Gamma Decay of Isovector Giant Resonances Built on Highly Excited States in ^{111}Sn*

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(Received 1 March 1985; revised manuscript received 26 February 1986)

Gamma-ray transition-energy spectra up to $E_\gamma \simeq 33$ MeV have been measured for the decay of the compound nucleus ^{111}Sn* populated at excitation energies up to $E^* \simeq 100$ MeV. Above $E_\gamma \simeq 20$ MeV an excess of gamma rays over the contribution from the isovector giant dipole resonance is observed in the energy range where the isovectors giant quadrupole resonance built on excited states is expected. The width of the giant dipole resonance in ^{108,111}Sn* shows a large increase with increasing nuclear temperature and angular momentum.

PACS numbers: 21.10.Re, 23.20.Lv, 24.30.Cz, 27.60.+j

Most of the detailed information which is available today on the structure of atomic nuclei has been obtained through the study of "cold" nuclei, i.e., nuclei which carry only little thermal excitation energy. This particle-bound region which extends a few megaelectronvolts above the yrast line is studied extensively by γ-ray as well as by particle-spectroscopic methods. At very high excitation energies most of the effort has been focused on the understanding of more macroscopic aspects of the nuclear force (potential) by studying the fragments which result when nuclei are subjected to violent collisions. The region between these two extremes has not been accessible to γ spectroscopy until a few years ago when γ rays from the deexcitation of isovector giant-dipole-resonance (GDR) modes built on excited states of high spin were detected.[1] These γ rays are emitted in competition with particles in the first few steps of the decay of compound nuclei,[2] and therefore constitute a tool by which to study the structure of highly excited nuclei. Indeed, it has been possible to determine the deformation and shape of nuclei populated at excitation energies far above the yrast line.[3,4] So far, only the dipole component of excited-state giant resonances has been observed, and the systematic information is still scarce. In particular, because of the low production cross section for these γ rays (typically $\simeq 10$ μb/250 keV at $E_\gamma \simeq 15$ MeV), it has been difficult to extend the transition energy spectra beyond $E_\gamma \simeq 20$ MeV in heavier systems.

This Letter reports on a study of the high-energy γ decay of the system ^{111}Sn* in which γ rays with energies up to $E_\gamma \simeq 33$ MeV are observed above the background. In the range 20 MeV $< E_\gamma <$ 33 MeV a statistically significant excess of counts is observed above the main contribution from the GDR located at 15.5 MeV. Structures on the high-energy side of the GDR have previously been measured in Sn isotopes for giant resonances built on the ground state,[5] by use of (γ,xn) reactions. These have tentatively been associated with quadrupole emission on the basis of comparison to calculations, although an $E1$ mechanism cannot be excluded. Recent angular distribution measurements[6] have identified the giant quadrupole resonance (GQR) in ^{41}Ca, by use of the (n,γ) reactions. While most studies of the GQR rely on inelastic-scattering experiments,[7] the GQR has also been studied at low excitation energies via the (p,γ)[8] and (α,γ)[9] reactions. In the present analysis of the decay of a compound system formed at very high excitation energy, the observed spectral shape can be well described by the assumption of the presence of a statistically decaying isovector GQR built on excited states in mainly ^{111}Sn*, centered at $E_\gamma \simeq 27$ MeV and with a width of $\simeq 8$ MeV. In addition, the present data taken together with the data of Ref. 3 for ^{108}Sn* show a strong ($\simeq 100\%$) increase in the width $\Gamma_{\rm GDR}$ of the dipole resonance when the excitation energy E^* and angular momentum I transferred to the compound system are increased. A possible explanation for part of this effect is a shape change of the Sn isotopes from spherical to oblate with increasing I. A dependence of the GDR width on excitation energy has earlier been reported based on studies of deep-inelastic reactions[10] and in (p,γ) capture reactions.[11]

The experiments were performed with the reaction ^{20}Ne + ^{91}Zr $\rightarrow$ ^{111}Sn* at $E_{\rm lab} = 100$ and 140 MeV with a beam from the Lawrence Berkeley Laboratory 88-in. cyclotron. The self-supporting targets ($\simeq 4$ mg/cm^2 thick) were isotopically enriched to 97% in the isotope of interest. The high-energy γ rays were recorded in an array of twelve 12.5-cm-diam $\times$ 15-cm NaI(Tl) detectors located 50 cm from the target. The detectors were shielded with 6 mm Pb to reduce the counting rate due to low-energy transitions, and discriminator levels were set such that only γ rays with $E_\gamma \geqslant 6$ MeV were recorded. The contribution from cosmic rays to the spectra, which is the main limiting factor at high

