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Radiative fusion from very symmetric reactions: the giant dipole resonance in the ^{179}Au nucleus

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Abstract

The spectra of high-energy γ rays emitted by the Giant Dipole Resonance (GDR) built on moderately excited states associated with the evaporation of 0, 1 and 2 nucleons were measured in the ^{90}Zr + ^{89}Y symmetric fusion reaction. The radiative fusion data suggest statistical emission from the compound nucleus. In addition, the analysis of the high-energy γ-ray spectra associated with the different evaporation channels at the present temperature of 0.7 MeV and spin range 15–20 $\hbar$ show a fairly narrow width of 5.0 ± 0.35 MeV. This value is smaller than what would be expected in a nucleus where shell effects do not play a role.

In the past, the Giant Dipole Resonance (GDR) built on highly excited nuclear states has been investigated in experiments with high-energy γ-ray spectra from the decay of hot nuclei, formed in heavy-ion fusion reactions or inelastic scattering [1]. In particular, the GDR has been used as an important experimental tool to probe the properties of hot rotating nuclei, mainly because of its coupling to the quadrupole deformation of the nuclear shape. The emission

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of γ rays with energies (E_γ) larger than the particle binding energy, in competition with particle evaporation, occurs mainly in the first steps of the decay process. Two important regions in the energy-spin plane can be identified for such studies. There is the non-collective regime at higher excitation energies and spins (corresponding to temperatures $T > 1$ MeV), where the nucleus behaves as a liquid drop. This region has been extensively investigated by probing the GDR lineshape as a function of temperature and angular momentum. In contrast, the collective regime at low excitation energy and at medium spin, which is very important for the study of the vanishing of shell effects, has been minimally explored with GDR measurements [2,3]. A powerful way to selectively populate nuclei at rather low excitation energy and finite spin is to use cold fusion in symmetric heavy-ion reactions. This is achieved with fusion near the classical threshold, leading to compound nuclei with excitation energies of about 10 to 40 MeV. In symmetric reactions induced by ^{90}Zr beams, one can also exploit the fact that exclusive emission of γ rays, i.e., radiative capture, occurs with unexpectedly large cross sections (several tenths of microbarn) [4]. The first question about the radiative capture process in these heavy nuclei is whether this is a direct process, as suggested for light nuclei. The first γ-spectroscopic investigations of the radiative fusion reaction $^{90}\text{Zr} + {}^{90}\text{Zr}$ were based on measured γ-ray spectra which extended up to $E_\gamma = 6$–7 MeV [5]. They gave only first indications about the nature of the process responsible for the emission of high-energy γ rays. The latter seemed to originate from an equilibrated compound nucleus rather than from a fast, direct process. However, to put this assertion on a firmer basis, information on the shape of the emitting system was lacking as the corresponding γ-ray spectrum should be measured at least up to the centroid of the GDR ($\simeq 13$ MeV).

In the present Letter, we report on an experiment focusing on the high-energy γ rays emitted in the radiative fusion reaction $^{90}\text{Zr} + {}^{89}\text{Y}$ at $E_{\text{beam}} = 352$ MeV. There are two main motivations to this work. The first is to investigate further the nature of the radiative fusion process by measuring the relative yields of the final products, the high-energy γ rays up to 13–14 MeV, and the γ-ray multiplicity. The second is to deduce the shape of the emitting nucleus from both the GDR decay and the width of the GDR state at low temperature. The present study of the GDR is unique because it provides the first investigation in the temperature region $T = 0.5$–1 MeV at finite spins 15–20 $\hbar$ and uses a reaction channel in which only γ decay occurs. As a consequence of the latter, the nucleus emitting the GDR γ rays is completely specified, as well as its excitation energy; neither is the case in earlier experiments on GDR γ rays.

It is interesting to probe nuclear shapes in the region of temperature $T = 0.5$–1 MeV, since one can learn about how shell effects decrease with increasing temperature. In addition, the GDR spectral shape is expected to give information not only on the equilibrated nucleus, but also on the compound nucleus formation process [7]. In fact, for symmetric reactions, strong dissipative effects have been predicted, which could result in long formation times [6]. Under such conditions, the GDR γ-ray emission could already occur during the formation process where the shape degrees of freedom are not yet equilibrated and very large deformations might be present. If this scenario holds, the use of symmetric reactions would be relevant for the optimal production of very deformed nuclei (super- or hyper-deformed).

