$(e,e'n)$ Coincidence Studies of the Giant Multipole Resonances of ^{208}Pb

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The isoscalar monopole and quadrupole giant multipole resonances of ^{208}Pb have been studied in the excitation region of 9 to 16 MeV by coincident electron scattering. Concentrations of strength have been found at 10.4 and 14.2 MeV, in reasonable agreement with the predictions of mean-field theory. The measurements reported are the first nuclear-structure investigation carried out by use of the $(e,e'n)$ reaction.

Giant multipole resonances are the most important manifestations of collective behavior in atomic nuclei. Our knowledge concerning these fundamental modes of excitation is still rather primitive (as compared, for example, to our knowledge of the corresponding bound excitations), despite extensive theoretical and experimental research efforts over the last thirty years.[1,2] Perhaps the most significant reason for this unsatisfactory situation has been the lack of a probe of sufficient versatility and precision. Photonuclear reactions are well suited for the study of dipole excitations, but they can neither excite higher multipoles easily nor study the spatial characteristics of the excitation matrix elements. Hadronic probes are limited in accuracy because of their complicated reaction mechanisms and their lack of multipole selectivity. Inclusive electron scattering, the probe most often used for high-precision studies of nuclear structure, is of limited use for the study of continuum excitations because of the larger "background" due to the elastic-scattering radiative tail.

The recent development of cw electron accelerators has provided a powerful new probe for the study of giant resonances: coincident electron scattering. The coincidence requirement removes the contribution of the elastic radiative tail, allowing the study of the giant resonances with the same precision and versatility routinely available in (e,e') studies of discrete, low-energy excitations.

Giant multipole resonances, being collective excitations, are best studied in heavy nuclei. The substantial Coulomb barrier that characterizes these nuclei inhibits charged-particle decay, making $(e,e'n)$ the reaction channel of choice. However, the detection of low-energy (0.5–10 MeV) neutrons in the hostile environment of electron-scattering halls presents formidable technical problems. As a consequence, $(e,e'n)$ experiments have not been feasible at low-duty-factor electron-accelerator facilities. We report in this Letter the development of an $(e,e'n)$ facility and its use for the study of the giant multipole resonances in ^{208}Pb.

^{208}Pb, the heaviest doubly closed-shell nucleus, offers the best case available for testing our understanding of collective motion. Its excitation spectrum at low energies has been carefully investigated both theoretically and experimentally. Mean-field theory, in the form of density-dependent Hartree-Fock calculations, provides a satisfactory description of the ground-state properties of ^{208}Pb (and other doubly closed-shell nuclei).[3,4] It has been suggested that the dynamic behavior of these nuclei might be adequately described by extensions of this framework,[1,4,5] such as the time-dependent Hartree-Fock (TDHF) theory or the random-phase approximation (RPA). The RPA has proven quite successful in describing the spectrum and the transition charge densities of low-frequency collective excitations of spherical nuclei, such as the octupole excitations in doubly closed-shell nuclei.[6]

Unfortunately, tests of the predictions of these theories for higher-frequency collective excitations have been hindered by the fact that the experimental determination of the location and particularly the strength of resonances other than the isovector giant dipole resonance has been controversial.[7-20] Our study was undertaken for the purpose of determining the location and strength of monopole and quadrupole excitations in the giant resonance region in order to provide such a test in ^{208}Pb. We used the 100%-duty-factor electron beam available from the University of Illinois MUSL-2 accelerator. The excitation region of ^{208}Pb between 9 and 16 MeV was studied for three values of the effective momentum transfer (q_{eff}=0.26, 0.31, and 0.47 fm^{-1}). Coincident $(e,e'n)$ cross sections were measured for an electron-scattering angle of 60° for incident beam energies of 57.0, 67.6, and 80.4 MeV. Electrons scattered from a 38.5-mg/cm^2 target, enriched to 98.7% in ^{208}Pb, were detected in a magnetic spectrometer that subtended 5 msr and had a momentum acceptance of 5% and an energy resolution of 0.1%. The decay neutrons were detected by two NE-213 liquid-scintillator detectors placed antiparallel and perpendicular to the momentum-transfer axis at a distance of 1 m. These detectors each subtended 64 msr, and were placed in the scattering plane. The γ-ray background in the neutron detectors was reduced to acceptable levels through a combination of analog and digital pulse-shape discrimination techniques. The true-to-accidental ratios observed in the timing spectra ranged from 0.3 to 2 depending on the beam intensity and energy, and on the position of the neutron detector. The acceptance and efficiency of the neutron detectors was determined to a typical accuracy of 20% with standard calibration techniques.[21]

