Tandem-Alpi proposal: **88Mo-GARFIELD**

TEMPERATURE EVOLUTION OF THE GDR WIDTH AND JACOBI SHAPE TRANSITION IN HOT ROTATING ^{88}Mo NUCLEI

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ABSTRACT

We propose to investigate the charged particle and GDR decay of hot and rotating ^{88}Mo, formed in the reaction with ^{48}Ti beam and ^{40}Ca target, using the GARFIELD and HECTOR detector arrays. The primary goal of the proposal is to measure the temperature evolution of GDR width, in the temperature range 3 - 4.5 MeV. The secondary aim is to try to observe the expected Jacobi shape transition, in this nucleus, using either the long chain of emitted α-particles or, as a test of feasibility, fission fragments as the trigger. The total request of beam time is 12 days (not including tuning of ALPI). A 1-2 pnA pulsed beam with a resolution of 1 ns and a repetition time of 200 ns is required. Target, ^{40}Ca, will be 0.5 mg/cm^2 thick.

1. Motivation

The study of the properties of the giant dipole resonance (GDR) at high temperature and angular momentum is one of the central topics in nuclear structure as it provides insight into the behavior of nuclei under extreme conditions. The wealth of experimental data on this subject covers in most cases an interval of temperatures up to 2.5 MeV and is mainly based on the study of the GDR gamma-decay from fusion-evaporation reactions. These data have been shown to provide an important testing ground for the theoretical models. In particular, the change of the GDR width with angular momentum and temperature reflects the role played by quantal and thermal fluctuations in the damping of the giant vibrations [1–7]. While, in general, the experimental results at T < 2 MeV are rather well understood within the thermal fluctuation model [8], at a temperature higher than 2.0 MeV the situation is more complex.

Our recent work, based on the results from the GARFIELD + HECTOR experiment in Legnaro [10], shed some light on the A=130 mass region in temperature interval T=2-4 MeV using a symmetric reaction ^{64}Ni + ^{68}Zn leading to ^{132}Ce.

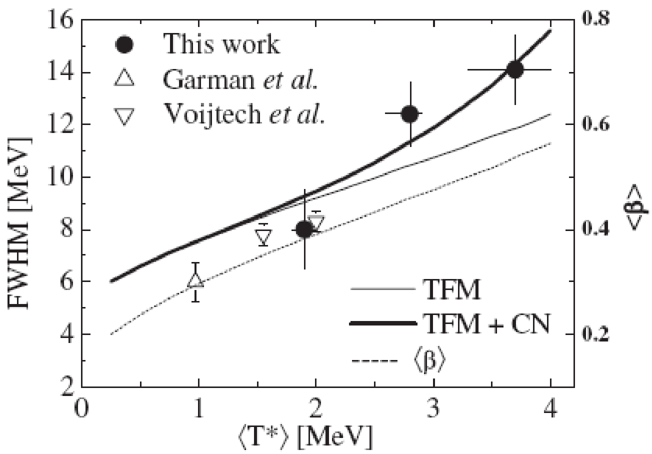

Fig.1. GDR width (experimental and calculated) for A ≈ 130 nuclei as a function of temperature. See [10] for details.

The main results of this paper were that the GDR width for the mass A≈130 nuclei does not saturate, as suggested earlier [11-15], at least up to 4 MeV, and that the larger values of the GDR width at high temperatures, as those from the standard thermal shape fluctuation model, can be related to the compound nucleus lifetime [16]. Additionally it was shown, that pre-equilibrium emission, that could change the temperature of the compound nucleus, is almost negligible (at studied excitation energies) for mass symmetric entrance channel, but it has large effect in mass asymmetric reactions.

It would be interesting to study the temperature dependence of the GDR width also in different mass regions and up to higher temperatures (4-6 MeV), as this might also have implication on understanding the onset of multifragmentation.

