Summary of the hot GDR workshop

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The workshop on the giant dipole resonance (GDR) in hot nuclei consisted of nine theoretical and two experimental talks, which will be described in detail in the corresponding contributions to this proceedings. In addition, a very stimulating discussion session covered the present status and future opportunities of studying the GDR in hot nuclei.

Introduction

How do the properties of atomic nuclei change when they acquire a large amount of internal energy? How do nuclear properties vary with their temperature? The giant dipole resonance (GDR) built upon highly excited states has provided a probe for addressing this question. For example, this resonance is strongly coupled to the nuclear shape degrees of freedom. Measurements of the GDR have provided strong indications of how the nuclear deformation varies with internal energy or temperature. The most common scenario considers a nucleus with a prolate ground state deformation. When such nuclei are heated and rotated, there are signatures for a shape transition at a critical temperature $T_{c1}(I)$, which is spin dependent. There is a transition from a prolate (or triaxial) shape rotating collectively at temperatures below $T_{c1}$ to an oblate shape rotating noncollectively at temperatures above $T_{c1}$. (In collective rotation, the rotation axis is perpendicular to the shape symmetry axis, whereas in noncollective rotation, the two axes coincide.)

Second shape transition temperature

Recent calculations have shown that 31 even-even isotopes with $50 < Z < 82$ and $82 < N < 126$ have a second shape transition temperature $T_{c2}(I)$, where $T_{c2} > T_{c1}$. For $I = 0$, $T_{c1}$ and $T_{c2}$ were evaluated only for $I = 0$. For temperatures between $T_{c1}$ and $T_{c2}$ there is prolate noncollective rotation, and for temperatures above $T_{c2}$ there is oblate noncollective rotation. The angular anisotropy coefficient $a_2(E_γ)$ for prolate noncollective has the opposite sign of $a_2(E_γ)$ for oblate noncollective. Therefore the shape transition at $T_{c2}$ should have a clear experimental signal.

The microscopic finite-temperature HFB cranking theory can provide a phase diagram for the equilibrium nuclear shape, showing how it varies with temperature and spin. However because this is very time-consuming, HFB phase diagrams have been completed for only two isotopes which display $T_{c2}$, $^{188}$Os and $^{196}$Pt. It is clearly desirable to have an alternative method to investigate this effect which is not so time-consuming. The macroscopic Landau theory of shape transitions as developed by Alhassid et al. has been widely used to interpret GDR experiments. It is much less time-consuming than HFB. However in the Landau universal phase diagram there is only one shape transition temperature $T_{c1}$, with the prolate (or triaxial) collective phase for temperatures below $T_{c1}$, and the oblate noncollective phase for temperatures above $T_{c1}$. This Landau phase diagram does not have the second shape transition temperature $T_{c2}$ or the prolate noncollective phase. Why should the HFB theory and the Landau theory give such different phase diagrams?

Of the 31 isotopes mentioned above which have the second shape transition temperature and the hot prolate noncollective phase, about two-thirds have oblate ground state deformation, one-sixth have prolate ground state shapes, and one-sixth have triaxial ground state shapes. In the Landau theory of shape transitions of Alhassid et al., the assumption was made that the ground state shape was prolate. This occurs in the choice of the sign of the prolate-oblate asymmetry coefficient, i.e., the sign of the $β^3$ term in the free energy expansion, which was chosen to be negative. The Landau universal phase diagram was determined for this sign choice. To describe nuclei with oblate ground state shapes, the sign of the $β^3$ term in the free energy would be chosen as positive. This requires the determination of a new Landau universal phase diagram, which has not been done. Would such a phase diagram show the second shape transition temperature? At low temperatures there would be an oblate (or triaxial) shape. At high temperatures ($T > 2$ MeV) one should obtain the classical liquid drop limit, which is oblate noncollective rotation. What happens at intermediate temperatures? Can the coefficients in the free energy expansion be chosen so that $T_{c2}$ and the hot prolate noncollective phase appear?

The difficulty may reside in the Landau moment of inertia. In the equilibrium state, the shape should rotate about the axis with the largest moment of inertia. The macroscopic classical expressions which Alhassid et al. have used for the moment of inertia appear to prohibit the rotation of a prolate shape about its symmetry axis. The HFB calculations show that when a hot ($T > T_{c1}$) spherical nucleus is rotated, the rotation creates a quantum shell effect (breaking the degeneracy in the magnetic quantum number $m$) which directly generates the hot prolate noncollective phase in particular isotopes. Is it possible to incorporate this shell effect into the Landau expression for the moment of inertia?

