Observation of the High-Energy Octupole Giant Resonance with 800-MeV Protons

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Inelastic scattering of 800-MeV protons from ^{40}Ca, ^{116}Sn, and ^{208}Pb shows a broad giant resonance at an excitation energy of $110/A^{1/3}$ MeV. The angular distributions are consistent only with scalar-isoscalar $l=3$ transfer. The excitation energy and width of this high-energy octupole giant resonance are in reasonable accord with theory. However, its energy-weighted sum-rule strength (~20%) is only about one half that predicted by random-phase-approximation calculations.

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In recent years great strides have been made in understanding the nuclear response function; for the multipoles $l=0$, 1, and 2, giant resonances (GR) are the dominant feature.[1,2] For $l=3$ the experimental situation is less clear. Collective isoscalar transitions with $l=3$ are well known, but in general these states contain only a few percent of the energy-weighted sum-rule (EWSR) strength. A GR-like structure with $l=3$ has been found to occur systematically at $\sim 30/A^{1/3}$ MeV in medium-mass nuclei ($60 \leq A \leq 200$).[3] This low-energy octupole resonance (LEOR) together with low-lying 3^- states accounts for about 25–30% of the EWSR.

In this Letter we report studies of the (p,p') reaction at $E_p = 800$ MeV on ^{40}Ca, ^{116}Sn, and ^{208}Pb. This work shows the first clear evidence of a systematically occurring octupole GR with an excitation energy $E_x \simeq 110/A^{1/3}$ MeV. Surprisingly, this state exhausts only ~20% of the $l=3$ EWSR compared to the ~40% expected theoretically.

Numerous attempts have been made to locate and define the properties of the high-energy octupole resonance (HEOR—in the terminology of Ref. 3). Evidence for an $l=3$ state near $E_x = 17$ MeV in ^{208}Pb exhausting ~90% of the EWSR has been reported in electron scattering.[4,5] Given the enormous uncertainties in unraveling the very complex spectra, this evidence must be regarded as only suggestive of the existence of an HEOR. Heavy ions have also been used to search for high-multipolarity GR's.[6] A promising peak was seen in the reaction ^{208}Pb(^{16}O, ^{16}O')^{208}Pb but it has more recently been explained in terms of neutron pickup to unbound states of ^{17}O.[7]

Beams of 800-MeV protons from the Clinton P. Anderson Meson Physics Facility were used to study the GR region in ^{40}Ca, ^{116}Sn, and ^{208}Pb. Inelastically scattered protons were momentum analyzed by the high-resolution spectrometer (HRS) and detected in an array of multiwire drift chambers and scintillation detectors which has been described previously.[8] Extensive ray tracing coupled with an extremely small (1 mm wide by 2 mm high) beam spot on target allowed contributions to the spectra from slit and pole-face scattering to be minimized. At each spectrometer setting data were accumulated in five missing-mass spectra, each one corresponding to a separate 0.40° range of scattering angle. Since the

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usable portion of the HRS focal plane corresponds to ~25 MeV of excitation for incident 800-MeV protons, two such sets of spectra were obtained at each central angular setting in order to cover the excitation energy range from 0 to ~42 MeV. The energy resolution was better than 150 keV throughout this range.

Spectra near both a maximum and a minimum for $l=3$ are shown in Fig. 1. A dramatic picture of the giant resonance structure of nuclei is seen in the ^{116}Sn spectrum where the low-energy octupole, giant quadrupole, and high-energy octupole resonances are all visible. The HEOR peak is very wide in ^{40}Ca. However, the pronounced change in the appearance of this broad structure as a function of scattering angle is a strong indication of the dominance of a single l transfer. As will be discussed below, the HEOR is expected to be very broad in light nuclei.

The appearance of peaks at these high excitation energies is due to the favorable resonance-to-continuum ratios seen with 800-MeV protons; e.g., $\frac{2}{1}$ ratios are found for the giant quadrupole resonances near the peak of the $l=2$ angular distribution. Extensive studies of continuum spectra from inelastic scattering of 800-MeV protons reveal the expected quasielastic peaks.[9] However, they are greater than 80 MeV wide [full width at half maximum (FWHM)] for targets with $A \geq 40$ and for lab angles $\theta_L \geq 11°$. Extrapolation of data from Ref. 9 to smaller angles shows that even for $\theta_L = 3°$ the quasielastic peaks from nuclei heavier than ^{6}Li should have FWHM > 40 MeV. Hence these structures cannot be confused with GR's.

