Dependence of the Giant Dipole Strength Function on Excitation Energy

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Spectra of γ rays associated with deep-inelastic products from the 1150-MeV ^{136}Xe + ^{181}Ta reaction have been measured. The yield of 10–20-MeV γ rays initially increases rapidly with the excitation energy of the products and then more slowly for excitation energies in excess of 120 MeV. Statistical-model calculations with ground-state values of the giant dipole strength function fail to reproduce the shape of the measured γ-ray spectra. This suggests a dependence of the giant dipole strength function on excitation energy.

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Even at excitation energies in excess of the particle binding energies, γ-ray emission will compete with particle emission. For γ-ray energies $E_\gamma < 25$ MeV, absorption is mainly $E1$. Therefore, if one assumes that the emission and absorption strength functions are equal, γ rays emitted in this energy region can be used to study the $E1$ giant dipole resonances (GDR) built on excited states[1] as well as the dependence of the giant-dipole strength function on excitation energy.

Recent studies[2] along these lines have shown that the γ-ray spectra from the deexcitation of compound nuclei with excitation energies E^* of ~50 MeV could be reproduced by statistical-model calculations using a Lorentzian strength function with the ground-state GDR parameters. Studies of this type rely on a comparison of the experimental γ-ray spectra to those of the statistical model, which in a simplified form is presented below.

The yield per megaelectronvolt of γ rays[3] of energy E_γ from a compound nucleus at excitation energy E^* is

$$Y^{(E^*)}(E_\gamma) = \Gamma_\gamma^{(E^*)}(E_\gamma)/\Gamma_T^{(E^*)}, \tag{1}$$

where

$$\Gamma_\gamma^{(E^*)}(E_\gamma) = \frac{1}{2\pi\rho(E^*)}\left\{\frac{2E_\gamma^2}{\pi(c\hbar)^2}\sigma_\gamma(E_\gamma)\rho(E^*-E_\gamma)\right\}. \tag{2}$$

If the total width Γ_T is approximated by the neutron width Γ_n, then

$$\Gamma_T^{(E^*)} \cong \Gamma_n^{(E^*)} = \frac{1}{2\pi\rho(E^*)}\left\{\frac{4MT^2}{\pi\hbar^2}\sigma_n\rho(E^*-B_n)\right\}. \tag{3}$$

In this expression B_n, M, and T are the neutron binding energy, neutron mass, and nuclear temperature, respectively. If we employ the logarithmic expansion[4] of the level densities $\rho(x)$ and neglect terms of second order and higher, Eq. (1) becomes

$$Y^{(E^*)}(E_\gamma) = \frac{E_\gamma^2\sigma_\gamma(E_\gamma)}{2c^2T^2M_n\sigma_n}\exp\left(\frac{B_n-E_\gamma}{T}\right). \tag{4}$$

The neutron absorption cross section σ_n is at a neutron energy of $\sim T$, and the photon absorption cross section $\sigma_\gamma(E_\gamma)$ can be written as

$$\sigma_\gamma(E_\gamma) = \mathcal{L}E_\gamma f(E_\gamma), \tag{5}$$

where $\mathcal{L}$ is the integrated cross section for $E1$ absorption.[3] The ground-state strength function $\mathcal{L}f(E_\gamma)$ for the GDR is well reproduced by a Lorentzian form with

$$f(E_\gamma) = \frac{\Gamma_G E_\gamma}{(E_\gamma^2 - E_G^2)^2 + \Gamma_G^2E_G^2}, \tag{6}$$

where E_G and Γ_G are the resonance energy and width, respectively. The γ-ray yield for a given E^* in this simplified statistical model becomes

$$Y^{(E^*)}(E_\gamma) \propto \frac{E_\gamma^3}{T^2}\exp\left(\frac{B_n-E_\gamma}{T}\right)\left\{\frac{\Gamma_G E_\gamma}{(E_\gamma^2-E_G^2)^2+\Gamma_G^2E_G^2}\right\}. \tag{7}$$

The objective of the present study is to obtain information on the energy (temperature) dependence of the $E1$ strength function by comparing the yield of 8 to 20 MeV γ rays to statistical-model predictions. To obtain a large range of excitation energies, we employed the deep-inelastic reaction 1150-MeV ^{136}Xe + ^{181}Ta. In this Letter we present the first experimental evidence for the dependence of the shape of the GDR strength function on the excitation energy.

