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Observation of $2\hbar\omega$ hexadecapole strength in lead nuclei from 200 MeV inelastic proton scattering

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Excitation of strength peaked at 12.0 MeV is observed in ^{208}Pb and ^{206}Pb via the inelastic scattering of 200 MeV protons. Based upon angular distribution measurements in ^{208}Pb we interpret the strength as an isoscalar $2\hbar\omega$, $L=4$, excitation.

[NUCLEAR REACTIONS ^{208}Pb, ^{206}Pb (p,p′), $R_p=200$ MeV; measured E_x, $\sigma(\theta)$ for giant resonances; deduced, E_R, Γ_R, $B(E4)$.]

Since 1971 several nondipole giant resonances have been observed.[1] The isoscalar giant quadrupole resonance (GQR), located at $\sim 63A^{-1/3}$ MeV, the isoscalar giant monopole resonance (GMR) at $\sim 80A^{-1/3}$ MeV, and the $3\hbar\omega$, giant octupole resonance (GOR) have been well established in nuclei spanning much of the periodic table. In addition, in ^{208}Pb some evidence has been provided for excitation of the isovector quadrupole[2,3] and isoscalar dipole[4] resonances.

The observation of higher multipolarity giant resonances ($L>3$) is made difficult by the fact that the strength for each multipole may be split among several classes of excitations.[1] For example, the hexadecapole (GHR) strength should be distributed among $0\hbar\omega$, $2\hbar\omega$, and $4\hbar\omega$ transitions. This is to be contrasted with the giant dipole resonance (GDR) strength which is localized in $1\hbar\omega$ transitions at $\sim 77A^{-1/3}$ MeV and quadrupole strength which is found in low-lying, $0\hbar\omega$ states and higher-lying, $2\hbar\omega$ excitations near $63A^{-1/3}$ MeV. Further complicating the observation of GHR strength is the prediction[5] that the $L=4$, $2\hbar\omega$ strength will be located at nearly the same energy as the $2\hbar\omega$ GQR. Recent calculations[6] for ^{208}Pb predict a $T=0$ $2\hbar\omega$, $L=4$ state at 11.0 MeV with a 2.2 MeV width and an 18% depletion of the energy weighted sum rule (EWSR), whereas the GQR in ^{208}Pb is located[1] at 10.6 MeV with a 2.4 MeV width full width at half maximum (FWHM) and exhausts 75% of the EWSR. The $4\hbar\omega$, $L=4$ strength would be expected to lie much higher in excitation energy and should be quite broad, considerably broader than the 6 MeV width of the giant octupole resonance which is located near 20 MeV in ^{208}Pb.

In order to experimentally observe $2\hbar\omega$, GHR strength located near the GQR, the GHR must be excited with a probe that provides multipole selectivity. Intermediate energy protons provide such a probe since for inelastic scattering of 200 MeV protons the cross section for $L=2$ excitation is at a minimum where the $L=4$ cross section is maximum. We have previously used[7] this feature of 200 MeV (p,p′) reactions to set upper limits on the amount of $L=4$ strength present in the GQR region of ^{90}Zr and ^{120}Sn. Additional inferred evidence[8] for $L=4$ strength has been obtained also from (α,α') scattering on ^{208}Pb and lower energy (p,p′) reactions on ^{90}Zr and ^{92}Zr. However, evidence from the (α,α') reaction is rather uncertain since the $L=4$ and $L=2$ angular distributions are nearly in phase, and lower energy (p,p′) reactions do not have as clearly L-characteristic angular distributions as obtained in the present work. In these previous measurements no direct observation of a peak from excitation of $L=4$ strength was made. In the present work we present evidence for direct observation of a $2\hbar\omega$, $L=4$ peak at 12.0 MeV in ^{208}Pb and ^{206}Pb.

