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Statistical and nonstatistical neutron decay of the giant electric dipole resonance of ^{208}Pb

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The neutron decay of the giant electric dipole resonance of ^{208}Pb has been determined by a measurement of the differential cross section, $d\sigma(E_\gamma,E_n)/dE_n$, of the ^{208}Pb$(\gamma,n)$ reaction for 20 contiguous photon energy bands between 11.2 and 15.7 MeV. The statistical component of the decay was calculated in the Hauser-Feshbach formalism. A nonstatistical component of the decay to low-lying hole states is unambiguously identified. The magnitude of this component is strongly energy dependent.

The large volume of experimental and theoretical work on giant multipole resonances has given them a familiarity which has also tended to hide important open questions. Two of these questions are: what are the mechanisms by which giant multipole resonances acquire their substantial widths; and, how do giant multipole resonances decay? The answers to these questions are important for understanding the microscopic structure of giant resonances. Experiments have determined the total width of many of the giant multipole resonances. Many-body theories[1] attribute the total width to three contributions: fragmentation of the particle-hole spectrum, coupling to the continuum, and coupling to more complicated excitations. Associated with these contributions are, respectively, the fragmentation width, $\Gamma_{\rm fr}$, the escape width, $\Gamma\uparrow$, and the spreading width, $\Gamma\downarrow$. Some measurements of giant resonance decay have been made with the goal of testing this theoretical framework. Unfortunately, the theoretical widths cannot be directly identified with experimental quantities, and the goal of testing the theoretical framework remains largely unsatisfied. We present here the results of a new measurement of the neutron decay of the giant electric dipole resonance of ^{208}Pb which should represent an optimal test of theory.

The neutron decay of the other giant multipole resonances in ^{208}Pb has been studied by the Karlsruhe[2] and Groningen[3] groups, who have used inelastic α-particle scattering to excite the resonances, and by the Oak Ridge group,[4] who has used inelastic heavy-ion scattering. With inelastic α-particle scattering, however, there were uncertain contributions from nonresonance processes, e.g., knock-out reactions, that contaminated the neutron spectrum. Thus, a precise measurement of the giant resonance decay alone has not been possible. Both reactions also excited a number of giant resonances simultaneously, and, in the case of inelastic α-particle scattering, in uncertain proportions. Since the decay spectrum was strongly influenced by the multipolarity of the giant resonance, the decay spectrum was difficult to interpret. In addition, to obtain adequate statistical precision, these studies have been forced to integrate over excitation energy, often the entire width of the giant resonance. Since the spectrum was strongly dependent on the energy for decay, ambiguities were again introduced. With these limitations it has been difficult to identify unambiguously the small nonstatistical component in the neutron decay.[5] In the present experiment there are no competing reaction mechanisms, only one multipole is excited, and the decay spectrum is measured for 20 contiguous energy bands over the width of the resonance. The present experiment is similar to, but more extensive than, the measurements on ^{209}Bi by Kuchnir *et al.*[6] and on ^{208}Pb by Calarco.[7]

The differential cross section for the ^{208}Pb$(\gamma,n)^{207}$Pb reaction was measured at three angles, 55°, 90°, and 125°, using the University of Illinois tagged-photon facility.[8] With a 24.2-MeV electron beam, photons between 9.3–15.7 MeV were tagged with a resolution of approximately 100 keV. The photon flux was determined to an accuracy of 5% (1σ). To obtain sufficient target material, two samples of radiogenic lead with different isotopic composition were used. The yield for ^{208}Pb was found by combining data from the two targets. Corrections for photon[9] and neutron[10] attenuation in the targets were calculated from tabulated cross sections. The neutron detector[11] was a heavily shielded liquid-scintillator cell. Neutron energy was determined by time-of-flight over a 1.5-m flight path. With an overall time resolution of 1.8 ns (full width at half maximum), the neutron-energy resolution varied between 0.17 at 2 MeV and 1.0 at 8 MeV. The response of the shielded detector to monoenergetic neutrons was determined in an independent experiment at the Ohio University Accelerator Laboratory. The detector efficiency was determined to an accuracy of 10% (1σ) for neutron energies greater than 1.2 MeV.