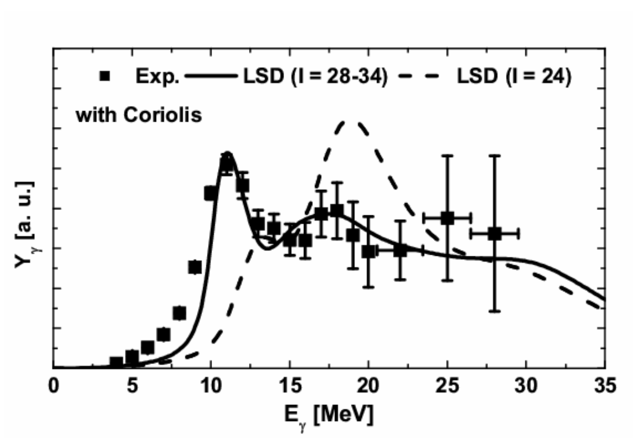

Fig. 2. Experimental (points) GDR strength function for ^{46}Ti compared to the LSD model predictions for the Jacobi spin window (28<I<34) and for the oblate regime (I=24). See [18] for details.

Another challenging aspect of hot nuclei is the study of so called Jacobi shape transitions. From the point of view of the liquid drop models, the shape of hot atomic nuclei is predicted to change under stress of rotation and the shape evolution pattern depends among others on the mass. With increasing angular momentum, heavy nuclei with A>160 change their equilibrium shape from spherical to oblate, the size of the oblate deformation increases and at certain angular momentum the nucleus undergoes fission. Very heavy nuclei, as ^{216}Rn, do not even evolve with spin via oblate shapes - they retain near-spherical shape almost up to the scission limit. This behavior was found in our recent work from the isomer tagged HECTOR experiment in LNL [6]. In contrast, lighter nuclei with A<<160, besides this standard evolution, are expected to exhibit more exotic behavior – *the Jacobi shape transition.* This phenomenon is predicted as an abrupt change of an oblate shape at the so called critical value of spin. Above that critical spin, the nucleus follows a series of triaxial, more and more elongated shapes, and finally undergoes scission. So far the signature of the Jacobi shape transition in hot nuclei was seen only in light nuclei: in ^{45}Sc [17] from an inclusive experiment, and especially in ^{46}Ti [18,19] from our highly exclusive HECTOR + EUROBALL experiment. In the latter case of ^{46}Ti very large deformations at high angular momentum were also suggested by the spectra of emitted α-particles [20].

2. On the Physics Case

We propose to study both *the GDR width-evolution* and the *Jacobi shape transition* in ^{88}Mo compound nucleus. The evolution of the equilibrium shape of this nucleus, calculated within the newest liquid drop model LSD [21], is shown in Fig.3a. The nucleus, spherical at low spins, becomes oblate with increasing size of the deformation up to $\beta \approx 0.3$ at I=50 $\hbar$. Above this value an abrupt Jacobi shape transition occurs and nucleus becomes triaxial (around I=54 $\hbar$), then very elongated prolate ($0.6<\beta<0.9$) and undergoes fission around I=62 $\hbar$. The predicted GDR strength functions from the thermal shape fluctuation method based on LSD [9,22], integrated over the whole angular momentum distribution from 0 up to 58 $\hbar$, are shown for different temperatures in Fig.3b. In this model the GDR becomes wider, both due to thermal shape fluctuations, as well as due to the influence of large deformed shapes, whose contribution becomes more and more important at higher temperatures.