The basic features of the coincidence technique are illustrated in Fig. 1, where inclusive (e,e') and coincident $(e,e'n)$ spectra are compared. The (e,e') spectrum is dominated by the elastic-scattering radiative tail; less than 3% of the observed cross section is due to the inelastic scattering of interest. Clearly it would be exceedingly difficult to isolate the nuclear excitation in the region of interest. The imposition of the coincidence requirement removes completely the contribution of the elastic scattering and its associated radiative tail, revealing the excitation spectrum of ^{208}Pb. Because of the very high Coulomb barrier in ^{208}Pb, the branching ratio, Γ_n/Γ, for neutron decay is essentially unity for energies significantly above the neutron threshold energy (7.368 MeV). As a result, the coincident $(e,e'n)$ cross section, corrected for the neutron-detector efficiency and solid angle and integrated over all neutron emission angles (also shown in Fig. 1) corresponds to the inclusive (e,e') cross section. Two dominant resonance shapes can be seen easily in these data at 10.6 and 14 MeV. On the basis of the systematic mass dependence of the giant multipole resonances and the results of other reactions on ^{208}Pb (see, e.g., Refs. 17 and 20), one can associate the lower-energy excitation with the isoscalar quadrupole resonance and the higher-energy excitation with both the isovector dipole and the isoscalar monopole resonances.

The contribution of the isovector dipole resonance (IVDR) was separated from the spectra and the sum of the monopole and quadrupole multipole strength functions was extracted by a combined analysis of our $(e,e'n)$ data and earlier (γ,n) data of Veyssiere *et al.*[22] and Bell, Cardman, and Axel[23] following the procedures outlined in Refs. 7 and 24. Our measurements were performed at low momentum transfers and at forward electron-scattering angles, conditions that favor the excitation of low-multipolarity electric (longitudinal) resonances. In our analysis we have considered the contributions from monopole, dipole, and quadrupole excitations. The transverse contributions to the measured cross sections were taken into account by application of the continuity equation to the transition charge densities.

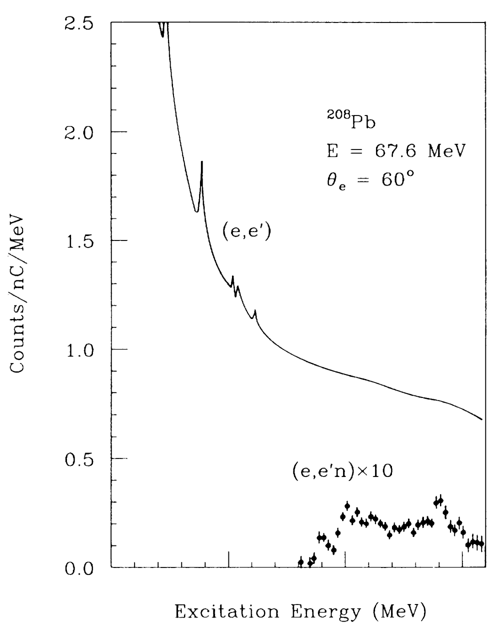

FIG. 1. Inclusive (e,e') and coincident $(e,e'n)$ spectra from ^{208}Pb. The coincidence condition removes the radiative tail, revealing the nuclear response.

The transition charge densities associated with each multipole were taken from the RPA calculation of Wambach and Co'.[25] This calculation used a phenomenological Woods-Saxon basis and an effective interaction of the Migdal type. It is similar in spirit to earlier calculations of Rinker and Speth.[1,26] For each multipole considered the low-q form factors predicted by the RPA transition charge densities are remarkably similar throughout the range of excitation energies covered by the present experiment. We have simplified the data analysis by using a single transition charge density for each multipole; this density was obtained from the theory by a strength-weighted average over the predicted states of that multipolarity. The form factors predicted by the averaged monopole and quadrupole densities are essentially identical over the q values of this experiment; as a consequence our analysis is sensitive only to the sum of the monopole and quadrupole strength. Because the dipole strength is essentially fixed by the (γ,n) data, the procedure followed is roughly equivalent to removing the dipole contribution to the measured electron-scattering spectra by extrapolation from $q=\omega$ with the form factors predicted by the RPA theory. The remaining (nondipole) cross sections are then extrapolated back to the photon point with use of the RPA form factors to infer the sum of the $E0$ and $E2$ strength functions. The resulting strength and its statistical uncertainty are displayed in Fig. 2.