E_γ, was kept low by requiring a high data rate and by employing fast coincidence timing. This background was further suppressed by arrangement of the detectors in a closely packed geometry (see Fig. 1) and by the requirement that only one γ ray with $E_\gamma > 6$ MeV be detected in the array for each event. This is effective because there is a high probability for a cosmic ray which hits the detector array to trigger more than one detector, while the probability of detecting two high-energy γ rays from the target in the same event is extremely low ($< 10^{-13}$). A very significant reduction of the background results from the use of a small-volume CsF detector, located close to the target, as an event trigger. Since the density of cosmic rays from the same shower is low, the geometrical probability to trigger both this detector and one of the 12.5-cm-diam × 15-cm detectors is very low. The use of the CsF detector and the long flight path to the 12.5-cm-diam × 15-cm detectors allow an excellent discrimination against slow and fast neutrons.

To enhance the selection of high-multiplicity events from the decay of the compound system two 20-cm × 33-cm-diam NaI(Tl) detectors, each subdivided into four parts and positioned above and below the target, were used. An event was then defined by the requirement that at least four γ rays be detected in this array in addition to the participation of the CsF and of one NaI. Energy calibration at high E_γ was accomplished with the use of the 17.3-MeV γ rays from the $p + {}^{11}B$ reaction at 3 MeV on a thick target. Targets of C and Al were also studied, and the contamination from such light target impurities was found to be completely negligible. The shape of the remaining cosmic-ray background was found to be flat in the region of interest.

Measured continuum γ-ray spectra from the decay of $^{111}Sn^*$ are shown in Fig. 2. The spectra correspond to excitation energies (estimated at the center of the target) of $E^* = 99.2$ MeV (top) and $E^* = 66.4$ MeV (bottom). The transferred maximum angular momentum was $l_{max}\hbar \simeq 60\hbar$ and $\simeq 40\hbar$, respectively. The γ rays from the decay of the GDR are recognized in the bump centered at $E_\gamma \simeq 15$ MeV, which starts at $E_\gamma \simeq 9$ MeV where the spectrum deviates from the exponential slope characteristic of the near-yrast statistical decay. In the spectrum corresponding to the highest excitation energy another change of slope occurs at $E_\gamma \simeq 20$ MeV, indicating an excess of γ rays centered around $E_\gamma \simeq 27$ MeV, above the main contribution from the GDR and in the region where the GQR resonance is expected[12] ($E_{GQR} \simeq 127 A^{-1/3}$ MeV).

It has previously been found[2,3,13] that such spectra can be well described up to $E_\gamma \simeq 20$ MeV by calculations assuming statistically decaying GDR modes built on excited states. In the present work we have attempted to analyze the spectral shape over the entire range by including in the analysis the statistical decay of an isovector giant quadrupole resonance located at higher energy than the GDR. Although the experiments cannot discriminate between a GQR and a high-energy component of $E1$ character, such a component appears improbable in this energy range. In particular, the isospin splitting[6] of the GDR $[E_> - E_< \simeq 60(T_0 + 1)/A$ MeV$]$ which is important in the (γ,n) measurements is avoided here since the $T_>$ component is not populated in the reaction. Statistical-model calculations done with a modified

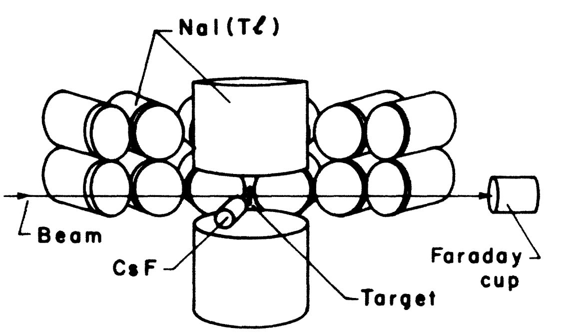

FIG. 1. Schematic illustration of the detector arrangement discussed in the text. The high-energy γ rays were detected in the array of twelve 12.5-cm-diam × 15-cm NaI(Tl) detectors with 0.6-cm Pb absorbers.