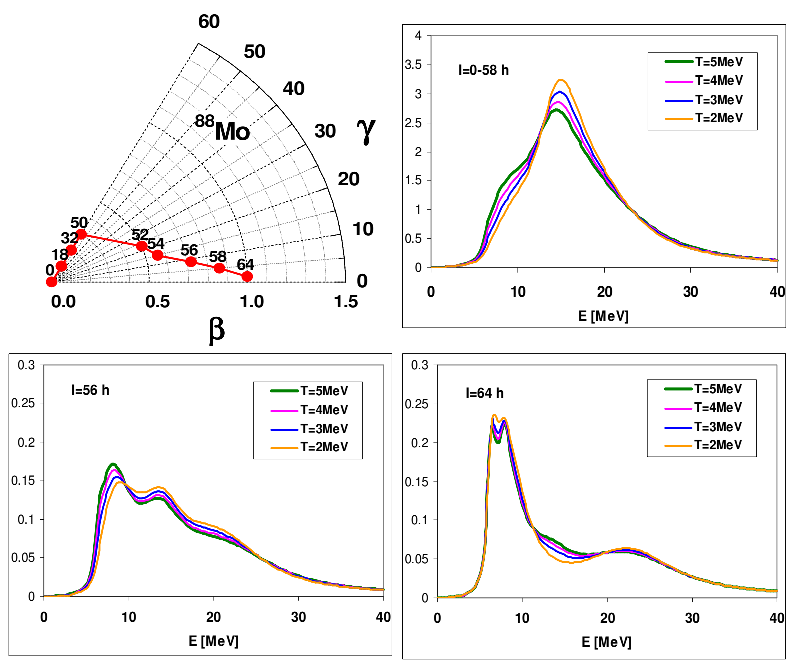

Fig. 3.a) Angular momentum evolution of the equilibrium shape of ^{88}Mo. Calculated GDR strength functions at different temperatures: b) integrated over whole spin distribution of the compound nucleus; c) for I=56, at the Jacobi regime; d) for I=64, i.e. slightly above the fission limit.

The Jacobi shape transition is clearly visible in the GDR strength calculated for I=56 $\hbar$ (Fig.3c) – three well separated GDR components correspond to the vibration along three different axes of the triaxial nucleus. Much more dramatic change of the strength function occurs for the spins just above those at which fission occurs (Fig.3d) – one can see very strong narrow low-energy component (8-10 MeV) corresponding to the vibration along longest axis. It is additionally split due to the Coriolis effect. A broad high-energy component, corresponding to the vibration along short axis, is visible at 18-25 MeV.

3. On the Experimental Conditions

a) Choice of the reaction

We propose to study ^{88}Mo formed in reaction ^{48}Ti + ^{40}Ca at beam energies E_{beam} = 300, 450 and 600 MeV. The compound nucleus is created at the excitation energies from 120 to 260 MeV covering 3.0 – 4.5 MeV temperature range. The maximum angular momentum transferred in the reaction corresponds to 75 – 110 $\hbar$, which is well above the fission barrier, expected to be around 60-64 $\hbar$. Therefore compound nuclei in all reactions, if tagged by the evaporation residues, will have almost the same spin distributions [31], so that one can study the *temperature dependence only* of the total (summed over all spins) GDR width. We have chosen the mass symmetric reaction in order to minimize [10] the possible pre-equilibrium particle emission, which will lower the temperature of the equilibrated compound nucleus. However at the highest bombarding energy (600 MeV) some pre-equilibrium effects are expected. Such effect and the amount of the energy removed by this possible emission can be controlled by the measurement of proton and α-particle energy and angular distribution spectra.

In the available setup there is no place for the gamma multiplicity filter, that could be used for choosing highest spins. However one can use the *α-particle multiplicity tagging* method [23] to reach the highest spin values of the Jacobi regime. This method relies on the fact, that in the case of hot nucleus with a steep yrast line, the emission of α-particles proceeds preferentially to lower spin region, as there the density of states is higher. Consequently each emitted α-particle removes substantial amount of angular momenta. Gating on long evaporation chain will enhance the contribution of GDR γ-decay from highest spins.

Alternatively we propose to try using *detections of fission fragments*, in order to see the pre-fission GDR decay, which might take place in the "fission" region of spins 60-64 $\hbar$.