The experiment was performed at Argonne National Laboratory, using a ^{90}Zr beam, provided by the ATLAS accelerator, impinging on a ^{89}Y target 400 μg/cm^2 thick. The isotopic purity of the target is guaranteed as ^{89}Y is the only stable isotope of yttrium. The chosen bombarding energy, 352 MeV (346 in the middle of the target), corresponds to the formation of the compound nucleus ^{179}Au, at an excitation energy $E^* \simeq 20$ MeV. The recoiling products passed through the Argonne Fragment Mass Analyzer (FMA) and were dispersed according to their mass-to-charge (M/q) ratio at the focal plane. A position-sensitive parallel grid avalanche counter (PGAC), located at the FMA focal plane, provided the M/q information, as well as the arrival time and energy-loss signals of the evaporation residues. The recoiling nuclei were subsequently implanted into a double-sided silicon strip detector (DSSD) with 40×40 strips, located 40 cm behind the PGAC. This DSSD was used not only to detect the implantation of a residue and its time of arrival with respect to the prompt γ rays detected at the target, but also to measure the subsequent alpha decay(s) of the implanted ions. The high segmentation of the DSSD provided effective spatial and time correlations between the implants and their subsequent decays. The γ rays were measured with a set up of BaF_2 detectors from the ORNL/MSU/TAMU array, each having an hexagonal shape (with internal radius of 3.25 cm) and being 20 cm deep. These detectors were grouped in 4 packs, each with 37 crystals. They were positioned at 90 and 149 degrees on either side of the beam, at a distance of 39 cm from the target to the front face of the central crystals. In addition, low-energy γ rays were also detected by a BGO multiplicity/sum-energy array, which was used primarily as a multiplicity filter with an efficiency of $\simeq 30\%$ and a cross-talk probability of $\simeq 12\%$.

The energy calibration of the BaF_2 detectors was obtained using low-energy γ-ray sources up to 6 MeV. For the high-energy part, the reaction $^{11}B(p,\gamma)$ at $E_p = 7.2$ MeV was used, producing γ transitions at 4.44, 18.12 and 22.56 MeV. During the experiment, the temperature and detector gains were monitored every 8 hours. Neutron events were rejected using a time-of-flight measurement with respect to the beam. Pile-up events were eliminated by setting appropriate gates on the correlation between the fast and slow components of the BaF_2 signals.

From the distribution of the coincidence fold of the low-energy γ rays, we have extracted information on the angular momentum of the compound nuclei. Fig. 1 (left panel) displays the coincidence-fold distribution measured with the multiplicity filter and associated with all detected evaporation residues. The curves correspond to calculations obtained by folding a triangular smoothed (with diffuseness $d = 2$) spin distribution for the compound nuclei with the calculated response function of the multiplicity filter. The calculations were carried out for different assumptions of the value of the maximum angular momentum. The best fit value of $L_{max} \simeq 16\hbar$ agrees with the prediction for this reaction by the grazing model [7]. In addition, the fold distributions shown in the right panel of Fig. 1, indicate that the radiative fusion channel (denoted with 0N in the figure) extends higher in the fold than those corresponding to 1 and 2 particle emission. Note that, as the cross sections of the different reaction channels are very different, the data are normalized to the counts in the low-fold region. Similar results have been obtained for the $^{90}Zr + {}^{90}Zr$ reaction, where the spin-energy distributions were measured with Gammasphere [8]. This finding is consistent with a statistical mechanism for the radiative fusion channel, in which the emission of high-energy γ rays is more probable at high spins, since particle emission is inhibited because of the lower internal energy available (given by the difference between the energy of the entry point in the compound nucleus and the yrast line).

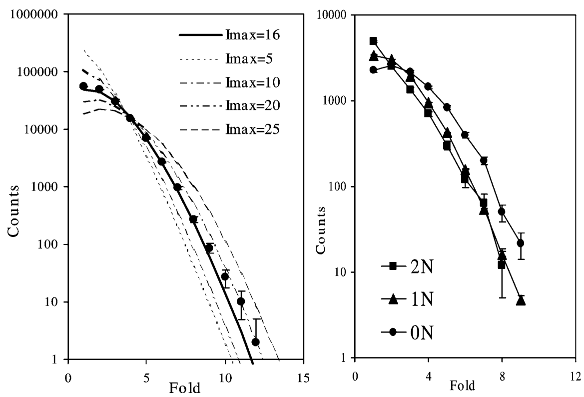

Fig. 1. Left panel: the fold distribution associated with all evaporation residues is compared to predictions based on different spin distributions of the compound nucleus. Right panel: the fold distributions of low-energy γ rays in coincidence with high-energy γ rays in the 0, 1 and 2-particle emission channels (denoted in the legend, respectively as 0N, 1N and 2N). The three distributions are normalized at low folds. Note that the 0N fold distribution is weighted towards higher folds. The lines in the right panel are to guide the eye.