Distorted-wave impulse-approximation calculations in which both GR's and quasielastic scattering are treated consistently should be possible in the near future. Until then one must estimate the continuum underlying the giant resonance region and subtract it. The shape of the continuum used here is indicated by dashed lines in Fig. 1. Figure 2 shows the resulting angular distributions of the HEOR along with distorted-wave Born-approximation (DWBA) calculations for $l=2-4$. For each target the points near the $l=3$ minima were plotted halfway between zero and an upper limit

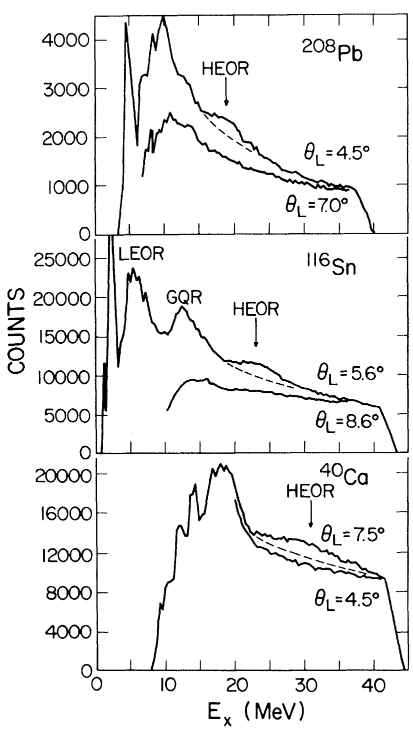

FIG. 1. Spectra from the (p,p') reaction at $E_p = 800$ MeV. For each target the upper and lower spectra correspond to a maximum and a minimum, respectively, of the $l=3$ angular distribution; the spectra are plotted in 400-keV wide bins. The low-excitation-energy regions for ^{40}Ca and ^{208}Pb have been cutoff for display purposes.

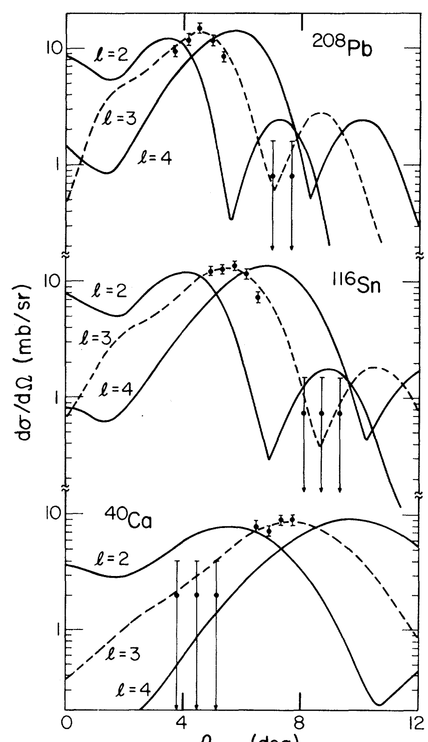

FIG. 2. Angular distributions of the HEOR's compared to DWBA predictions which are described in the text. The $l=3$ calculations are normalized to the data. The $l=2$ and $l=4$ normalizations are arbitrary.

on the resonance strength which is given by the top of the corresponding error bar; as is seen in Fig. 1 no HEOR peak was observable at these angles. The error bars on the larger cross-section points indicate the relative uncertainty among these angle bins, given a certain choice of background shape which was kept constant for all angles. Uncertainties in the magnitude of the background give an overall ± 25% error to the strength extracted for the resonance peak.

The EWSR strengths for the HEOR's have been evaluated according to the standard collective-model procedure.[10] The form factor was the derivative of the proton-nucleus optical potential, less the spin-orbit term. This term is unimportant for forward-angle 800-MeV (p,p') cross sections.[11] Coulomb excitation was included. The optical potentials were taken from extensive analyses of 800-MeV proton elastic-scattering data.[12]

It is clear that only $l=3$ is consistent with the data. At 800 MeV the central spin- and isospin-independent term is by far the dominant component of the nucleon-nucleon interaction.[13] Hence the observed strength of the broad peak is consistent only with its being a scalar-isoscalar resonance.