Protons of 200 MeV from the TRIUMF accelerator were inelastically scattered from ~ 80 mg/cm^2 targets and detected in the focal plane of the MRS, a broad range magnetic spectrograph facility.[9] Typical spectra cover an excitation energy range of ~ 40 MeV for a single field setting of the spectrograph. The MRS detector system consists of a thin plastic scintillator and a 12.5×12.5 cm^2 wire chamber located in front of the magnet, and two larger wire chambers after the magnet which intersect the focal plane which are followed by a thick plastic scintillator. The front wire chamber determines the acceptance solid angle, allowing absolute determination of cross sections. The scintillators provide time-of-flight particle identification and, along with the fast wire chamber pulses, form the event trigger. We have measured the spectrograph response and beam quality at 0° using a reduced intensity beam and find no spurious background that would affect our results. At all angles studied no deleterious background was observed from blank target frames. Typical beam intensities ranged from 0.1–1.5 nA. The absolute beam current was determined with use of a calibrated monitor of proton-proton scattering from a thin CH_2 target located upstream of the spectrograph. The energy resolution was typically 900–1100 keV (FWHM). Measurements were made every two degrees between 6° and 20°. Our measurements of proton scattering cross sections from hydrogen using a CH_2 target agree to within 5% with phase-shift values.[10]

Spectra for ^{208}Pb and ^{206}Pb at angles for which the $L=2$ angular distributions should be maximized (8°) and where any $L=4$ contribution should be maximized relative to the GQR (14°, 16°) are shown in Fig. 1. The spectra were analyzed by assuming, as shown on the figure, a smooth shape for the nuclear continuum, and by fitting the resonance peaks with Gaussian shapes. The peak widths, centroids, and magnitudes were varied by an automatic peak

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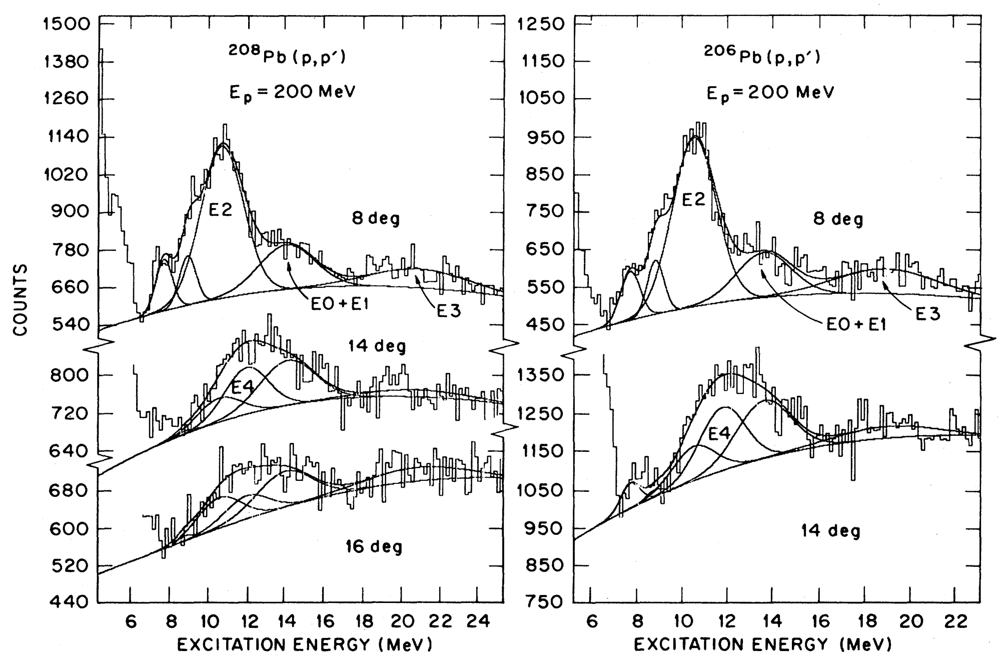

FIG. 1. Giant resonance spectra from inelastic scattering of 200 MeV protons from ^{208}Pb and ^{206}Pb. The multipolarities shown for the resonance peaks are discussed in the text. The smooth solid curve under the resonance peaks shows the shape and magnitude assumed for the nuclear continuum underlying the resonances. The shapes of the individual resonance peaks and the sum of the assumed continuum and peak shapes are shown.

fitting routine in order to minimize a χ^2 test of the total fit to the spectrum. Parameters for each peak were determined where the cross section is largest for a given peak, and those parameters were then used for peak extraction at all other angles.

