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THE ROLE OF M1 TRANSITIONS IN THE QUASICONTINUUM

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Abstract M1 transition rates are strongly structure dependent and may therefore reveal the structure in a quasicontinuum of nuclear excited states. The theoretical interpretations of low-energy stretched dipole bumps are briefly reviewed. Furthermore, it is suggested that there are higher-energy M1 bumps with a significant unstretched component, and that the related shell effects influence the cooling which feeds the yrast cascade.

I. INTRODUCTION

Recently, many quasicontinuum γ-ray spectra following (HI, xn) reactions have been found to contain low-energy dipole bumps which seem to be as sensitive to structure as the collective E2 bumps. A list of references is given in Ref. 1, recent measurements have been reported in Refs. 2,3 and in several contributions to this conference.[4-7] Most statistical dipole radiation is believed to be E1, but the available experimental and theoretical evidence seems to indicate M1 character for the non-statistical bumps. There are many suggestions about the nature of the structure that could give rise to low-energy M1 bumps and some theoretical calculations have been made for comparison with the data.

These are briefly reviewed in section 3, following a discussion in section 2 on how to extract quasicontinuum spectra from structure models. Calculations presented in section 3 suggest the possibility of hitherto unobserved M1 bumps, not so low in energy, and section 4 shows how the structure mechanism underlying these bumps could also lead to shell effects in the cooling process down to the yrast line.

II. PROBABILITY SPECTRA

The obvious way to construct a spectrum from a structure model is to simulate the gamma cascade by Monte Carlo or master-equation techniques, as was done for example in Refs. 8 and 9, respectively. However, in theoretical work which aims to explore models rather than to reproduce specific experiments it can be more instructive to use a schematic but straightforward and standardized procedure. A probability spectrum is defined for this purpose as[1,10]

$$I(E_\gamma) = \sum_i P_i \sum_f \sum_{O\lambda} \alpha(O\lambda;i\to f)\ \delta(E\gamma = E_i - E_f)$$

where the sums run over all initial states i, final states f and electromagnetic decay modes Oλ. Here $\alpha(O\lambda;\ i\to f)$ is the fraction of the total transition rate out of initial state i which is contributed by the Oλ mode going to final state f. This quantity and the transition energies E_γ are fixed by the model, but the population P_i of the initial states i must be assigned ad hoc.

In order to see what realistic population distributions might look like we have carried out Monte Carlo calculations[8,11] based on the supposedly realistic level densities of the statistical model. It turns out that the population per level decreases exponentially as a function of the excitation energy above the yrast line, but near yrast this decrease is more than compensated by an increase of the level density. The resulting population per energy interval is rather evenly distributed over an energy range above yrast whose width depends on the competition between collective and statistical transitions. In spectroscopic models based on diagonalization of a finite Hamiltonian matrix the level density does not increase with energy in a realistic way. Therefore, an exponential damping of P_i would place too much intensity in the lowest bands, and we use P_i constant up to some cutoff to get a realistic distribution per energy interval. In the calculated results presented below, this cutoff is set at 4 MeV. When the probability spectrum from such a simple distribution is known and understood, it is straight-forward to estimate what the modifications might be for a specific reaction.

III. M1 BUMPS BELOW THE COLLECTIVE E2 BUMP

An M1 bump can come from $\Delta I = 1$ rotational bands or the wobbling motion of a triaxial rotor.[12] Phenomenological models using adjustable parameters have been based on these two mechanisms, separately.[13-15] More microscopic calculations have produced a richer variety of sources of M1 radiation.

High-j shells are found to be generally important[10,16] because selection rules strongly favor low-energy M1 transitions, between rotational one-quasiparticle states, regardless of whether the particle is strong-coupled, decoupled or in some intermediate coupling situation relative to the core.

