Excitation of Giant Resonances by Inelastic ^{3}He Scattering*

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Inelastic ^{3}He scattering at 71 MeV on twelve nuclei ranging from ^{27}Al to ^{209}Bi shows an enhancement of the continuum very similar to that observed in electron and proton scattering. The effect is ascribed to a giant multipole state. The strength of the excitation indicates an $E2$ character for the state.

Inelastic scattering of ^{3}He particles favors states of collective character in the final nucleus, and therefore this process should excite strongly the regions of the continuum in which the various multipole strengths are located. Recent work, however, is conflicting concerning the excitation of the proposed $E2$ giant resonance by inelastic scattering of ^{3}He particles.[1,2] Since such a state could exhaust a large fraction of the energy-weighted sum rule[3] (EWSR) in a relatively narrow region of excitation energy (3–4 MeV), it should appear strongly in ^{3}He spectra. The energy of the state is predicted to lie 2 MeV below the giant dipole resonance (GDR), and this appears to be well corroborated by inelastic electron and proton scattering.[4-9] However, the effects observed in these experiments can also be explained by the assumptions of an $E0$ giant resonance.[10]

Previous studies[1,11] of ^{3}He and ^{4}He scattering from Pb and Au at several forward angles indicate some enhancement in the region 2 MeV below the GDR, whereas at 41 MeV no enhancement of the continuum was observed in ^{3}He scattering from ^{24}Mg, ^{26}Mg, ^{50}Cr, ^{60}Ni, and ^{90}Zr.[2] Broad enhancements of the continuum at high excitation energies present special experimental problems. For example, slit scattering and nonlinearities or dead regions of the detection apparatus can easily produce or, alternatively, obscure such effects. The present experiment was undertaken to determine whether the effect observed in ^{3}He scattering is real, and, if so, to attempt to test the $E2$ character of the excitation.

The spectra of ^{3}He particles scattered from nuclei from ^{27}Al to ^{209}Bi were detected at forward angles. The data shown in Fig. 1 were taken with a silicon detector telescope. Similar spectra were obtained with a current-division wire proportional counter on the focal plane of a spectrograph. A plastic scintillator behind the wire counter gave total energy and time-of-flight information. This setup gave very clean spectra which were essentially identical to the data shown in Fig. 1 except that a smaller range of excitation energy was covered. Target thicknesses were kept relatively large (~ 2 mg/cm^2) to minimize the relative yield from light contaminants in the target. The energy of the beam was 71 MeV, and the energy resolution was typically 200 keV. In Fig. 1 spectra from seven nuclei ranging from ^{27}Al to ^{209}Bi are shown at a lab angle of 20°. No subtractions or corrections have been applied to the data. Similar results were obtained for ^{54}Fe, ^{120}Sn, and ^{197}Au, and, in fact, no targets which were bombarded failed to display an enhancement of the continuum like that shown in Fig. 1.

There is a very strong yield to excitation energies 2–3 MeV below the GDR, the position of which is shown by an arrow in Fig. 1, and the shape of the peak is asymmetric with the lower-energy edge being much sharper and more well defined. The width of the observed structure is considerably wider than that expected from photonuclear reaction for the GDR. However, in the lighter nuclei ($A \leq 58$) the spectra exhibit a considerable amount of structure just as they do in photonuclear reactions. The differential cross sections are very forward peaked with a rate of falloff similar to direct excitation of known collective states at the same beam energy.

The proposed $E2$ state and the GDR cannot be resolved from each other because the width of the two states exceeds their separation. Hence, the strength and position of the $E2$ state can only be estimated under various assumptions and then assigned an appropriate error. One procedure which gave reasonable results on the heavier nuclei consisted of the following steps: (1) A flat background was subtracted using points well below and above the GDR; (2) the largest possible GDR contribution was subtracted using the known width and position from photonuclear work; (3) the resulting peak was checked to see if it moved correctly kinematically. It displayed, in fact, a smooth symmetric shape about 3 MeV wide. The flat background, the assumed GDR, the