Parameters derived for the HEOR, LEOR (in ^{116}Sn), and low-lying 3^- states are given in Table I. Previously obtained data[14,15] for the lowest 3^- states in ^{40}Ca and ^{208}Pb at 800 MeV were used in conjunction with the present data to determine EWSR strengths for these states. Errors given for the EWSR strengths of the HEOR are dominated by uncertainties in the continuum subtraction.

A simple but reliable model of GR's starts with the harmonic-oscillator (HO) spectrum of allowed particle-hole excitations.[16,17] The particles and holes interact through a potential, V_{ph}, which is proportional to the change in density. The strength of V_{ph} is determined by the requirement of self-consistency.[17] For $l=3$ this model predicts two states: the LEOR and the HEOR, associated roughly with $1\hbar\omega$ and $3\hbar\omega$ excitations, at energies of 0 MeV and $7^{1/2}\hbar\omega$, respectively. Real nuclei do not, of course, exhibit 3^- ground states. More realistic random-phase-approximation (RPA) calculations[18-20] show that ~25% of the $l=3$ EWSR occurs in low-lying 3^- states, including the LEOR. The result $7^{1/2}\hbar\omega = 108/A^{1/3}$ MeV for the HEOR changes little in going from the HO model to the RPA results as is seen in Table I. An identical value of $108/A^{1/3}$ MeV for the HEOR can be derived from a macroscopic theory of GR's.[21]

The experimental EWSR strengths for the HEOR are substantially smaller than those expected from either simple theory or the RPA calculation.[19] This is surprising in view of the excellent agreement between theory and experiment found for the low-lying 3^- states and for other GR's. Caution must be used when comparing experimental resonances to RPA calculations which do not include a spreading width. This would only seem to increase the discrepancy in the case of the HEOR, however, since the $l=3$ response function of Liu and Brown[19] has been averaged over an interval which is considerably smaller (~2 MeV) than the observed widths. Other RPA calculations[18,20] of the $l=3$ response function yield similar HEOR strengths. Hence, one must conclude that present theory cannot account for the observed weakness of the HEOR.

The widths of GR's are also a source of very interesting physics. Microscopically it appears that the dominant term in the spreading width comes from couplings of the GR to low-lying collective states.[22] Macroscopically the GR widths

TABLE I. Comparison of experiment and theory. HO refers to the harmonic-oscillator model described in the text. Energy-weighted sum-rule (EWSR) strengths are in percent and excitation energies and widths (FWHM) are in megaelectronvolts.

		HEOR experiment			HEOR theory HO		Ref. 19		Ref. 21	
Nucleus	EWSR (lowest 3^-)	EWSR	E_x	Width	EWSR	E_x	EWSR	E_x	Width[a]	Width[b]
^{208}Pb	17 ± 4	20 ± 6	19.1 ± 1	5.3 ± 0.8	57	18.3	41	20	4.3	4.7
^{116}Sn	11 ± 3 25 ± 8[c]	22 ± 6	22.9 ± 1	6.5 ± 1.0	57	22.2	...	...	7.6	6.9
^{40}Ca	14 ± 3	20 ± 9	31 ± 2	10 ± 2	57	31.7	35.5	31	22.2	14.1

[a]One-body dissipation.
[b]Two-body viscosity.
[c]Low-energy octupole resonance strength.

can be interpreted as due to the damping of hydrodynamical flow by the viscosity of the nuclear fluid. Nix and Sierk[21] have evaluated the width of the HEOR based on one- and two-body dissipation mechanisms. Table I shows that the two-body viscosity model yields widths in good agreement with the data. Nix and Sierk caution, however, that the two-body viscosity calculations should not be valid for small-amplitude oscillations such as GR's. Because of a more rapid A dependence an alternative one-body dissipation model predicts an HEOR in ^{40}Ca which is so broad that it would not be visible experimentally.

With the discovery of the HEOR all of the expected gross features of the isoscalar $l=3$ response function have now been seen experimentally. The distribution of $l=3$ strength into the low-lying 3^- states and the LEOR is well reproduced by present RPA calculations. Nevertheless, the RPA predicts the HEOR to be about twice as strong as is found experimentally. Theoretical work on this problem is clearly required. On the experimental side extensive systematics should be obtained, particularly for deformed nuclei where quadrupole coupling effects should lead to a splitting of the HEOR.

The prognosis for finding GR's with $l>3$ containing large fractions of EWSR strength is rather bleak if one extrapolates from the relatively weak HEOR. This search will present a challenge to the new probes—medium-energy protons, pions, and heavy ions—in the coming years.

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