The Xe-like fragments were detected at 29°, near the classical grazing angle, so that a large Q-value range could be studied in a single measurement (Fig. 1). In order to improve statistics, eight solid-state detectors ($d\Omega = 6.4$ msr/detector) were located in a ring centered around the beam axis. The reaction products are concentrated near the projectile and target masses[5] and the targetlike fragments tend to recoil to angles much larger than 29° and therefore are usually not detected. Thus, no Z or A identification was deemed necessary to reconstruct the two-body kinematics. The energy calibration of the heavy-ion detectors was obtained by elastic scattering of ^{136}Xe from a thin ^{197}Au target at several bombarding energies. γ rays were detected in seven 12.7 $\times$ 15.2 cm^2 NaI(Tl) detectors located 50 cm from the target. Six were in the horizontal plane at $\pm 90°$, $\pm 120°$, and $\pm 150°$ from the beam, and one was above the target (Fig. 1). A 3.2-mm Pb absorber in front of each NaI attenuated the intense background of low-energy γ rays. The NaI response function was measured in a separate experiment using the 4.43- and 11.68-MeV γ rays from the reaction ^{11}B$(p,\gamma)^{12}$C. For $E_\gamma > 10$ MeV, neutrons were completely separated from γ rays by time of flight. However, the energy region of the γ-ray spectrum less than 10 MeV may have a neutron contamination of up to 25% because of poorer timing and the larger number of neutrons.

Scaled-down particle singles and particle-γ-ray coincidences were recorded on magnetic tape, event by event. In Fig. 1 the energy spectrum of the Xe-like fragments and the five Q-value bins used in the analysis are shown. The mean excitation energies corresponding to bins 1 – 5 are 34, 80, 119, 159, and 199 MeV, respectively. These values were inferred from the energy of the Xe-like fragments by use of two-body kinematics and correcting for the evaporated mass. We estimate that the uncertainty in this calculation due to both the large solid angle of the heavy-ion detectors and the uncertainty in the detected fragment's mass is $< \pm 6\%$.

In Fig. 2 are shown the γ-ray spectra associated with the five Q-value bins, corrected for the average Doppler shifts. All spectra are approximately exponential for $E_\gamma < 9$ MeV, and above 10 MeV they increase significantly above the exponential line. As the excitation energy E^* increases, the yield of 10–20-MeV γ rays rises rapidly, indicating that γ-ray decay is competing more successfully with particle emission. At the highest studied values of E^*, the high-energy γ-ray yield tends towards saturation. This last result is in qualitative agreement with Eq. (7).

In order to obtain more quantitative predictions, calculations were performed with the code[6] GROG12 for deexcitation of a symmetric product, ^{158}Gd. (Only small changes in the total γ-ray spectrum result when calculations are made separately for the actual products ^{136}Xe and ^{181}Ta, assumed to be formed at equal temperatures.) The

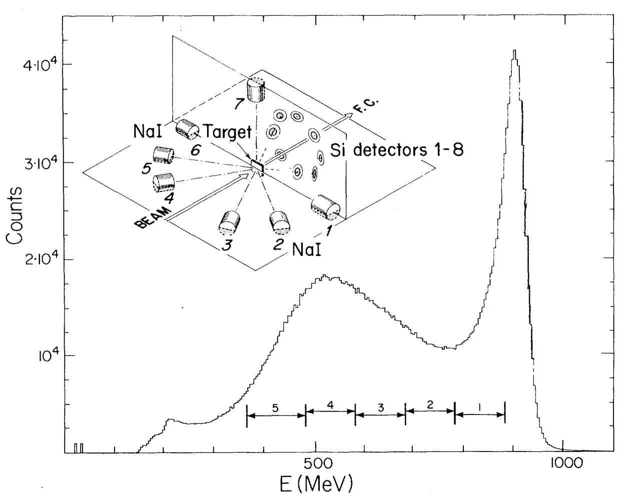

FIG. 1. Summed laboratory energy spectrum for Xe-like fragments detected at 29° in the eight silicon detectors. A schematic view of the experimental apparatus is shown in the inset.

