Columbia, Vancouver V6T 1W5, B. C., Canada.
[b]Present address: New Mexico State University, Las Cruces, N. Mex. 88001.
[c]Present address: Los Alamos Scientific Laboratory, Los Alamos, N. Mex. 87545.
[1]G. R. Satchler, Nucl. Phys. 55, 1 (1964).
[2]G. S. Blanpied *et al.*, Phys. Rev. C 18, 1436 (1978).
[3]W. R. Coker, L. Ray, and G. W. Hoffmann, Phys. Lett. 64B, 403 (1976).
[4]I. Ahmad, Nucl. Phys. A247, 418 (1975); C. Gustafsson and E. Lambert, Ann. Phys. (N.Y.) 111, 304 (1978).
[5]L. Ray and W. R. Coker, Phys. Lett. 79B, 182 (1978).
[6]G. R. Satchler, in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1971), p. 155; M. P. Fricke *et al.*, Phys. Rev. Lett. 16, 746 (1966).
[7]B. J. Verhaar *et al.*, Nucl. Phys. A195, 379 (1972).
[8]J. Raynal, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions, Zürich, Switzerland,* edited by W. Grüebler and V. König (Birkhauser-Verlag, Basel and Stuttgart, 1976), p. 271.
[9]H. Sherif and J. S. Blair, Phys. Lett. 26B, 489 (1968), and Nucl. Phys. A140, 33 (1970).
[10]A. Ingemarsson *et al.*, Nucl. Phys. A216, 271 (1973).
[11]P. J. Van Hall *et al.*, Nucl. Phys. A291, 63 (1977).
[12]R. de Swiniarski *et al.*, Phys. Lett. 79B, 47 (1978).
[13]G. W. Hoffmann *et al.*, Phys. Rev. Lett. 40, 1256 (1978).
[14]G. W. Hoffmann *et al.*, Phys. Lett. 76B, 383 (1978).
[15]G. R. Satchler, Nucl. Phys. A100, 497 (1967).
[16]E. L. Peterson *et al.*, Nucl. Phys. A102, 145 (1967); J. L. Friedes *et al.*, Nucl. Phys. A104, 294 (1967).
[17]O. Beer *et al.*, Nucl. Phys. A147, 326 (1970).
[18]G. Bruge *et al.*, Nucl. Phys A146, 597 (1970).
[19]A. K. Kerman, H. McManus, and R. Thaler, Ann. Phys. (N.Y.) 8, 551 (1959).
[20]In the microscopic KMT theory in which deformed densities are assumed, different central and spin-orbit *potential* deformation lengths result if the ranges of the spin-independent and -dependent *N-N* interactions differ significantly. At ~1 GeV these ranges are similar, and insignificant differences of only ~5–20% in $\beta_I^{s.o.}R_{s.o.}$ and $\beta_I R_I$ could result from this source.
[21]T. Tamura *et al.*, Comput. Phys. Commun. 2, 94 (1971).

Giant-Resonance Studies with High-Energy Heavy Ions

P. Doll,[a] D. L. Hendrie,[b] J. Mahoney, A. Menchaca-Rocha,[c] D. K. Scott, T. J. M. Symons, K. Van Bibber, Y. P. Viyogi,[d] and H. Wieman
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 20 November 1978)

Evidence is presented for the excitation of giant multipole resonances in inelastic scattering of 315-MeV ^{16}O ions on ^{12}C, ^{58}Ni, and ^{208}Pb targets. Highly excited modes around 20 MeV of excitation energy in ^{208}Pb exhaust a large fraction of the energy-weighted isoscalar $E3$ and $E5$ sum-rule strengths.

For the study of energy dissipation processes in heavy-ion reactions it is important to understand the response function[1] of the nuclei involved in the collisions. It is natural to assume that in the initial reaction step the excitation of simple one-particle, one-hole states absorbs part of the kinetic energy of relative motion. Therefore, giant multipole resonances may also be involved[2] if, in the adiabatic limit, the collision times are of the same order of magnitude as the corresponding quantum transition times.[3] In addition, angular-momentum matching conditions in heavy-ion reactions allow large angular momentum transfers. While several low-energy, heavy-ion scattering experiments ($\leq$10 MeV/nucleon)[4-6] have reported the observation of giant quadrupole structures in nuclei, it was the goal of the present experiment to improve these studies with a high-energy ^{16}O beam at 315 MeV on ^{12}C, ^{58}Ni, and ^{208}Pb, and to search for excitations of higher multipolarity, which have been reported so far only in electron scattering on ^{208}Pb.[7,8]