A typical ^{208}Pb$(\gamma,n)^{207}$Pb time-of-flight spectrum for a mean photon energy of 13.5 MeV and a neutron-detector angle of 125° is shown in Fig. 1. This histogram in 0.5-ns bins is obtained after the yield from ^{208}Pb has been separated, the time scale calibrated, the random coincidences subtracted, and the two tagging counters summed. The histogram is shown before the data have been corrected for the energy-dependent neutron efficiency. The peak at a flight time of 47 ns (5-MeV neutrons) is due to the unresolved ground, first, second, and third excited states. The broad maximum centered around a flight time of 90 ns (2-MeV neutrons) shows the preponderance of low-energy neutrons.

The absolute cross sections, differential in neutron ener-

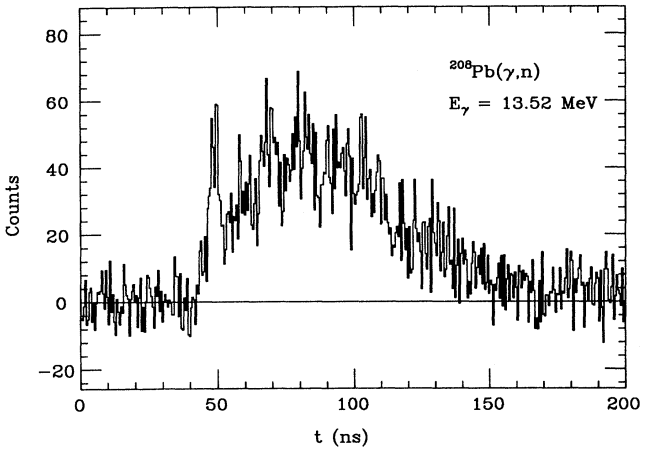

FIG. 1. Neutron time-of-flight histogram, measured over a 1.5-m flight path and binned in 0.5-ns bins, for ^{208}Pb(γ,n) at $E_\gamma = 13.52$ MeV and $\theta_n = 125°$. The zero of the time scale is the time at which a photon interacts in the target. The energy-dependent neutron-efficiency correction has not yet been applied to these data.

gy and angle, are obtained by normalizing these spectra by the photon flux, effective-target thickness, detector efficiency, and solid angle, and by transforming flight time to energy. By integrating the differential cross section over neutron energy and averaging the forward and backward angles, we can obtain the total photoneutron cross section,[12] which has been measured previously at Saclay.[13] Our total cross section is shown in Fig. 2. The curve is a Lorentzian fit to the data. The resonance energy of (13.6 ± 0.1) MeV and width of (4.2 ± 0.2) MeV are in good agreement with the Saclay values of 13.4 and 4.05 MeV. The peak cross section is, however, only (88 ± 2)% of that measured at Saclay. The difference is due to yield below our 0.7-MeV neutron-detection threshold. We estimate, using the Hauser-Feshbach calculation (described below), that an additional (13 ± 2)% of the yield is below our threshold. The sum is then in good agreement with Saclay, which shows that there are no large difficulties in the normalization of our experiment over its entire range of photon and neutron energies.

We have measured essentially complete neutron spectra from the decay of the giant dipole resonance for 20 slices of excitation energy over its entire width. The spectrum at a mean photon energy of 13.5 MeV is shown in Fig. 3. The data are the angle-averaged cross section, differential in neutron energy, divided by the Saclay total cross section at the appropriate photon energy. The data then represent the branching ratios for neutron decay to different final states. We assume that at each photon energy these spectra can be decomposed into two components, one due to statistical decay, and one due to nonstatistical decay, i.e., $\sigma(E_\gamma,E_n) = \sigma_{st}(E_\gamma,E_n) + \sigma_{nst}(E_\gamma,E_n)$. We use the Hauser-Feshbach formalism[14] to calculate the statistical component. In fact, the histogram in Fig. 3 is a Hauser-Feshbach calculation, the details of which are described below. Any significant difference between the statistical component and the data can be interpreted as due to a nonstatistical component.

To apply the Hauser-Feshbach formalism, we must specify the transmission coefficients in all energetically open channels. Since our highest photon energy is 15.7 MeV, we need the levels of ^{207}Pb up to 8.3 MeV.[15] Up to 3.5 MeV, we use the levels identified in direct-reaction studies.[16] Above 3.5 MeV, we describe the levels of ^{207}Pb by level-density formulas.[17] The formulas join smoothly to the discrete levels and reproduce the level density at neutron threshold.[18] The Groningen and ORNL (but not the Sao Paulo) groups also have followed this prescription. The transmission coefficients are calculated with the ABACUS[19] code using the optical-potential parameters of the Ohio University group.[20] To compare the Hauser-Feshbach calculations directly to the experimental spectra, the calculations are convoluted with the empirical energy resolution. This convolution includes the effects of overall time and photon energy resolution, and detector thickness.