This latter case is rather *a test of feasibility*, because only in case of close to symmetric-fission the fission fragments can be well separated and efficiently detected in GARFIELD set-up. To our knowledge it is not known, whether the symmetric fission occurs in ^{88}Mo at these temperatures. For heavy nuclei the energy of the saddle point increases with fragment mass asymmetry, hence mass symmetric fission is most probably. In light nuclei the situation is opposite, the energy of the saddle point decreases with mass asymmetry, hence emission of light charged particles or light clusters becomes more probable. Those two regions are separated by so called Businaro-Gallone point (or rather region) [24], for which the saddle barrier has a *plateau* as a function of mass asymmetry. The Businaro-Gallone point seems, from the experimental evidence, to be located between A=85 and A=145, so that the studied ^{88}Mo falls into the region. For nuclei around Bussinaro-Galone point the fission asymmetry behavior will depend on other features, as for example temperature, entrance channel or shell effects. Our expectation that in ^{88}Mo indeed the symmetric fission occurs is based on the fact, that the recent experiments for $^{90-98}$Mo isotopes [25,26], very close to ^{88}Mo, indeed show a sizeable amount of symmetric fission contribution. We plan to check this in our experiment for ^{88}Mo and if possible, use fission fragments after the symmetric fission to measure the pre-fission GDR spectra.

Such GDR spectra, measured in coincidence with fission fragments, may contain, apart from the pre-scission GDR from the compound nucleus, also the GDR from the hot fission fragments. Since the GDR component from the fission fragments (A≈45) is expected to be around 20 MeV, it will overlap the high-energy component of GDR from highly elongated ^{88}Mo, but we believe there should be no problem to resolve the narrow, low energy component (see Fig. 3d) of GDR from compound nucleus. In addition the post-fission GDR component, coming from the hot fission products, can be subtracted, if the spectra are collected at different excitation energies. This was shown in the HECTOR experiment in very heavy mass region [27].

b) GARFIELD+HECTOR Set-up

The proposed setup consists of the GARFIELD [28,29] array and the HECTOR [30] detectors. The GARFIELD array is employed to measure light charged particles from $\theta=29^o$ to $\theta=82^o$ and 2π of φ. It is made of ΔE-E gaseous micro-strip and CsI(Tl) scintillation detectors lodged in the same gas volume. The evaporated residues are detected by a wall of phoswich detectors [31] placed at forward angles. The 8 large volume BaF_2 crystals of the HECTOR are used for high energy γ-ray detection. To measure fission fragments phoswich detectors at appropriate angles will be used.

This setup allows measuring the high energy γ-ray spectra emitted from compound nucleus decay. By gating on residues measured in the GARFIELD array [10] we will obtain the GDR γ-spectra without any contributions from non fusion reactions. By gating on long chain of emitted α-particles [23], we will enhance the decay from high angular momenta, possibly from the Jacobi regime. In addition we will try a possibility to employ gating on fission fragments. In this way we might be able [27] to obtain spectra of γ-rays emitted from nucleus on the fission path.

c) Beam time request

The beam-time required is based both on cross-section estimates and on our previous experiments [10] with GARFIELD and HECTOR.

A 1-2 pnA pulsed beam with a resolution of 1 ns and a repetition time of 200 ns is required. Target, ^{40}Ca, will be 0.5 mg/cm^2 thick.

The request of the beam time was estimated, assuming that the average (over the experiment time) gamma counting rate in 1 MeV bin at 15 MeV is $\approx 6\text{x}10^{-4}$ cts/s for 450 and 600 MeV beam, and $1\text{x}10^{-3}$ for 300 MeV beam (as in this case only 1 stripper foil can be used), and that the required number of counts in such bin should be at least 200, in order to deduce the precise information on the GDR shape.

The **total request of beam time is 12 days** (not including tuning of ALPI) divided as follows:
2 days for 300 MeV ^{48}Ti beam on ^{40}Ca target (required beam: 2 pnA, 1 stripper foil);
4 days for 450 MeV ^{48}Ti beam on ^{40}Ca target (required beam: 1 pnA, 2 stripper foils);
4 days for 600 MeV ^{48}Ti beam on ^{40}Ca target (required beam: 1 pnA, 2 stripper foils);
1 day for calibration of BaF_2 of HECTOR with 45 MeV ^{11}B + ^{2}D (with a gold foil);
1 day for calibration of GARFIELD detectors.

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