The experiments were performed at the Lawrence Berkeley Laboratory 88-in. cyclotron. A beam of 315-MeV $^{16}O^{6+}$ ions was scattered from self-supporting ^{208}Pb (1.03 mg/cm^2), ^{58}Ni (1.67 mg/cm^2), and ^{12}C (0.36 mg/cm^2) foils. The reaction products were identified in the focal plane of a magnetic quadrupole–single-dipole spectrometer, using a counter which determines the position ($B\rho$), energy loss (ΔE), and time of flight (TOF) of the reaction products. Position spectra of inelastically scattered ^{16}O particles on ^{208}Pb, ^{58}Ni, and ^{12}C targets are shown in Figs. 1(a)–1(c). Single-nucleon–transfer reactions were also investigated to assess the competition between

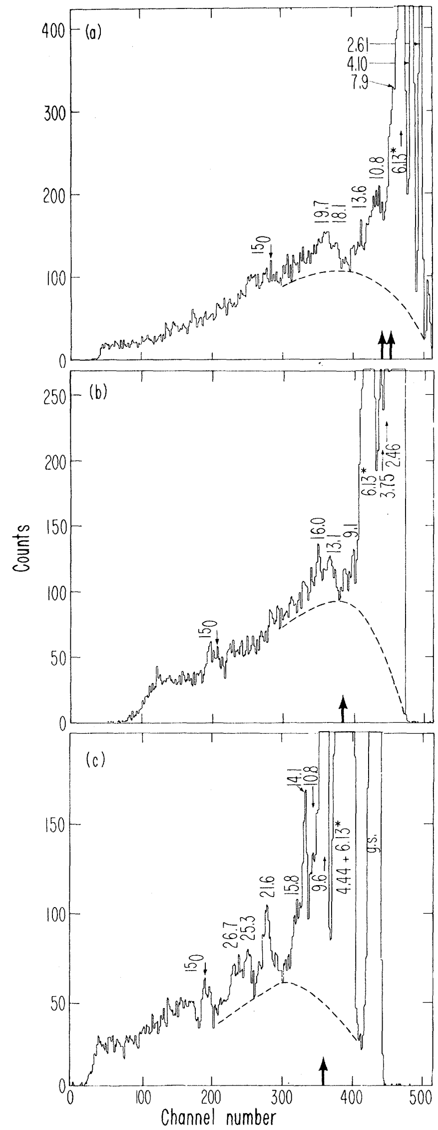

FIG. 1. Energy spectra for inelastic scattering of ^{16}O at 315 MeV on (a) ^{208}Pb, (b) ^{58}Ni, and (c) ^{12}C. The arrows on the horizontal axis indicate expected positions of projectile excitations built up on low-lying target states. The label ^{15}O denotes the position of low-lying transitions in the (^{16}O, ^{15}O) reaction.

transfer and inelastic scattering as the energy-loss mechanism in heavy-ion collisions. A more detailed presentation of these data will be given elsewhere.

All spectra exhibit pronounced structures in the continuum. The spectrum for ^{208}Pb, taken close to the grazing angle, shows strong excitation of giant resonance structures, which become pronounced for ^{58}Ni only at angles more forward than the grazing angle ($\theta_g^{lab} \simeq 9°$). For the $^{16}O + ^{12}C$ system the grazing angle is ~2° in the laboratory system and at such forward angles hydrogen contamination in the ^{12}C target obscured the ^{16}O energy spectrum in the giant resonance region.

Compared to hadron ($A \leq 4$) scattering data, the spectra reveal an improved peak-to-continuum ratio, possibly equaled only by a recent high-energy ^{6}Li scattering experiment.[9] The contributions from sequential decay of ejectiles following α, proton, or neutron pickup lie outside the region of the giant resonance structures in all three nuclei at 315 MeV incident energy. These processes are known[10] to be a severe problem in inclusive light-ion scattering spectra. At high excitation energies there is some contribution from ^{15}O ground-state groups as indicated in Fig. 1. The broad peak at a Q value of approximately 6 MeV in all spectra is attributed to the 3^-, 6.13-MeV projectile excitation, Doppler broadened by the subsequent γ decay and by underlying target states. The kinematically expected positions of projectile excitations built up on the strongest low-lying target states are indicated by arrows on the horizontal axis of each spectrum (see Fig. 1).

We interpret the 10.8-MeV ($\Gamma \simeq 2.5$ MeV) structure in ^{208}Pb,[11] the 16-MeV ($\Gamma \simeq 3.2$ MeV) side group in ^{58}Ni[11] (the 13.1-MeV group is found in electron scattering[12] to be of $E3$ nature), and the 25.3- to 26.7-MeV ($\Gamma \simeq 4$ MeV) groups in ^{12}C (Ref. 10) as the known isoscalar giant quadrupole resonances in these nuclei. The structure at 13.6 MeV in ^{208}Pb [see Fig. 1(a)], which is more pronounced in the present experiment than in light-ion scattering experiments, has been identified[13] previously as the giant monopole resonance. The distinctive structure of the spectra in the giant resonance region invites a detailed comparison with light-ion coincidence experiments especially for the ^{12}C case.[10] At a scattering angle of 3° the excitation of giant resonance structure seems to be even stronger than at 4° [Fig. 1(c)], but is superimposed on a 10- to 15-MeV-wide bump from hydrogen contamination in the ^{12}C target.

