 transitions within the parity-doubled rotational bands of such nuclei. Recently, several bands have been found where the E1 cascade transitions are competitive with the E2 cross-over transitions.

Early theoretical work had anticipated such bands. The assumption that the E1 moments could be estimated from the leading order term of the liquid drop model was not borne out by the data, however. This term is proportional to $\beta_2\beta_3$ so the B(E1)/B(E2) branching ratios would depend only on the effective value of $\beta_3{}^2$. The experimental data, however, exhibit a large variation of the B(E1)/B(E2) branching ratios over a sequence of Ra and Th isotopes (Fig. 5) whose equilibrium β_3 deformations are calculated to be quite similar. This behavior is

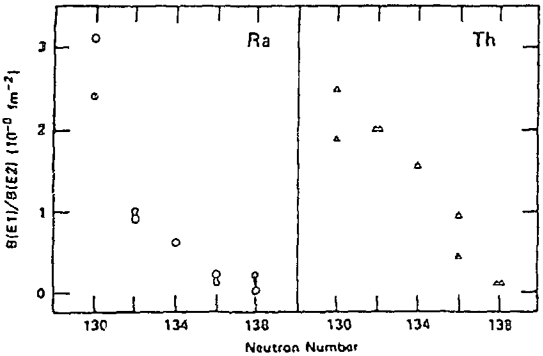

Fig. 5. B(E1)/B(E2) ratios at moderately high spins in the radium and light thorium isotopes, from experiment (solid symbols) and from a cranked shell model calculation [39] (open symbols). The theoretical value for ^{218}Ra is an average of the values at the prolate and oblate minima

explained by a strong shell effect on the E1 moment [39]. The center of gravity for both protons and neutrons in an octupole-deformed mean field is displaced toward the thick end of the "pear shape" near the spherical magic numbers, and toward the pointed end at mid-shell. Varying the neutron number while keeping the proton number fixed at an intermediate value relative to the shell closure, the shell correction to the E1 moment then changes sign. The B(E1)/B(E2) ratios are large for the lower neutron numbers because the shell correction and the liquid drop contribution have the same sign, and small for the higher neutron numbers because the two terms have opposite signs and cancel. Fig. 5 shows that there is quantitative agreement between the data and results from a cranked Woods-Saxon Bogolyubov Strutinsky model calculation of equilibrium deformations, including the isovector dipole deformation.

There are both experimental and theoretical indications that octupole deformation may occur at high spins in regions of nuclei where it does not occur at low spins [38-40]. The observation of two or more consecutive members of the $\Delta I = 1$ E1 cascade, as in ^{148,149,150}Sm and ^{146}Nd [41], provides strong evidence for such breaking of the reflection symmetry at high spins.

6. New Regions of Z and N. The electromagnetic properties of rotational states are helpful in studying the structure of nuclei far from stability. A single example of this will be given from the region of Z and N to be considered in another contribution to this volume. In the $Z \sim N \sim 36$ region, the search is on for a unique, strongly oblate band structure. These oblate bands were predicted a long time ago [42] to coexist with the strongly prolate bands that have since been observed in this region. Three 3/2⁻ bands are expected in the low-energy spectrum of ^{73}Kr: the prolate 3/2[312] and 3/2[301] bands, and the oblate 3/2[321] band. They could be distinguished by the cascade to cross over branching ratio from their 7/2⁻ band members, which would be 1:10, 2:1, and 8:1, respectively.

In conclusion, the study of electromagnetic properties in rotating nuclei has shed light on several new phenomena during the last few years, and rapid experimental progress is encouraging the theorists to ask new or more refined questions.

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