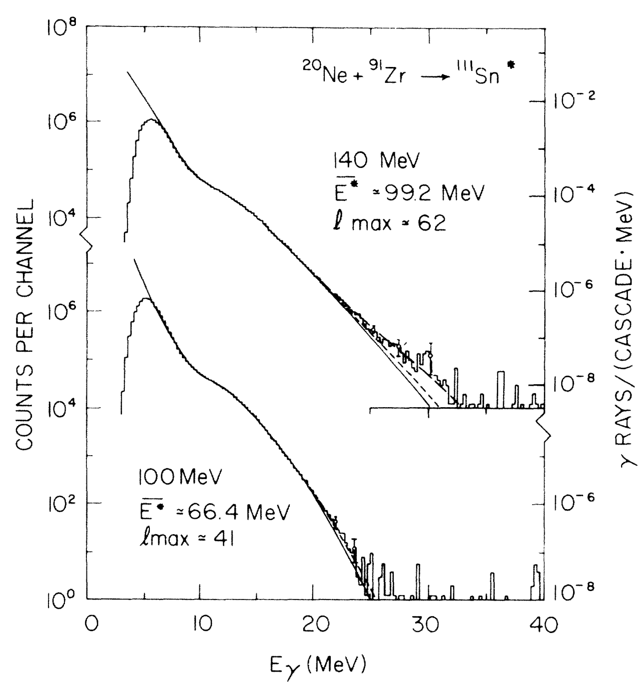

FIG. 2. Measured γ-ray spectra from the decay of $^{111}Sn^*$ at two excitation energies. The spectra have been fitted with statistical-model calculations using (i) only $E1$ strength and $a = A/8$ (thin full-drawn curve), (ii) $E1$ strength and $a = A/8.5$ (short-dashed), and (iii) $E1$ and $E2$ strength (long-dashed in top part).

version of the code CASCADE[14] and folded with the calculated detector response[3] are also shown in Fig. 2. In the calculations, the isovector dipole and quadrupole emission probabilities had the form

$$\Gamma_\gamma^\lambda(E_\gamma) \propto S_\lambda E_\gamma^{2\lambda+1} f_\lambda(E_\gamma), \quad \lambda=1,2. \tag{1}$$

The energy dependence of the transition matrix elements for $E1$ and $E2$ radiation is expressed through the Lorentzian functions f_1 and f_2, which depend on the average excitation energies $\bar{E}_{\rm GR}$ and widths $\Gamma_{\rm GR}$ of the respective resonances. For deformed systems the f function may be a superposition of several Lorentzians.[3] The adjustable parameters S_1 and S_2 measure the fraction of the appropriate energy-weighted sum rules (EWSR)

$$\sum_{K=0}^{\pm 1} S_{\rm EWSR}(rY_{1K}) = 14.8\frac{NZ}{A}\ e^2\cdot{\rm fm}^2\ {\rm MeV} \tag{2}$$

and

$$\sum_{K=0}^{\pm 2} S_{\rm EWSR}(r^2Y_{2K}) = 71.25ZA^{2/3}\ e^2\cdot{\rm fm}^4\ {\rm MeV}, \tag{3}$$

derived by use of a general momentum-independent potential.[14] As a result of the additional E_γ^2 factor, quadrupole radiation is expected to dominate the spectrum at high E_γ.

By adjusting the parameters describing the giant resonances in Eq. (1), we find that the spectrum of lower E^* can be well reproduced (full drawn curve) with $E1$ strength alone by use of a single Lorentzian function for the GDR with $\bar{E}_{\rm GDR} \simeq 15.5$ MeV and $\Gamma_{\rm GDR}=7.5$ MeV. The liquid-drop level-density parameter $a=A/8$ was used. The $E1$ EWSR fraction ($S_1 \simeq 1.0 \pm 0.1$) was determined from the calculations by the requirement that both the spectrum shape and the measured number of high-energy γ rays per cascade be reproduced. It is seen, however, that the upper tail of the spectrum is slightly underestimated in this calculation. This can be improved either by decreasing the level-density parameter to $A/8.5$ (short-dashed curve) or by including quadrupole radiation with full EWSR strength at $E_\gamma \simeq 27$ MeV and with $\Gamma_{\rm GQR} \simeq 8$ MeV. Nevertheless, the range of allowed parameter variations is small if the spectrum is to be adequately reproduced. Similar calculations are also shown for the $E^*=99$ MeV spectrum. The GDR is well reproduced (full drawn curve) by a calculation with $S_1=1.0\pm0.1$, $\bar{E}_{\rm GDR}=15.5\pm0.5$ MeV, and $a=A/8$, although a larger width, $\Gamma_{\rm GDR}\simeq 11$ MeV, is needed. It is apparent that this calculation cannot account for the intensity at $E_\gamma > 20$ MeV even if the smaller level-density parameter allowed by the fit to the lower E^* spectrum (short-dashed curve) is used. The upper part of the spectrum can, however, be accounted for by inclusion in the calculation of an isovector GQR component with full sum-rule strength (long-dashed curve) in good agreement with the expected $T_<$ strength of the GQR[6]

$$[S_>/S_< = T_0^{-1}(1-2T_0/A)/(1+2/A)].$$

In particular, the use of a much smaller value of the parameter a for the spectrum of highest E^* would reduce the quality of the fit to the GDR, and still not reproduce the observed change of slope at $E_\gamma \simeq 20$ MeV. The values used, $\bar{E}_{\rm GQR}=27$ MeV and $\Gamma_{\rm GQR}\simeq 8$ MeV, are in good agreement with the systematics for GQR's built on the ground state.