One of the most striking and novel features of the spectra for ^{208}Pb is the observation of a pronounced gross-structure peak at an excitation energy of approximately 20 MeV. No structure around this excitation energy was found in the inelastic scattering of ^{16}O at 140 MeV,[6] nor has any hadron scattering experiment revealed gross structure in this region. However, two electron-scattering[7,8] experiments and several theoretical calculations[1,11] imply a strong concentration of the $L=3$ and $L=5$ strength function at similar excitation energies. In particular, the structures found at 18.1 and 19.7 MeV in the present experiment are well reproduced by continuum random-phase-approximation calculations.[1,11] An additional hint that these highly excited structures in ^{208}Pb represent higher multipole modes comes from the simple liquid-drop model,[3] which predicts that, for increasing target mass (A), the response times $\tau \propto A^{2/3}/L^{3/2}$ of higher multipolarities (L) become better matched for the projectile collision times typical of this experiment.

Angular distributions were measured (see Fig. 2) for low-lying discrete states and the highly excited broad structures. Only typical examples are discussed here. The 25.3- and 26.7-MeV components in ^{12}C were analyzed separately (after subtracting a smooth background through the minima in the spectra as indicated in Fig. 1 by dashed curves) and revealed no significant differences in the diffraction patterns. The same result holds for the 18.1- and 19.7-MeV groups in ^{208}Pb. Distorted-wave Born-approximation (DWBA) calculations have been performed using optical-model parameters obtained for ^{208}Pb at an incident energy of 315 MeV (set Q in Olmer *et al.*[14]); the same parameters were used for ^{58}Ni. For ^{12}C the $E18$ potential from Cramer *et al.*[15] was used. We included 250 partial waves for ^{208}Pb and 150 partial waves for ^{58}Ni and ^{12}C. A complex-coupling plus Coulomb-excitation form factor was used. The resulting curves are shown in Fig. 2. No attempt was made to improve the fit to the data by adjusting the phase angle between the nuclear and Coulomb interaction amplitudes. The DWBA cross sections are normalized to the data at the grazing angle to give the Coulomb-excitation strengths β_{CE} ($R_{CE}=1.2A^{1/3}$). We obtained, for example, $\beta_{CE}=0.41$, 0.09, and 0.10 for the low-lying 4.44-MeV (2^+), 2.46-MeV (4^+), and 2.61-MeV (3^-) transitions in ^{12}C, ^{58}Ni, and ^{208}Pb, respectively, in good agreement with known $B(EL)$ values.[10,16,17] The energy-weighted sum-rule strengths were deduced on the assumption of a uniform mass distribution[18] ($r_0=1.2$ fm) and result in $25^{+15}_{-10}\%$ $E2$ strength for the 25.3- to 26.7-MeV groups in ^{12}C, $(40\pm15)\%$ $E2$ strength for the 16-MeV group in ^{58}Ni, and $(87\pm20)\%$ $E2$ strength for the 10.8-MeV group in ^{208}Pb. If we assume that the pronounced structures around 20 MeV in ^{208}Pb belong to the $3\hbar\omega$ components of the isoscalar 3^- and 5^- giant resonances, and first exhaust 100% of the $E3$ sum-rule strength (using about 30% of the observed cross section at the grazing angle), we are left with 10–20% of the $E5$ sum-rule strength. Approximately the same total strength is predicted by the random-phase-approximation calculations,[1,11] but with more equal division between the modes. Although the quoted $E2$ strengths for ^{58}Ni and ^{208}Pb agree reasonably well with hadron-scattering data,[17] the $E2$ strength in ^{12}C is almost 3 times larger than is found in a recent light-ion coincidence experiment.[10] These results, combined with the suggestive l-dependent angular distributions observed for ^{12}C (see Fig. 2), make high-energy heavy-ion scattering a promising tool for the study of giant resonances.