Since Hauser-Feshbach produces only a statistical branching ratio, $\sigma_{st}(E_\gamma,E_n)/\sigma_{st}(E_\gamma) \equiv BR_{st}(E_\gamma,E_n)$, some

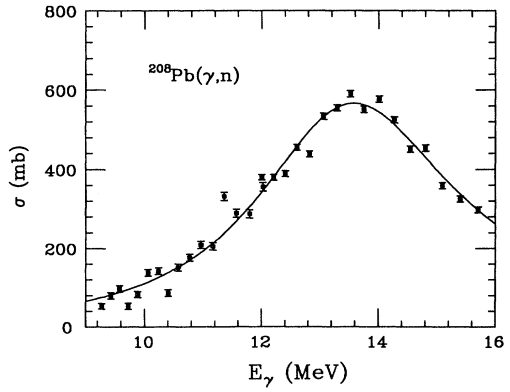

FIG. 2. Total cross section for ^{208}Pb(γ,n), obtained by integrating the differential cross section over neutron energies and angles. The smooth curve is a Lorentzian fit to the data, the parameters of which are described in the text.

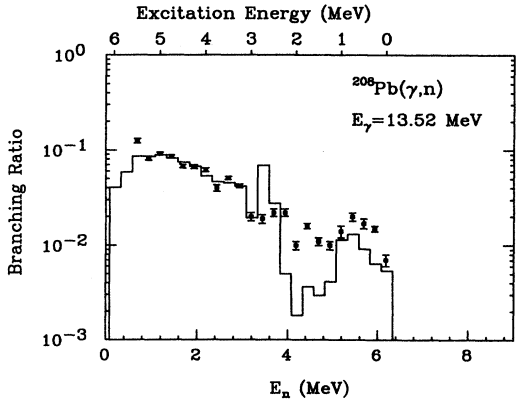

FIG. 3. A comparison of the normalized Hauser-Feshbach calculation (histogram) to the experimental branching ratio at $E_\gamma = 13.52$ MeV. The excess of strength at a high neutron energy is attributed to nonstatistical decay of the giant resonance.

normalization is needed to compare the calculation to the data. If we assume that the cross section, $\sigma(E_\gamma,E_n)$, is statistical at $E_n \cong 2$ MeV, we can find (for each photon energy) a constant, $\alpha(E_\gamma)$, for which $\sigma(E_\gamma,E_n)/\sigma(E_\gamma) = \alpha(E_\gamma)\mathrm{Br}_{\mathrm{st}}(E_\gamma,E_n)$. Then for all E_n we use $\sigma_{\mathrm{st}}(E_\gamma,E_n)/\sigma(E_\gamma) = \alpha(E_\gamma)\mathrm{BR}_{\mathrm{st}}(E_\gamma,E_n)$. The normalized Hauser-Feshbach calculation is compared to the experimental branching ratio in Fig. 3. This normalization produces sensible results. For excitation energies above 12 MeV in ^{208}Pb, the constants decrease monotonically from 1.0 at 12 MeV to 0.8 at 15 MeV. Below 12 MeV, the constants are set to 1.0, which appears to best match the calculations to the data. In principle, a normalization constant of 1.0 implies that the cross section is consistent with purely statistical decay for all neutron energies.

Figure 3 shows four features that occur at all photon energies. First, for $E_x > 3.0$ MeV, the calculation reproduces the experimental spectrum.[21] For these excitation energies, then, there is no apparent nonstatistical contribution. Second, for $E_x < 3.0$ MeV, the data exceed the calculations, suggesting that there is a significant nonstatistical contribution in the decay to low-lying hole states.[22] Third, the calculations have a prominent peak at $E_x \cong 2.8$ MeV, which does not appear in the data. The yield to states at this energy, identified as $^{208}\mathrm{Pb}(3^-)\otimes p_{1/2}^{-1}$, is not enhanced. The yield to the 4.1 MeV, $^{208}\mathrm{Pb}(2^+)\otimes p_{1/2}^{-1}$ states, is also not enhanced.[23] Fourth, the calculations have deep minima at the excitation energy of the 1.6 MeV, $13/2^+$ state, where the spectra exhibit considerable strength.[24]