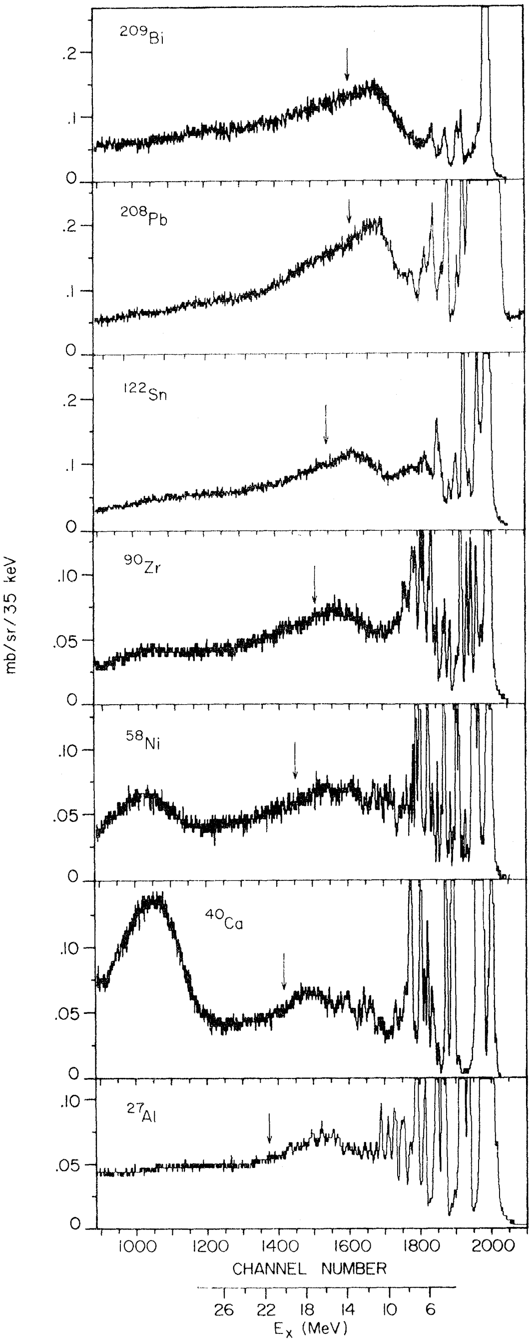

FIG. 1. Spectra from the (^{3}He, ^{3}He′) reaction on ^{27}Al, ^{40}Ca, ^{58}Ni, ^{90}Zr, ^{122}Sn, ^{208}Pb, and ^{209}Bi at 20°. The arrow indicates the position of the GDR as determined from photonuclear experiments. The broad peak near channel 1000 is due to elastic scattering from hydrogen.

resultant proposed $E2$ state, and the sum of the three are demonstrated in Fig. 2 for ^{208}Pb. The error in applying the above assumptions to a determination of the cross section is estimated to

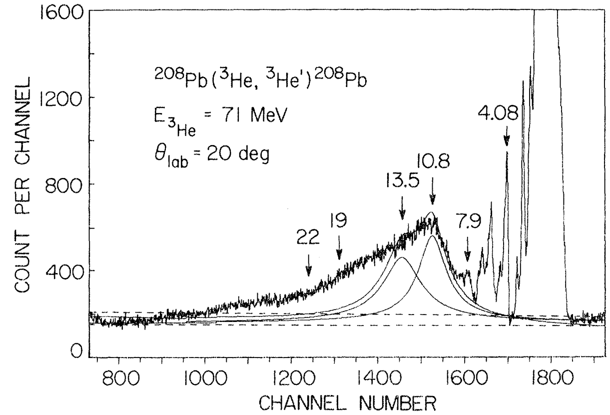

FIG. 2. Resonance unfolding of the observed structure. The dashed curves mark the linear background, and the solid lines are the GDR and GQR constituents (assumed to have a Lorentz shape) and their sum. The energy centroid and width for the GDR are taken from Ref. 12. Excitation energies shown are in MeV.

be 30%; the background subtraction contributes 25%, and the decomposition of the two peaks, 15%. These errors dominate over the other experimental uncertainties in determining the cross section.