Inclusive probability spectra have been calculated in the cranked modified oscillator model with the inclusion of pairing.[10] These calculations consider the competition between the allowed branches of M1 decay, taking into account the effect of a collective rotational energy contribution $\pm\hbar\omega$ to the stretched transitions. The competition from in-band collective E2 transitions is also considered and found to be dominant at high spins in the collective regime. Only one-quasiparticle states are considered, which is qualitatitively justified since 'spectator' quasi-particles sometimes enhance in-band M1 rates (c.f. the classical model presented by Frauendorf in this volume) but the extra intensity is taken away again by high-energy transitions that reduce the quasi-particle number.[1]

Fig. 1 shows results of such a calculation for three

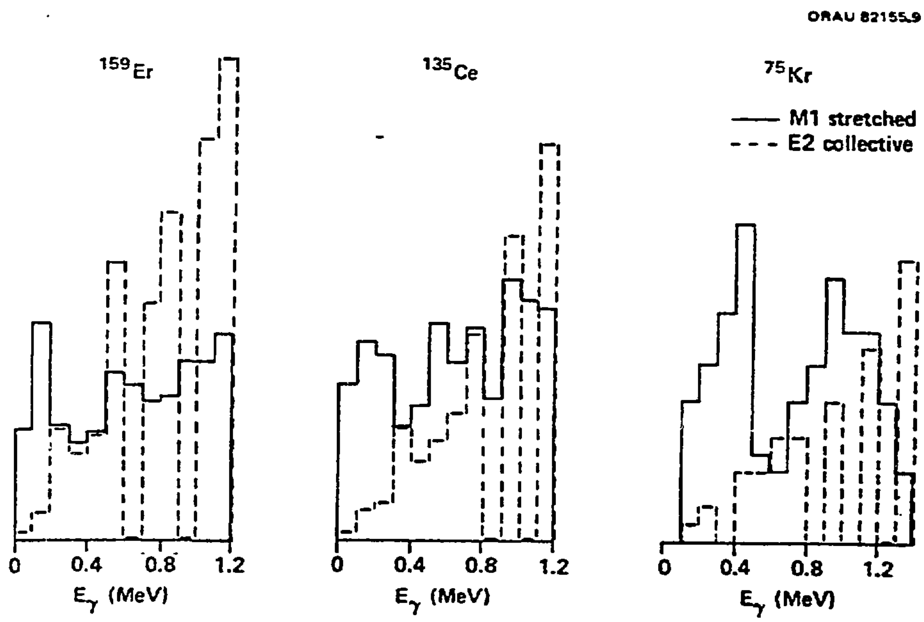

FIGURE 1. Gamma-ray probability spectra calculated with the cranking model for nuclei in different mass regions.

nuclei in different mass regions. The deformation is assumed to be prolate, ε = 0.22, 0.22 and 0.25, respectively. The stretched M1 component comes out larger than the stretched E2 component up to $E_\gamma \sim 500$ keV in ^{159}Er, 800 keV in ^{135}Ce and 1200 keV in ^{75}Kr. This turning point can also be obtained from experimental spectra taken at 90° and 0°. Agreement was found earlier between theory[10] and experiment[14] in Yb, and the present value for neighbouring ^{159}Er is quite similar. The larger ^{135}Ce value agrees with a more recent measurement.[17] It would be interesting to see an experimental result in the lightest mass region.

Probability spectra from the particle-rotor model[1] have on the whole confirmed the cranking results. Calculations for sequences of isotopes and isotones have also shown the trends in going from near-closed shell to well-deformed nuclei. An additional source of M1's emerged, namely the deexcitation of the γ mode in the presence of quasiparticles.

In microscopic models the yrast states are sometimes of aligned single-particle type, connected mainly by 'statistical' dipole transitions which give rise to a broad dipole bump. Such a bump can be simulated by statistical cascade calculations.[18,19] A related mechanism for a narrow dipole bump instead at very high spins has been found in cranking calculations[20] where the deformation is allowed to change selfconsistently within each band, instead of being held fixed as in Ref. 10. A change in the direction of the aligned single-particle limit reduces the E2 collectivity. The M1 branch becomes predominant near the top of such bands if $\Delta I = 1$.