The statistical nature of the 0-particle emission process is also suggested by the fact that the population cross sections for the different final nuclei change when high-energy γ rays are measured in coincidence with the heavy recoiling nuclei. This effect is illustrated in Fig. 2, where two mass spectra of the heavy recoiling nuclei are shown. The two spectra were obtained with and without a requirement of the presence of a high-energy γ ray ($E_\gamma > 5.0$ MeV). The two spectra are normalized at the ($A_{CN} - 1 = 178$) peak, where A_{CN} is the mass number of the compound nucleus. As the figure illustrates, when a high-energy γ ray is detected, the cross section of the 0-particle channel increases while that for 2-nucleon emission decreases.

The high-energy γ-ray spectra corresponding to 0, 1 and 2-nucleon evaporation shown in Fig. 3 reflect the difference in the phase space available in the three decay channels. The spectrum corresponding to 2 nucleon emission is very steep and dies out at rather low energy. In contrast, those corresponding to

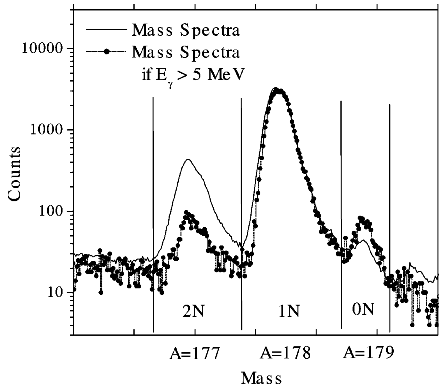

Fig. 2. Mass distributions of the residue nuclei with (dots) and without (continuous line) the requirement of a coincidence with high-energy γ rays.

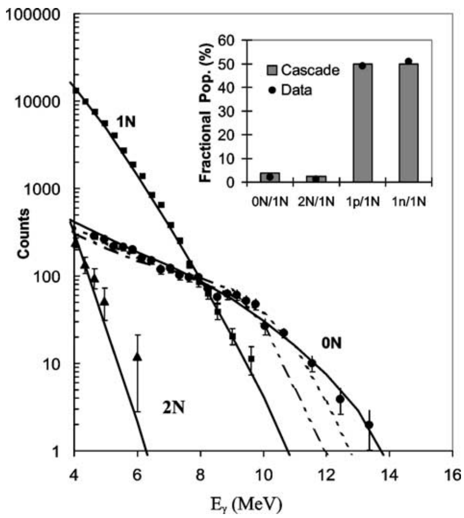

Fig. 3. The high-energy γ-ray spectra associated with the 0, 1 and 2-nucleon emission channels (filled circles, squares and triangles, respectively) are shown in comparison with statistical model calculations. In the inset the measured fractional populations of the different residual nuclei are shown in comparison with statistical model predictions. The dotted and dash-dotted lines show the calculations for a prolate $\beta = 0.4$ and 0.6 nucleus.

1 and 0 particle emission extend to higher energy and are characterized by very different spectral shapes. In particular, the 0-particle emission spectrum is much less steep and, therefore, has an enhanced sensitivity to the details of the low-energy tail of the GDR lineshape.

The measured spectra have been analyzed within the framework of the statistical decay of the compound nucleus ^{179}Au. Because of the bias introduced by channel selection, a Monte Carlo approach was employed [9]. Statistical model calculations were carried out with a level density parameter $a = A/8\ \mathrm{MeV}^{-1}$ and 100% of the energy weighted sum rule strength of the GDR. In addition, a parabolic parameterization for the yrast line [10] was used. The spin distribution was triangular shaped with $L_{\max} = 16\hbar$ and diffuseness 2. At each value of the deformation parameter (β, γ), the values of the GDR centroids and widths were deduced using the Hill–Wheeler parameterization [11,12], with the spherical value $E_0 = 14.2$ MeV. For the intrinsic width, $\Gamma_0^{\downarrow}$, values ranging from 4 to 6 MeV were employed. The total width was assumed to be given by $\Gamma = \Gamma_0^{\downarrow}(E_{\mathrm{GDR}}/E_0)^{1.6}$ [1]. The calculations were folded with the response function of the BaF_2 array (calculated with the GEANT libraries) and were then normalized to minimize χ^2_{corr} between 5–9 MeV. In the calculation of χ^2_{corr} the exponential behavior of the spectrum has been weighted accordingly [13]. For the best fit of the quadrupole deformation parameter β and the width $\Gamma_0^{\downarrow}$, the χ^2_{corr} was calculated in the interval of E_γ between 9 and 13 MeV.