One can see in Fig. 2 that there is no evidence in the present experiment for the fine structure of the ^{208}Pb resonance observed in electron scattering.[7] The (e, e') experiment showed the region near 11 MeV to consist of five peaks, while the present spectra taken from 10° to 42° give no evidence for this even though the resolution was the same in both experiments. In addition to the resonance at 11 MeV, the present spectra of ^{208}Pb seem to suggest (see Fig. 2) a broad bump in the 16- to 30-MeV region, in agreement with the work of Nagao and Torizuka[7] and Klawansky *et al.*[13]

Angular distributions of the new state, obtained by the procedure described above, are shown for ^{197}Au and ^{208}Pb in Fig. 3. Angular distributions for the GDR display similar shape and magnitude. Also shown are the distorted-wave Born approximation (DWBA) calculations for an $L=0$ and $L=2$ transfer. The prescription of Satchler[10] for a breathing-mode $E0$ excitation was used in the $L=0$ calculation, and the conventional collective model was used for the $L=2$ calculation.

The shape of the angular distribution in Fig. 3 cannot be used for an identification of L transfer because the error bars are larger than the small differences observed for the various L transfers at this energy. Evidently only the strength of the cross section can be used to distinguish between

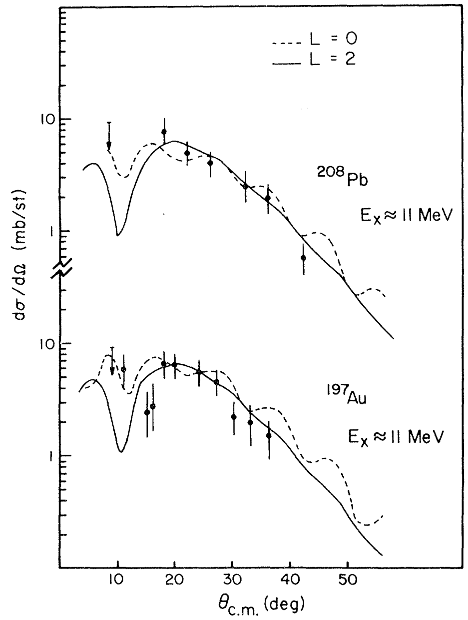

FIG. 3. Angular distributions for (^{3}He, ^{3}He$'$) leading to a region near 11 MeV in ^{197}Au and ^{209}Bi. The theoretical method for determining the curves for $L=0$ and $L=2$ is described in the text.

these two possibilities [originally raised in the (e,e') and (p,p') experiments]. The very strong yield argues for an $E2$ interpretation of the excitation. 100% of the EWSR for an $E0$ breathing-mode excitation gives only 10% of the measured cross section. However, there is considerable uncertainty in calculating an $L=0$ excitation because of the very small amount of data on inelastic scattering of ^{3}He's from 0^+ states in this region. On the other hand, the reason why so little data exist is that the yield of $L=0$ transitions is very low. In the case of $L=2$, however, one can compare directly to the excitation of the 4.1-MeV, 2^+state in ^{208}Pb measured at the same time as the giant multipole states. The ratio of the two yields is independent of angle and gives a $\beta_2 = 0.094$ for the state. This is almost exactly what one expects from the EWSR for an isoscalar $E2$ excitation which exhausts the remaining strength. That portion of the spectrum which was attributed to the GDR also appears to exhaust the EWSR. DWBA calculations for the $L=1$, $T=1$ excitation were carried out using the Goldhaber-Teller model. These calculations, which are similar to those of Satchler,[10] are quite sensitive to the radius of the imaginary isovector coupling interaction. However, with a reasonable choice ($r=1.6$ F, $a=0.8$ F) one obtains a good fit to the shape and magnitude of the measured GDR cross section. The comparison of the measured cross sections to those calculated by the EWSR and DWBA is given in Table I.

TABLE I. Energy, width, and fraction of the exhausted EWSR.