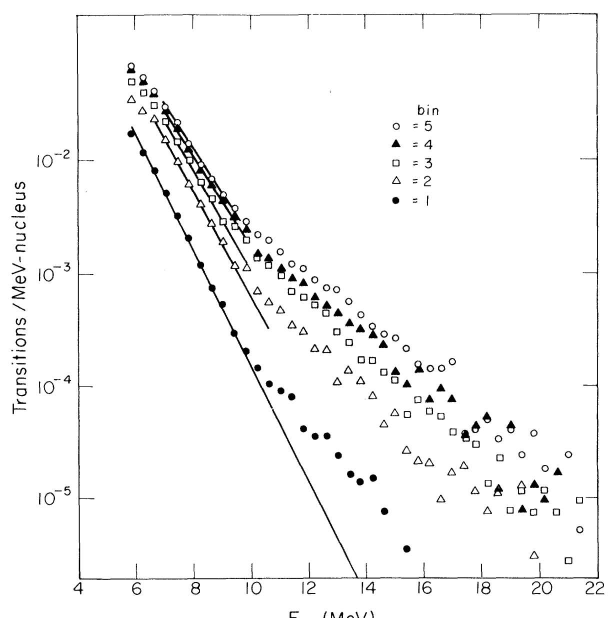

FIG. 2. γ-ray pulse-height spectra (combined for all seven NaI counters) associated with the five Q-value bins indicated in Fig. 1.

fragment spins were deduced from γ-ray multiplicities of similar systems[7] by scaling with ratios of the grazing angular momenta. However, the calculations were not very sensitive to these spins. It was assumed at each step in the deexcitation cascade that the small charged-particle decay branches produced the same γ-ray spectrum as the neutron branch.

To facilitate interpretation of the measured γ-ray spectra, several sets of calculations were done. The first set used a constant $E1$ strength function (no GDR). Set II employed the ground-state values of the resonance energy (14.6 MeV) and width (6.5 MeV). In Set III the width was increased linearly from 1.0 to 1.5 times the ground-state value, as E^* increased from 34 to 199 MeV. In Set IV the width was increased as in Set III, and the resonance energy of the GDR was decreased linearly from 1.0 to 0.66 times the ground-state value as E^* increased from 34 to 199 MeV. All the calculated spectra were folded with the NaI response function.

In Fig. 3 these calculated γ-ray spectra are shown for all but the lowest excitation energy bin, which was omitted because of the large percentage variation of the excitation energy across this bin. At all excitation energies, the calculation with a constant strength function (Set I) substantially underestimates the data, even though this calculation was normalized by assigning radiative widths that are a factor of ~3 larger than the values found in (n,γ) experiments with slow neutrons. For Sets II–IV, the normalization was calculated from the $E1$ sum rule. The calculations employing the ground-state values of the GDR (Set II) give a much better representation of the data than does Set I, although they overestimate the 15-MeV γ-ray yield at the highest excitation energies. Better agreement with the 15-MeV γ-ray region is obtained by increasing the resonance width (Set III), but the best overall agreement is obtained when the peak resonance energy is also decreased (Set IV). [Calculations were also made for bin 5 with a resonance energy of 14.6 MeV and widths of 15 and 25 MeV; however, these calculations do not reproduce the data as well as the calculation where the peak energy is decreased (Set IV). The calculation with a 15-MeV width crossed the data at 15 MeV, underestimating the yield at 9 MeV by a factor of 2.7. The spectrum calculated with use of a 25-MeV width was worse, being similar in shape to the calculation of Set I for $9 < E_\gamma < 19$ MeV but increased by a factor of 1.6.]