IV. M1 BUMPS ABOVE THE COLLECTIVE E2 BUMP

The one-quasiparticle probability spectra often exhibit M1 bumps at 2 MeV or more - see for example the cranking model spectrum for ^{173}Yb in Fig. 2. These bumps are not expected to be so high in a realistic spectrum, since the one-quasiparticle states above 2 MeV are embedded in a high density of many-quasiparticle states. Nevertheless, since they lie beyond the lower M1 bumps and beyond the collective E2 bump, but far below the giant dipole bump, it is possible that these intermediate M1 bumps could be discerned against the statistical background.

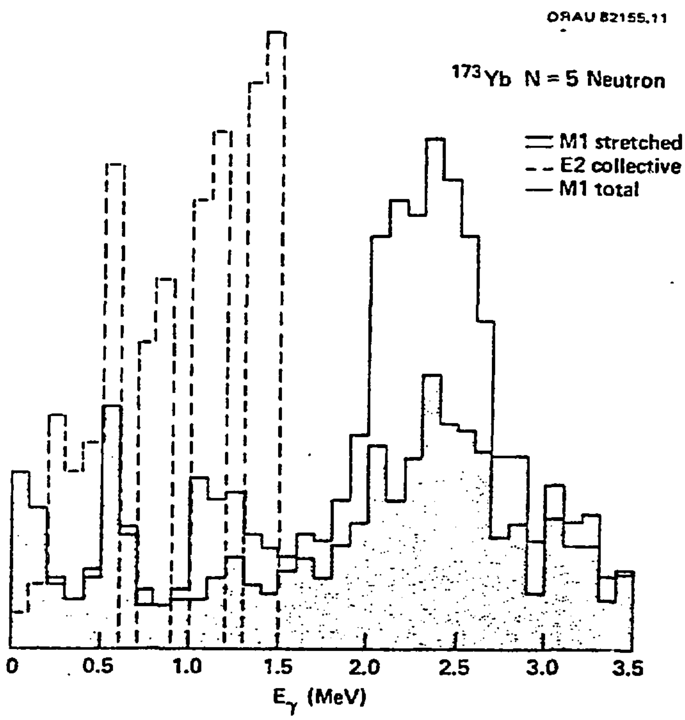

FIGURE 2. Contributions from different types of γ transitions to the probability spectrum for ^{173}Yb.

The structure mechanism is illustrated for N = 6 in Fig. 3. The 2-2.5 MeV bump in ^{173}Yb comes mainly from the neutron N = 5 shell, with large contributions from [503 7/2] → [512 5/2], [503 7/2] → [523 5/2], [514 9/2] → [505 11/2], and [512 3/2] → [521 1/2].

A notable feature of the 2-2.5 MeV bump in Figure 2 is the large fraction of unstretched M1 transitions. Thus transitions between quasiparticle states of the same signa-