	E_x (MeV)	Γ (MeV)	L, T	σ_m/σ_c [a]
^{208}Pb	11	3	2, 0	1.2 [c]
			0, 0	10. [b]
	13.42 [b]	4.05 [b]	1, 1	1.1
^{197}Au	11	3	2, 0	1.3
			0, 0	10.
	13.70 [b]	4.75 [b]	1, 1	1.1

[a]Ratio of measured (σ_m) to calculated (σ_c) cross section. The calculated cross-section scale is determined by exhausting the EWSR. Optical potential parameters are from Ref. 14.

[b]Values taken from Ref. 12.

[c]Compared to 0.5 and 0.85 obtained in (e,e') and previous (^{3}He, ^{3}He$'$) studies (see Refs. 1 and 7).

[d]In good agreement with Ref. 1.

The results from the inelastic scattering of 71-MeV ^{3}He particles are therefore seen to be consistent with the assumption of an $E2$ giant resonance. The failure to observe the enhancement with 41-MeV ^{3}He particles was probably due to the relatively low beam energy and the high background in the region of interest. The ^{3}He scattering, in addition, seems to rule out more strongly than electron and proton data the possibility of an $E0$ transition for the state. Proving the $E2$ nature positively is very difficult, and requires a measurement of either the polarization of the scattered particle[15] or the decay modes of the continuum region.

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New Approach to Cosmic-Ray Diffusion Theory

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We have investigated a new approach to deriving a diffusion equation for charged particles in a static, random magnetic field. Our method incorporates essential effects of the magnetic fluctuations in the lowest order particle orbits. Significant corrections to the usual quasilinear diffusion coefficient for cosmic rays with pitch angles near 90° are a consequence. Monte Carlo results bear out the validity of our theory.

We propose a new scheme for deriving a kinetic equation for the one-particle cosmic-ray distribution function $\langle f\rangle$ averaged over an ensemble of static, random magnetic fields $\vec{B}$. The essence of our new method is that the zeroth-order particle orbits partially contain the effects of the fluctuating magnetic component $\delta\vec{B}$. The result of our theory is that $\langle f\rangle$ satisfies a diffusion equation in $\mu=\cos\theta$, where θ is the particle pitch angle measured with respect to the average field $\langle\vec{B}\rangle$. So long as μ is not too small, the diffusion coefficient $D(\mu)$ is the same as that derived from quasilinear theories.[1-5] When $\mu\simeq 0$ ($\theta\simeq\pi/2$), a regime in which considerable controversy has existed,[5,6] we obtain a D which is finite and markedly different from previous incorrect results. The reason for this difference near $\theta\simeq\pi/2$ is that our theory adequately describes the motion of such particles over a coherence time of the fluctuations, while quasilinear theory follows the motion of particles as if only $\langle\vec{B}\rangle$ existed and is hence a very poor approximation to their actual motion. The correctness of our theory is substantiated by comparison with the results of a Monte Carlo analysis.

For computational simplicity we consider the slab model[4] in which $\vec{B}=\hat{e}_z\langle B\rangle+\hat{e}_x\,\delta B(z)$, $\langle B\rangle$ being spatially homogenous and δB depending only on the single spatial variable z. The method can be generalized to more complex geometries.

The theory begins from the continuity equation for F, the cosmic-ray distribution function in the phase space whose dimensions are z, μ, speed v, and gyrophase φ. It proceeds by a formalism analogous to Weinstock's[7] plasma turbulence theory to a diffusion equation for $\langle f\rangle=(2\pi)^{-1}\times\int_0^{2\pi}d\varphi\langle F\rangle$. The assumptions made in the derivation are that (a) $\delta F(t=0)\equiv 0$, (b) $\langle F\rangle$ has only a weak φ dependence, and (c) $\langle f\rangle$ has a slow phase space evolution so that the usual adiabatic approximation is valid. The diffusion coefficient $D(\mu,t)$ is given by

$$D(\mu,t)=\frac{q^2}{2\pi m^2c^2}(1-\mu^2)^{1/2}\int_0^{2\pi}d\varphi\sin\varphi\int_0^t d\tau\langle\delta B(z)U(t,\tau)(1-\mu^2)^{1/2}\sin\varphi\,\delta B(z)\rangle. \quad (1)$$