Discussions

Di Toro showed how the number of GDR phonons depends upon the time. Transitions from the compound nucleus to the

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dipole excitation of the compound nucleus are determined by the width $\Gamma_{feed}$ and transitions in the reverse direction are given by $\Gamma^I$. The time constants for these transitions are $\lambda$ and $\mu$, where $\Gamma_{feed} = \hbar \lambda$ and $\Gamma^I = \hbar \mu$. The number of GDR phonons at time $t$ is

$$n_{GDR}(t) = \frac{\lambda}{\mu} \left[ 1 - \left( 1 - n_0 \frac{\lambda}{\mu} \right) e^{-\lambda t} \right]$$

where $n_0$ is the number of GDR phonons at $t = 0$. The equilibrium value of $n_{GDR}$ at $t \to \infty$ is $\lambda/\mu$. There are then three possibilities: If $n_0 = \lambda/\mu$, then $n_{GDR}$ is constant with time. If $n_0 < \lambda/\mu$, then $n_{GDR}$ has an exponential increase towards the equilibrium value. If $n_0 > \lambda/\mu$, then $n_{GDR}$ has an exponential decrease towards the equilibrium value.

The GDR width $\Gamma$ depends upon temperature and angular momentum. In heavy ion fusion reactions, the temperature and spin dependencies of $\Gamma$ are coupled. Ansari showed how to separate these two dependencies, so that they can be studied individually. A harmonic oscillator model is used with $N = Z = 70$. The GDR width is found to be much more sensitive to spin than to temperature. For fixed temperature, $\Gamma$ has a linear increase with spin. For fixed spin, the dependence on temperature is relatively small.

Yan considered a microscopic mechanism for the dissipation of large amplitude collective motion. The time-dependent Hartree-Fock theory was used to study the interplay between collective and single-particle (intrinsic) degrees of freedom. The model includes one collective and two single-particle degrees of freedom, which are coupled by an interaction. The model shows how energy is transferred from the collective to the single-particle degrees of freedom. Before the coupling interaction is activated, the single-particle phase space diagram has ordered trajectories near the center, whereas outside the central ordered region there are forbidden regions interspersed in a sea of chaotic motion. When the coupling interaction is activated, the forbidden regions disappear and there is only chaotic motion outside the central ordered region. The interaction therefore makes the intrinsic sub-system more chaotic.

Fuhrmann considered the damping of the hot GDR, which is caused by interparticle collisions and surface (shape) damping. For low temperatures and high temperatures collisional damping is more important than surface damping. However for intermediate temperatures ($T \approx E_{centroid}/3$), the surface damping dominates. Since the relative importance of the two causes of damping is very different in light and heavy nuclei, this could provide a test for the theory.

Dang considered whether the GDR persists or disappears at high temperature ($T \approx 5$ MeV). Even at this temperature the GDR still exists, although it is strongly damped. Since the GDR is a form of collective order, the hot nucleus still has some order at $T \approx 5$ MeV. It is not completely chaotic. Therefore order and chaos co-exist at high temperature. There is not simply a transition from order to chaos.

Yoshida evaluated the single particle damping width in hot nuclei. There are contributions from (a) creation of a particle-hole pair, (b) scattering of a particle or a hole, and (c) annihilation of a particle-hole pair. The contribution from (a) is large at $T = 0$ and decreases with $T$, (b) is zero at $T = 0$ and increases with $T$ linearly, and (c) is zero at $T = 0$ and increases with $T$ quadratically.

Suppose that a nucleus is compressed and then released. How does it vibrate? Chomaz showed that a simple monopole scaling, where the density is constant (independent of position, not time) inside the surface region, is too simple and inaccurate. Time-dependent Hartree-Fock calculations at $T = 1$ MeV show that the vibrations are more complex. There are surface density oscillations and volume density oscillations. The damping of the vibration modes depends on the details of the volume and surface density oscillations. The density at the center of the nucleus has a time dependence which displays a beating of several modes.

### Experimental developments

Over the last years more and more exclusive experiments studying the GDR were performed. The additional information is needed to distinguish different reaction channels and to isolate different regions where the GDR is being studied. In the future it will be necessary to continue and expand these experiments and inclusive experiments are likely to become interesting only with the smaller beam intensities of radioactive beams to study the GDR in more exotic nuclei. The current interest of the GDR can be subdivided into two parts, the low energy/temperature regime where nuclear shapes are probed and the high energy/temperature where the saturation of the GDR width is an issue. In addition, the GDR can also be used to study reaction dynamical effects. These three topics will be discussed in the next three subsections.