$E3$ and other, higher multipolarity processes were neglected in our analysis. Their effect was estimated with use of the strength functions inferred from the (α,α') experiment of Morsch *et al.*[16] and extrapolation to the q values of our data using a Tassie-model form factor. This procedure estimates that the $E3$ contribution is less than 1% of the observed cross section for all but the highest-q data; for those data it is estimated to be $<1\%$ for excitation energies below 14 MeV, and to rise to about 7% by 16 MeV. Its effect on the inferred $E0/E2$ strength function would be negligible.

Broad concentrations of strength centered at 10.4 and 14.2 MeV are observed in the $E0/E2$ response (see Fig. 2). These two multipoles cannot be distinguished in electron scattering in a model-independent way. $E0$ and $E2$ transitions characterized by the same reduced transition probability amplitudes, $B(E\lambda)$, yield form factors differing by a factor of $16\pi/25\approx 2$. (This factor is exact

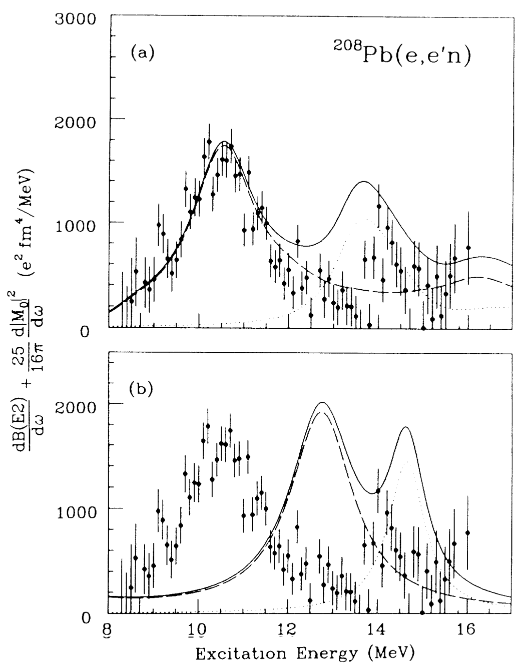

FIG. 2. The sum of the $E0$ and $E2$ nuclear responses, as inferred from the ^{208}Pb $(e,e'n)$ measurements, compared to (a) the RPA calculation of Wambach and Co' (Ref. 25) and (b) the TDHF-RPA calculation of Dechargé and Gogny (Ref. 27). The solid curve gives the total $E0/E2$ response. The dotted and the dashed curves give the monopole and quadrupole responses, respectively.

in the plane-wave Born approximation, and approximately correct for a distorted-wave Born-approximation calculation.) The measured $E0/E2$ response in the region between 9 and 12.5 MeV can be reasonably well described by a Lorentz peak centered at 10.4 ± 0.4 MeV with a width (FWHM) of 2.0 ± 0.3 MeV. This peak has been identified in a variety of reactions[7-20] as the isoscalar quadrupole resonance (ISQR). This naive, but economical parametrization facilitates a convenient and well-understood comparison to previous measurements. It implies that 67% (5.40×10^4 MeV e^2 fm^4) of the isoscalar energy-weighted sum rule[28] (EWSR) is exhausted; 3.76×10^4 MeV e^2 fm^4 of the total strength implied by the Gaussian fit lies between 9 and 12.5 MeV. The uncertainty in the derived strength in this region is dominated by the model dependence of the multipole unfolding procedure, estimated to be about 25%.

The amount of ISQR strength found is in agreement with the most recent hadronic measurements,[13-17] but it disagrees with the values obtained from earlier hadronic[9-12] and electron-scattering[8] measurements. The original claim for an anomalously low ISQR strength based on high-resolution (e,e') measurements[8] has been revised as a result of an improved analysis[9] of these data; their new results for the ISQR region are in good agreement with our results. The large $\sigma(\pi^-)/\sigma(\pi^+)$ ratio observed in recent pion scattering[18] measurements has been interpreted as implying that a significant fraction of the EWSR is exhausted only for neutrons in ^{208}Pb; our results contradict this interpretation.