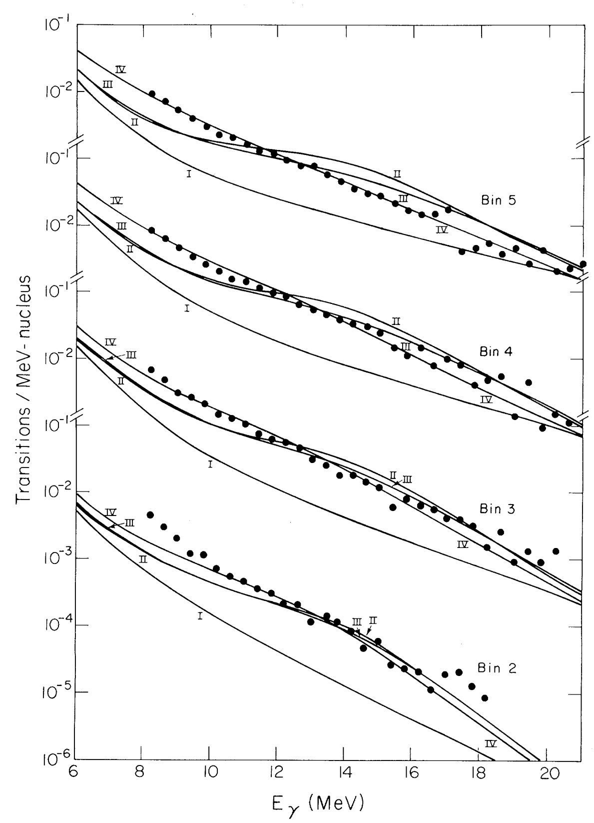

FIG. 3. Experimental (symbols) and calculated (curves) γ-ray pulse-height spectra associated with deep-inelastic products having mean excitation energies of 80, 119, 159, and 199 MeV for bin 2 through bin 5, respectively. The γ-ray spectra have been calculated for different widths and resonance energies of the giant-dipole strength function (see text) and have been folded with the measured NaI respones function.

The inferred increase in the resonance width might be trivially ascribed to the increasing width of the product mass distribution with increasing E^*. This explanation does not seem likely because of the weak $A^{-1/3}$ dependence of the ground-state resonance energy. An alternative explanation is that in deep-inelastic reactions the second moments[8] of the fragment spin distributions can be quite large even at a fixed Q value. This large range of angular momenta might lead to a variety of shapes, which would result in different values of the resonance energy and thus effectively broaden the resonance. A similar broadening occurs in rare-earth nuclei, where the apparent width is nearly twice that of a spherical nucleus.[9] An additional possibility is that the resonance width might increase with E^* because of an increase in the rate of dissipation of the collective state into the multitude of n-particle, n-hole states available at high excitation energies.

It is interesting to see whether a possible reduction of the resonance energy with excitation is indicated in simple theory. The energy $\hbar\omega$ of the dipole mode can be approximated[10] as

$$\omega \cong [\omega_0^2 + 3V_1/4M\langle r^2\rangle_0]^{1/2}$$

where V_1 is the symmetry potential, $\langle r^2\rangle$ is the mean squared radius, and $\hbar\omega_0$ is approximately $41A^{-1/3}$ near the Fermi surface. There are three quantities in the expression for ω that could depend on the excitation energy E^*: (1) For a harmonic oscillator $\hbar\omega_0$ is independent of E^*, but a more realistic well broadens at the top, so that the effective $\hbar\omega_0$ might be reduced for large E^*. (2) The symmetry potential measures the effect of the neutron-proton interaction as a restoring force for the GDR oscillation. Since the participating particles are spread over more shells at high excitation energies, the neutron-proton overlap will decrease and V_1 should also decrease. (3) Although one does not expect a large change in $\langle r^2\rangle$ with E^*, it should increase as a result of the particles in higher shells. These effects all decrease the resonance energy of a GDR built on a highly excited state. This agrees with the tentative conclusion from our experimental results. However, a quantitative theoretical analysis is beyond the scope of the present paper.

In summary, the yield of 10–20-MeV γ rays increases with the excitation energy of the deep-inelastic products and tends towards saturation at the highest excitation energies. A comparison of the γ-ray spectra with statistical-model calculations indicates that a constant strength function is unsatisfactory and a peaked strength function is needed. Although calculations using the ground-state values of the giant dipole resonance energy and width reproduce the γ-ray spectra at low excitation energies,[2] at high excitation energies better agreement is obtained with a smaller resonance energy and an increased width.

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