A comparison of the data and calculations as a function of photon energy is shown in Fig. 4. The data and calculations have been integrated over three different regions corresponding to excitation energies in (a) from 0 to 1.5 MeV, in (b) from 1.5 to 3.0 MeV, and in (c) above 3.0 MeV. In part (c), the agreement strongly suggests that these levels are populated statistically. (The small deviation is mostly due to the detector threshold.) In part (b), the calculation and the data have rather different energy dependences. The calculation is actually somewhat larger than the data for $11 < E_\gamma < 14$ MeV.[25] This result is unphysical, since with our normalization the nonstatistical contribution would be negative. Above 14 MeV, the calculation is somewhat smaller than the data. In part (a), there is reasonable agreement for $E_\gamma < 13$ MeV. Above 13 MeV, the calculation becomes increasingly smaller than the data. The slow decrease in the yield in part (a) with increasing photon energy is a very strong indication of nonstatistical decay, since four low-lying levels are competing with an exponentially increasing number of levels at high excitation energy.

The nonstatistical component of the neutron decay of the giant dipole resonance in ^{208}Pb depends strongly on excitation energy and on final-state energy. No nonstatistical component is apparent for $E_\gamma < 13$ MeV. For $E_\gamma > 13$ MeV, the nonstatistical component can only be unambiguously identified in the decay to the low-lying hole states. We would like to infer the escape width of the giant resonance from the nonstatistical component of its decay, but a quantitative estimate appears to be very uncertain given the inconsistencies in the Hauser-Feshbach calculation. A more complete treatment of the reaction is needed.

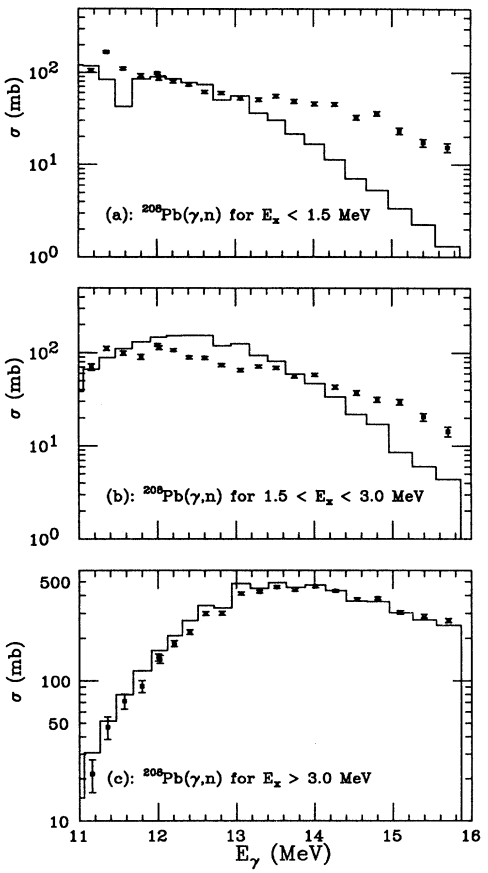

FIG. 4. A comparison of the normalized Hauser-Feshbach calculation (histograms) to the experimental branching ratio integrated over three regions of excitation energy: (a) $E_x < 1.5$ MeV, (b) $1.5 < E_x < 3.0$ MeV, and (c) $E_x > 3.0$ MeV. The nonstatistical component of the decay to the low-lying states is strongly energy dependent.

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[12]Consider an expansion of the differential cross section in Legendre polynomials. Since only a dipole and a quadrupole contribute for the photon energies in this experiment, the series only includes terms through the fourth order. Moreover, the quadrupole contribution is very small, such that the fourth-order term can be neglected. Then it is straightforward to obtain the total cross section from the forward and backward angle data, since the first- and third-order terms cancel out and the second-order term is zero.

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[21]Thus, at higher photon energies the calculation reproduces the neutron spectra for energies some 2–4 MeV greater than the energy at which the two are normalized.

[22]Since the giant resonance is a coherent particle-hole vibration, the hole states are preferentially populated when a particle escapes into the continuum.

[23]Thus, strong coupling of the dipole resonance to the low-lying vibrations is not apparent. See, for example, J. Wambach, V. K. Mishra, and Li Chu-Hsia, Nucl. Phys. A **380**, 285 (1982).

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[25]The strength is to a dense group of higher spin levels at about 2.8 MeV. For photon energies between 11–14 MeV, the transmission coefficients of the f and h waves, by which these levels are populated, become large enough that this dense group of levels acquires significant strength before, at higher photon energies, the increasing level density reduces their relative population. The discrepancy would be hidden if both the data and the calculations were integrated over the entire giant resonance.