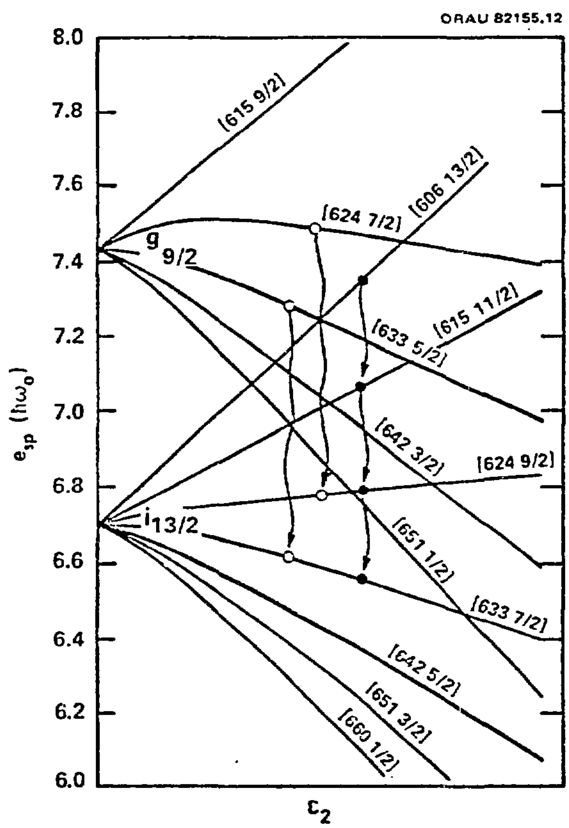

FIGURE 3. Large M1 single-particle matrix elements between levels well separated in energy. The ones between filled circles come from the orbital angular momentum part of the M1 operator. They are allowed by the selection rules of both the spherical and deformed representation.[12] The ones between open circles are allowed between the deformed states, where they correspond to an intrinsic spin flip.

ture do occur in this energy range, although they do not contribute significantly to lower-energy parts of the spectrum. The reason, if the final states lie in a band with small signature splitting, is that the collective rotational energy $\hbar\omega$ does not favor the stretched branch so much if $\hbar\omega$ is small compared to the total transition energy. In these cases the reduced B(M1) matrix elements are often about equal going to both signatures, and the branching is about equal. In a decoupled system of levels the mechanism is that the competing stretched transitions to lower spin are hindered by strong M1 selection rules.[16]

An experimental search for M1 bumps at higher energy therefore cannot require an angular distribution characteristic of stretched dipoles, though this has been used to identify the lower-energy M1 bumps.

V. NON-STATISTICAL COOLING BY M1 TRANSITIONS

The cooling rate is intended to measure, in some average sense, the amount of excitation energy above yrast which is radiated off, not per time unit but per gamma transition or multiplicity unit. The only measurable consequence of cooling at present is the intensity of discrete yrast transitions, but using devices like the spin spectrometer[7,21] it may become possible to measure the temperature at different stages of the gamma-ray cascade in more direct ways. Our present understanding of the cooling process in the gamma-cascade region is based on a theory of competition between statistical and in-band collective E2 transitions.[8,11,22-24]

The aim of this section is to point out shell effects in the cooling due to M1 transitions. The quantity studied below is a 1-quasiparticle cooling rate defined as

$$C_i = \sum_f (E_i^{qp} - E_f^{qp})\ \alpha(i \to f)\ /\ (E_i^{qp} - E_{yrast}^{qp})$$

for an initial state i of the active quasiparticle. Here $\alpha(i \to f)$ is the branching ratio to the possible final states f, E^{qp} is the quasiparticle energy in the rotating frame at frequency ω and $E^{qp}{}_{yrast}$ refers to the lowest quasiparticle state. The numerator is the average change in the excitation energy above yrast due to one gamma transition. Thus C_i expresses the fraction of the initial excitation energy which is lost on the average, a number less than or equal to unity. The cooling is zero for collective E2 transitions, due to the factor $(E_i{}^{qp} - E_f{}^{qp})$. It is negative for stretched M1 transitions of energy less than $\hbar\omega$, which heat the nucleus. An average cooling rate, $C(E^*,\omega)$ is defined as a function of the rotational frequency, ω, and the excitation energy above yrast, E^*, by taking an average of C_i for all the initial states i on 0.5 MeV intervals of E^*. It may be noted that (i) this definition of the cooling rate is not the same as in Ref. 10, (ii) it is a cooling rate for one active quasiparticle, connected but not identical with the cooling rate of the nucleus.