Clearly visible in the smaller angle spectra for both nuclei is a 2.4 MeV wide peak at 10.6 MeV from excitation of the GQR and a 3.4 MeV wide peak at 13.8 MeV, which arises[3,11] from combined excitation of the GMR and GDR. The width and location of the GQR extracted in these data are in excellent agreement with previous measurements[1] using a variety of probes. The location and width of the 13.8 MeV peak is consistent with the parameters of the GDR known from photonuclear measurements[12] and those of the GMR obtained from very small angle (α,α') (Ref. 13) and $(^3\text{He}, {}^3\text{He}')$ (Ref. 14) measurements. Another, broader, peak is observed at ~ 20 MeV. This peak is interpreted[11] as arising from excitation of the $3\hbar\omega$, $T=0$, giant octupole resonance. Smaller peaks are observed on the low-excitation energy side of the GQR peak that have been interpreted[3,11] in earlier measurements as $L=2$ excitations. The giant resonance spectra in the 9–16 MeV region at 8° (and smaller angles[11]) are fitted very well by inclusion of only the GQR and GMR + GDR peaks.

However, the spectra in the 9–16 MeV region at larger angles cannot be fitted by inclusion of only the GQR and GMR + GDR peaks with centroids and widths determined at the smaller angles. It is clear from the experimental spectra in Fig. 1 that the overall centroid of the peak strength in the 9–16 MeV region shifts to a higher excitation energy. This shift in strength cannot be explained by drifts in the spectrometer field since data taken during the same run for low-excitation energy peaks show no shift. Furthermore, the ^{206}Pb and ^{208}Pb data were taken during experiments several months apart. The "shifted" spectra persist at all angles larger than 12° thus ruling out spectral contamination from light elements. We find that consistently good fits to the larger angle ($\gtrsim 12°$) data can be achieved with the inclusion of a 2.7 ± 0.3 MeV wide peak located at 12.0 ± 0.3 MeV in both ^{208}Pb and ^{206}Pb.

Preliminary results[15] from inelastic scattering measurements that we have made with ~ 70 keV (FWHM) energy resolution on ^{208}Pb using 330 MeV protons from Los Alamos Meson Physics Facility show an identical shift in the spectra. These results are consistent with the need for inclusion of the same width peak at the same excitation energy.

Figure 2 shows the angular distribution for the 12.0 MeV peak extracted from the ^{208}Pb data. The uncertainties in the data are largely determined by the uncertainty in the assumed magnitude and shape of the underlying nuclear continuum and in the peak fitting procedure. Although data were taken at angles smaller than 10°, extraction of a statistically significant peak at 12.0 MeV is not possible because of the very large GQR cross section. Cross sections for the GQR were extracted[11] at all angles; however, for clarity, only the forward angle results are shown in Fig. 2.

The curves shown in Fig. 2 are distorted-wave Born approximation (DWBA) calculations with a collective model form factor for isoscalar, $L=2$, 3, and 4 excitations near 12 MeV in ^{208}Pb. The calculations were made using optical parameters extrapolated from proton elastic scattering measurements[16] up to 180 MeV. The $L=4$ and $L=3$ calculated angular distributions are normalized to the measured cross sections for the 12.0 MeV peak. The $L=2$ calculation is normalized to the measured cross section for the GQR