### GDR width at low temperatures

One important method to improve the sensitivity of the experiments to the initial conditions that has not been discussed is the “difference method”. Although it has been shown some time ago\(^3\) that it can be used to isolate a certain excitation energy range, no further experiments to extract shape information have been performed recently. Figure 1 shows as an example the $\gamma$-ray spectra of $^{162}$Yb and $^{161}$Yb at 50.8 and 38.8 MeV excitation energy, respectively. The difference energy spectrum at the bottom of the figure corresponds to $\gamma$-rays emitted from the GDR of the first step in $^{162}$Yb.

Another important observable is the angular distribution of the GDR $\gamma$-rays. Both these methods should be utilized to search for the predicted shape transitions from collective oblate (triaxial) through non-collective prolate to non-collective oblate in neutron deficient in the $Z = 78$ mass region. The angular distribution is very sensitive since at both of these transitions the sign of the angular distribution changes. The angular distribution should also be useful to search for the GDR built on excited states because the crossing energy depends on the size of the deformation. These experiments need high statistics in order to extract the crossing.

Another important topic at low temperatures is the correct comparison of the experimental data with theoretical calcu-
lations of the GDR width as a function of temperature. While the experiments average over a wide range of excitation energies, and thus temperatures, the calculations are performed at a specific temperature. However, quite often the data are presented at the initial excitation energy and thus one should correct these values for the average over many decay steps before comparing with the theory.

Even this presentation is not completely correct because it compares an instantaneous value with an average value. In principle it is necessary to calculate the average value from the temperature dependent width, averaged over the population contributing to the GDR $\gamma$-decay, which is also energy dependent:

$$\langle \Gamma(T) \rangle = \frac{\int_{E_{\text{initial}}}^{T_{\text{final}}} \Gamma(T) \sigma(T) dT}{\int_{E_{\text{initial}}}^{T_{\text{final}}} \sigma(T) dT}$$

(2)

However, the temperature dependence of the width as well as the population cross section is not strong enough to have a significant impact. An estimate yields a 1% correction from $\Gamma(T)$ to $\langle \Gamma(T) \rangle$.

Another way to compare experiment with theory is to include the calculated temperature dependent strength functions directly into the statistical model calculations. However, it seems that at least for strength functions that maintain a lorentzian distribution a calculation using the constant width (at the correct temperature) reproduces the full calculations very well. Figure 2 shows two examples of statistical model calculations (based on different theoretical models [See more detail in Ref. 6]) where a constant strength function at the average temperature was used (solid) and a calculation which used the correct temperature dependent strength function at each decay step (dashed). There are systematic differences only in the top model (the adiabatic coupling model), which are due to the deviation from a lorentzian strength function. For the bottom model (the collisional damping model) the average calculation reproduces the full calculation very well. Thus it seems that a full calculation is not necessary, however, since the code exist, it is a useful check to incorporate the different models into the full calculations at least for one temperature.

**GDR width at high temperatures**

At higher energies the correct comparison between calculations and experiment opens up the question again whether the GDR width saturates at about 150 MeV or not. Although most of the experimental data were taken at an average excitation energy, which does not substantially exceed 150 MeV, one has to take another observable into account. Several experiments reported a reduction of strength at high energies and the question is not whether the width saturates or not, but whether the GDR exists above these temperatures.\(^7\)

Another indication that there might not be large contributions from the GDR at these high excitation energies are recent calculations by DiToro which show that high energy heavy-ion collisions lead to the same initial compound nuclear excitation energy of not more than $\sim 250$ MeV independent of the initial beam energy. It was suggested that one might be able to study this energy region by using lighter projectiles ($\alpha$-particles for example) to form the initial compound nucleus.

The GDR is actually very sensitive to this initial stage of the reaction. Recently a difference of the GDR emission cross section between charge symmetric and charge asymmetric systems was reported.\(^6\) This leads directly to the next section where the GDR can be used to study reaction dynamical effects.

**GDR as a tool to study nuclear reactions**

The GDR is a very fast vibration and thus can be used to measure time-scales which occur in low and medium energy collisions. In addition, the GDR is sensitive to the deformation of the system and thus is able to measure shape equilibration of the reactions.\(^9\) The difference of charge symmetric and asymmetric systems mentioned above is a good example where the time scale for charge equilibration can be extracted.
A similar effect was observed in deep inelastic collisions, where before the difference in charge asymmetry is studied, the plain observation of the GDR in the intermediate system gives already information of the lifetime of the di-nuclear system.

These studies are closely related to similar studies of the fission lifetime using the GDR. This continues to be an important topic, where the enhanced observation of pre-fission GDR emission is a measure for the nuclear viscosity which slows down fission. The temperature dependence of the viscosity is still highly debated and further experiments are needed.

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References