Statistical calculations with larger deformations fail completely to reproduce the high-energy part of the spectrum as shown in Fig. 3. Therefore, there is no evidence in the present data for GDR emission from a pre-equilibrated system with very large deformation. Conversely, the data show that the effective average shape sampled by the GDR is characterized by a quadrupole deformation parameter $\beta = 0.1 \pm 0.1$ and $\Gamma_0^{\downarrow} = 5.0 \pm 0.35$ MeV. This effective deformation deduced from the GDR is expected for warm ^{179}Au which is known to be in a shape-coexistence region [12]. Because of the small size of the deformation, it is not possible with the present data to distinguish between oblate or prolate deformation.

It is also important to examine how well the statistical model calculations (with the best value of β and $\Gamma_0^{\downarrow}$) reproduce the spectra from both the 1 and 2 particle emission channels and the relative cross sections. This is illustrated in Fig. 3, where the statistical model predictions are shown for the three main decay channels. In the inset of the figure, we show the relative yield of the measured residual cross sections in comparison with the statistical model prediction. To obtain separately the relative yields for the one neutron and one proton emission channels, we have used the data

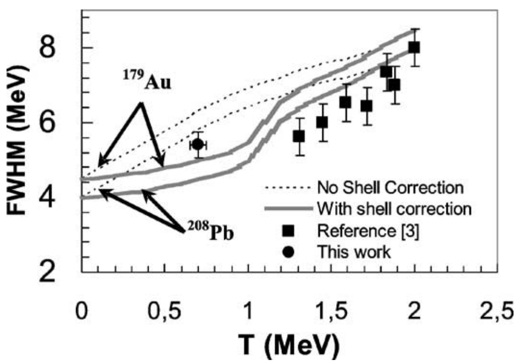

Fig. 4. The width of the GDR (filled point) deduced from the FWHM of the GDR lineshape ($\Gamma_0^{\downarrow} = 5.0$ MeV and $\beta = 0.1$). The error in the temperature value has been estimated by changing the level density parameter a between $A/7$ to $A/10$. Also shown are the widths for ^{208}Pb [3] and calculations from the thermal fluctuation model for ^{208}Pb [11] with (thick full drawn line) and without (thick dashed line) shell correction. The upper lines (thin full drawn and dashed) correspond to a rigid shift of 0.5 MeV to take into account the different $\Gamma_0^{\downarrow}$ value at $T = 0$ for the two nuclei (see text).

measured with the DSSD detectors. The energies of the alpha particles have been identified and their lifetimes were found to be in good agreement with the values known in the literature [14]. The statistical model can simultaneously reproduce the γ-ray spectra and the relative yield of various channels. This provides a stringent consistency check and, therefore, strengthens the conclusions about the GDR deduced from the radiative fusion γ-ray spectrum.

The measured total GDR width for the nucleus ^{179}Au deduced from the present analysis is $\Gamma_0^{\downarrow} = 5.0 \pm 0.35$ MeV. This value is not very different from the zero temperature value ($\Gamma_0^{\downarrow} \simeq 4.5$–$4.8$ MeV) while it is associated with an average temperature of 0.7 MeV, deduced from the relation $T = [(E^* - E_{\mathrm{GDR}} - E_{\mathrm{rot}})/a]^{1/2}$, where $a = A/8$. It is interesting to compare the present result for ^{179}Au with those obtained using inelastic scattering for ^{208}Pb [3]. As shown in Fig. 4, in the case of Pb, the experimental data have been compared with two model predictions based on the thermal fluctuation model [11], with and without the inclusion of shell corrections. Because calculations of this type are not presently available for ^{179}Au, one can only perform a simple rescaling of the ^{208}Pb predictions. In fact, photoabsorption measurements provide for $^{\mathrm{nat}}$Au and for $A = 180$ width values which are approximately 0.5 MeV larger than for the doubly magic ^{208}Pb [15]. Therefore, the thin continuous line in Fig. 4 represents the lower limit for the FWHM when shell corrections are assumed equal to those of ^{208}Pb. Smaller shell corrections, as expected for ^{179}Au, should result in larger FWHM values closer to the prediction for a simple liquid drop (short-dashed line).

In summary, the present γ-spectroscopic investigation of the radiative fusion reaction $^{90}\mathrm{Zr} + {}^{89}\mathrm{Y}$ provides clear evidence for the statistical nature of the radiative capture reaction mechanism. The data on the GDR width show a value smaller than what would be expected in a nucleus where shell effects do not play a role but specific calculations for this nucleus are necessary to draw more definitive conclusions.

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