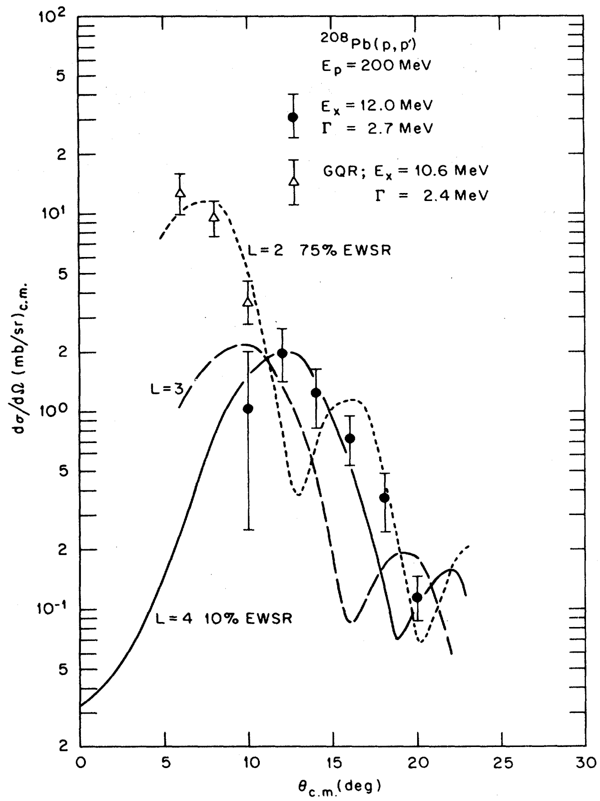

FIG. 2. Experimental angular distributions for the 12.0 MeV peak and the GQR peak (forward angles only) compared with $L=4$, 3, and 2 DWBA calculations which are denoted by the solid, long-dash, and short-dash curves, respectively. The EWSR depletions shown are obtained by normalizing the $L=2$ calculation to the GQR cross section as discussed in the text.

peak and is in excellent agreement[11] with the measured GQR angular distributions at all angles. The data for the 12.0 MeV peak agree with the shape of the calculated $L=4$ angular distribution. The $L=3$ calculation provides much poorer agreement and the $L=2$ calculation does not agree at all with the data. Comparison with DWBA calculations also rules out an $L=1$ or $L=5$ description.

Comparison of the measured cross sections with the normalized DWBA calculations shows that the $L=4$ excitation is expected to be weaker than the GQR at forward angles. At 10° the $L=4$ peak cross section is only $\sim\frac{1}{3}$ of the GQR cross section while at 8° the ratio of GQR to $L=4$ is calculated to be nearly 10 to 1. Such dominance of the GQR cross section precludes observation of the $L=4$ peak at smaller angles. The peak is only observable when the GQR and $L=4$ peak magnitudes are comparable.

Normalization of the calculated angular distribution to that measured provides a determination of the deformation parameter:

$$\beta_L{}^2=\frac{\sigma(L)_{\text{measured}}}{\sigma(L)_{\text{DWBA}}} .$$

If the assumption[1] is made that

$$\beta_L{}^2=B(EL)\left(\frac{4\pi}{3ZR^L}\right)^2 ,$$

then the EWSR strength depleted in the giant resonances may be deduced. This procedure yields 25% ± 5% and 3.5% ± 1% for the GQR and 12.0 MeV, $L=4$ peak, respectively. As we have previously pointed out,[7] the EWSR deduced for the GQR via 200 MeV inelastic proton scattering is considerably smaller than that deduced from other hadronic measurements. Our value for the ^{208}Pb GQR is a factor of 3 lower than accepted[1] values. However, our measurement[11] of the cross section for the 2.613 MeV, 3^- state in ^{208}Pb yields a $B(E3)$, which is also a factor of 3 smaller than accepted values. Because of the normalization deficiency in the DWBA for medium energy proton inelastic scattering we have normalized our results to a value of 75% for the GQR, EWSR depletion in ^{208}Pb. This normalization then yields a value of 10% ± 3% for the EWSR depletion of the $L=4$ strength at 12.0 MeV.

If, rather than separate a 12 MeV peak, we sum the entire cross section above the continuum and between 8 and 15 MeV of excitation following the same procedure we used in Ref. 7, we also find a need for inclusion of 10% of the $L=4$ EWSR to fit the angular distribution. Furthermore, as is detailed in Ref. 11, no need is found for inclusion of significant $L=4$ strength in the $E0+E1$ peaks in order to fit those angular distributions. These results support our contention that the peak we observe at 12 MeV certainly contains the major portion of the $2\hbar\omega$, $L=4$ strength located in this energy region.

In summary, we observe a heretofore unobserved peak at 12.0 ± 0.3 MeV in ^{208}Pb and ^{206}Pb. The angular distribution for the peak is consistent with an $L=4$ excitation depleting 10% ± 3% of the $T=0$, $L=4$ EWSR. We interpret the peak as arising from excitation of $2\hbar\omega$, hexadecapole strength. The location, width, and magnitude of this $2\hbar\omega$, $L=4$ strength are in excellent agreement with recent calculations[6] in ^{208}Pb. Although giant resonances are general properties of all nuclei, observation of the $2\hbar\omega$, $L=4$ strength in lighter nuclei will be more difficult than for lead. This is due to the fact that the width of the giant resonances is narrowest in lead nuclei and increases as $A^{-2/3}$. Based only on the present results for Pb the resonances may be expected to be located at the systematic energy of $\sim 70A^{-1/3}$ MeV.

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