Fig. 4 shows cranking model results for ^{159}Er. Separate contour plots of $C(E^*,\omega)$ are shown for the neutron N = 5 and neutron N = 6 families of one-quasiparticle states, in order to exhibit the difference that comes from having the Fermi level at the middle of a shell or at the bottom, respectively. Some features are common to both cases. The cooling rate decreases with increasing ω due to the increasing slope of the yrast line, which favors collective E2 transitions and also allows more heating transitions to occur. A ridge of maximum cooling runs diagonally across

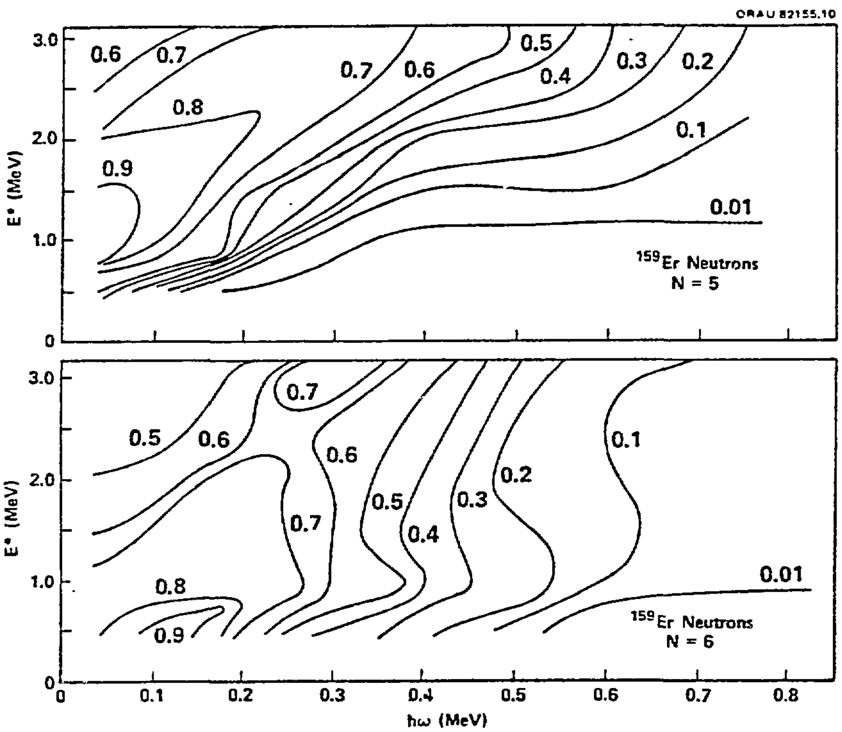

FIGURE 4. Cooling rate calculated with a Fermi level corresponding to ^{159}Er for neutron one-quasiparticle states in the N = 5 and N = 6 shells.

the plot, because the signature splitting between orbitals connected by strong M1 transitions is proportional to the frequency ω. However, differences between the N = 5 and N = 6 case occur at high rotational frequencies due to the structure of the orbitals near the Fermi level. The N = 6 orbitals near yrast are rotation-aligned, leading to a large signature splitting and efficient cooling near yrast. The higher-lying high-K orbitals lead to small signature splitting and less efficient cooling high above yrast. The situation is reversed for N = 5, where orbitals with large signature splitting lie further from the Fermi level. Thus the cooling for N = 5 is suppressed near yrast. It is more efficient high above yrast because there are high-lying orbitals with large M1 matrix elements to the low-lying orbitals (c.f. section IV).

Experimentally, nuclei whose yrast bands have a large amount of single-particle alignment are populated to the highest spins. This is probably partly due to the large cooling rate of the states just above yrast, corresponding to the lower case in Fig. 4.

VI. SUMMARY AND CONCLUSIONS

Theoretical calculations suggest a variety of structure mechanisms for low-energy M1 bumps in the quasicontinuum. They can be tested experimentally by systematic measurements. It is suggested that M1 bumps might also exist in the range of $E_\gamma \sim 2$-3 MeV, though with a large fraction of $\Delta I = 0$ transitions which would make it difficult to recognize such bumps by their angular distributions. The cooling contribution from M1 transitions is also sensitive to shell effects.

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