A second concentration of strength is found centered at 14.2 MeV, a value consistent with the location of the isoscalar monopole resonance as determined from a variety of hadronic measurements. The presence of the IVDR, which is centered at 13.4 MeV in ^{208}Pb, results in a substantial increase in the model error with which the $E0/E2$ strength function can be extracted in the region above 12 MeV. The subtraction of the $E1$ strength depends sensitively on the q dependence of the form factor used to extrapolate the (γ,n) data to the q values of our experiment. The analysis presented here, which uses the RPA form factors of Wambach and Co', results in a total strength of 3.61×10^4 MeV e^2 fm^4 from 12.5 to 16 MeV; this would correspond to 44% of the $E0$ EWSR, if all the strength in that region is assumed to be monopole. An earlier analysis,[29] using modified Tassie-model form factors, inferred a total strength in this region of 1.07×10^5 MeV e^2 fm^4, or 132% of the $E0$ EWSR. The difference between these values is a reasonable estimate of the model dependence in the extraction of the $E2/E0$ strength function in this region. The strength we infer from the RPA analysis in this region is less than the average value[17] of $90\% \pm 25\%$ of the EWSR obtained from Gaussian fits to data obtained with hadronic probes.

In Fig. 2, the experimental data are compared to two recent theoretical calculations. The first [Fig. 2(a)] is the result of the RPA calculation by Wambach and Co'[25] described briefly above. To account for the effects of the coupling to the continuum (the escape width) and of spreading, and to facilitate the comparison with the data, each theoretical multipole response function has been convoluted with a Breit-Wigner shape of adjustable width. A spreading width of 1.0 MeV was used for the monopole response, but a spreading width of 1.7 MeV was needed to match the measured quadrupole response. It can be seen that this calculation, which is based on the Landau-Migdal approach, describes our data reasonably well. Since the data were analyzed with the form factors obtained from this RPA calculation, the discrepancies between the inferred and calculated strength functions reflect the overall ability of the RPA theory to account for our measured cross sections.

The results of a TDHF-RPA calculation by Dechargé and Gogny[27] are displayed in Fig. 2(b). The basis functions used in this calculation were obtained self-consistently through a Hartree-Fock calculation with the same $D1$ effective interaction[3] as employed in the RPA. The results of this approach have been tested extensively throughout the periodic table and, in particular, in the lead region.[3,6,30] It describes successfully both the ground-state properties and the transition densities of low-frequency collective excitations of spherical nuclei. The calculated $E2$ and $E0$ responses were folded with the same Breit-Wigner shapes used for the RPA calculations of Wambach and Co', in order to facilitate a comparison with the data. It is evident that this calculation fails to describe the data satisfactorily. The energy of the quadrupole resonance is higher than the experimental value by about 2 MeV, as is the case for the IVDR (not shown). The energy of the monopole (breathing mode) is only slightly higher, reflecting the fact that the nuclear compressibility is well reproduced by the $D1$ force. As pointed out by Brown[31] the resolution of the discrepancy between the theoretical and experimental values for the centroid of the $E0$ strength may provide useful clues on how to extrapolate the Landau parameters to nuclear matter and thereby determine its compressibility. These deficiencies can be partly attributed[32] to the truncation of the Hartree-Fock basis ($10\hbar\omega$), and to the incorrect effective mass ($m^* \simeq 0.7$) implied by a collisionless, self-consistent theory. However, the gross features of the data, such as the concentrations of strength and the relative ordering of the various multipoles, are well reproduced by the calculation for the range of momentum transfers that have been explored.

In the self-consistent TDHF-RPA approach, the effective interaction is adjusted to fit the observed ground-state properties of finite nuclei; no further adjustments can be performed in order to describe the excitation spectra of nuclei. The shortcomings of this approach for the description of the electromagnetic response of ^{208}Pb in the giant resonance region is in marked contrast with its impressive success in describing the ground-state properties of nuclei throughout the periodic table. The data presented here provide a new benchmark for the mean-field description of finite nuclei in the relatively unexplored high-frequency sector. The need to extend these measurements in ^{208}Pb to higher momentum transfers and excitation energies is obvious, as is the need to determine the q dependence of the IVDR experimentally. Work in these areas is now underway.

In summary, we have performed the first coincident electron-scattering measurement of the $E2/E0$ electromagnetic response of ^{208}Pb in the region of the isoscalar quadrupole and monopole resonances. Our measurements contradict claims of anomalously low ISQR strength and claims that this strength arises mostly from neutron contributions. Microscopic calculations based on the Landau-Migdal phenomenology of finite Fermi systems yield a reasonably good description of our data. The self-consistent TDHF-RPA calculation of Dechargé and Gogny, which has proven highly successful in describing static or near-static properties of ^{208}Pb, correctly predicts the concentration of multipole strength, but fails to reproduce the energy distribution of the strength correctly.

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