In Fig. 3 the systematics of the GDR width as a function of E^* is displayed for the present data on ^{111}Sn* and for data on ^{108}Sn* taken from Ref. 3. It is seen that the widths obtained from this data set at the lowest E^* agree well with the ^{108}Sn* results at $E^*\simeq 60$ MeV and $l_{\rm max}\hbar \simeq 35\hbar$. It is also seen that $\Gamma_{\rm GDR}$ increases strongly (to approximately twice the width at $T=0$ MeV) when E^* and $l_{\rm max}$ increase. As discussed in Ref. 3 there are two possible explanations for such an increase: (i) an increase in the damping width of the GDR with increasing I and/or E^*, and (ii) a change of deformation (presumably towards an oblate shape) of the spherical Sn isotopes with increasing I and E^*. The present experiment cannot discriminate between these two possibilities. However, recent random-phase-approximation calculations[15] for ^{108}Sn*, including the effect of a changing and fluctuating deformation with T and I, predict a 3.5–4-MeV increase of $\Gamma_{\rm GDR}$ for the nuclei considered here in the range 70 MeV $< E^* <$ 100 MeV. In these calculations, which ignore couplings to degrees of freedom other than quadrupole, the increase of $\Gamma_{\rm GDR}$ arises from a change of shape from spherical to oblate (with deformation $\epsilon \simeq 0.30$) of the Sn isotopes with increasing I, and

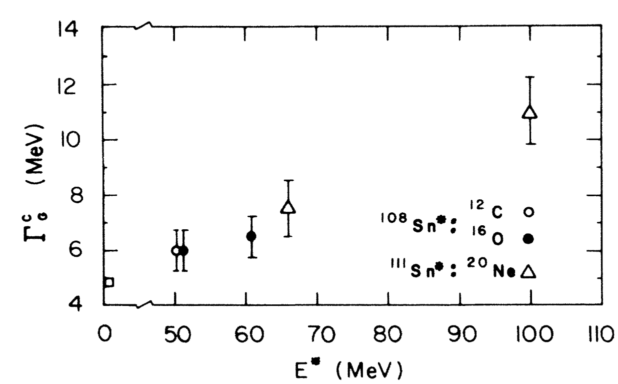

FIG. 3. Systematics of the GDR width Γ^c_o as a function of the excitation energy of the compound nucleus, obtained from the statistical-model fits to the present data on ^{111}Sn* and to data on ^{108}Sn* from Ref. 3. The GDR width at $E^*\simeq 0$ MeV obtained from (γ,xn) measurements (Ref. 5) on ^{116}Sn is also indicated (open square).

from a strong broadening of the potential energy surfaces due to the temperature increase. Although the GDR in deformed nuclei should split into two Lorentzians, the observed resonances can be adequately represented by a single Lorentzian function. This is probably due to the very shallow minima in the potential energy surfaces at $T > 2$ MeV, which smooth the fine structure of the response function observed in heavier systems and at lower temperature. Also it must be kept in mind that the experimental spectra analyzed here consist of γ rays emitted from the nuclei populated with a broad range of I and T values.

In summary, the high-energy γ decay of ^{111}Sn* in the range 6 MeV $\leq E_\gamma \leq$ 33 MeV has been measured as a function of E^*. A contribution to the γ-ray spectra in excess of the main GDR strength has been found in the GQR region, consistent with the expected strength of a GQR decaying statistically from highly excited states. The comparison of data on ^{108}Sn* and ^{111}Sn* indicates a dramatic increase in the GDR width with increasing E^* and l_{max}.

The study of the high-energy GR γ rays provides a unique tool in nuclear physics with which to study very selectively the structure of the excited compound nucleus. This is particularly the case for the γ rays in the GQR region detected in experiment, which are almost exclusively emitted in competition with the first emitted particle from the compound system. At higher excitation energies than those addressed here, studies of the GDR strength may constitute a sensitive probe to study the limits of existence of compound nuclei.

This work was supported by the Danish Natural Science Research Council and by the U.S. Department of Energy.

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