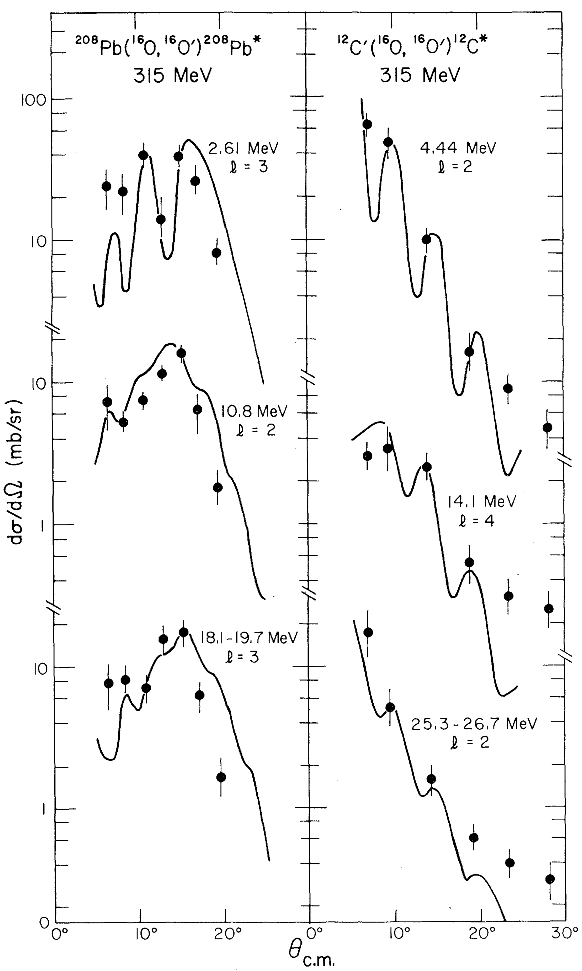

FIG. 2. Angular distributions of low-lying and highly excited groups for inelastic ^{16}O scattering on ^{208}Pb and ^{12}C. The solid curves represent DWBA calculations with the angular momentum transfers shown.

In this Letter, we have presented the most striking evidence yet for the excitation of giant resonances with heavy-ion beams. Whereas it is clear that improvements in the data will be achieved using coincidence techniques, as in the case of light-ion scattering,[10] we emphasize that we have already observed pronounced structures of high multipole states in a straightforward singles experiment. This suggests that there are exciting prospects for mapping the nuclear response function of high multipole resonances in nuclei with even higher-energy beams, which are required to match the corresponding quantum transition times.

The authors would like to thank G. R. Satchler and A. J. Baltz for help in performing the DWBA calculations, and H. Faraggi, C. K. Gelbke, K. T. Knöpfle, and A. Shotter for valuable discussions. This work was supported by the Nuclear Physics Division of the U. S. Department of Energy.

[a] NATO Fellow, on leave from Max Planck Institute, Heidelberg, West Germany.

[b] Present address: University of Maryland, College Park, Md. 20742.

[c] Present address: Universidad Nacional Autónoma de México, México 20, Distrito Federal, Mexico.

[d] IAEA Fellow, on deputation from Bhabha Atomic Research Centre, Calcutta, 700064, India.

[1] G. Bertsch and S. F. Tsai, Phys. Rep. 18C, 126 (1975).

[2] R. A. Broglia, C. H. Dasso, G. Pollarolo, and A. Winther, Phys. Rev. Lett. 41, 25 (1978).

[3] J. P. Bondorf, in *Nuclear Spectroscopy and Nuclear Reactions with Heavy Ions, Proceedings of the International School of Physics "Enrico Fermi", Course LXII,* edited by H. Faraggi and R. A. Ricci (North-Holland, Amsterdam, 1976), p. 221.

[4] R. R. Betts, S. B. DiCenzo, M. H. Mortensen, and R. L. White, Phys. Rev. Lett. 39, 1183 (1977).

[5] M. Buenerd, D. Lebrun, J. Chauvin, Y. Gaillard, J. M. Loiseaux, P. Martin, G. Perrin, and P. de Saintignon, Phys. Rev. Lett. 40, 1482 (1978).

[6] A. Guterman, D. Ashery, J. Alster, D. K. Scott, M. S. Zisman, C. K. Gelbke, H. Wieman, and D. L. Hendrie, to be published.

[7] M. Sasao and Y. Torizuka, Phys. Rev. C 15, 217 (1977).

[8] R. Pitthan, F. R. Buskirk, E. B. Dally, J. N. Dyer, and X. K. Maruyama, Phys. Rev. Lett. 33, 849 (1974).

[9] K. T. Knöpfle, G. J. Wagner, P. Doll, D. L. Hendrie, and H. Wieman, in Proceedings of the International Conference on Nuclear Interactions, Canberra, Australia, 1978, edited by B. A. Robson (Springer, Heidelberg, to be published).

[10] H. Riedesel, K. T. Knöpfle, H. Breuer, P. Doll, G. Mairle, and G. J. Wagner, Phys. Rev. Lett. 41, 377 (1978), and references therein.

[11] J. Speth, E. Werner, and W. Wild, Phys. Rev. 33C, 127 (1977).

[12] R. Pitthan, G. M. Bates, J. S. Beachy, F. R. Buskirk, E. B. Dally, D. H. Dubois, J. N. Dyer, and S. J. Dowalick, to be published.

[13] D. H. Youngblood, C. M. Rozsa, J. M. Moss, D. R. Brown, and J. D. Bronson, Phys. Rev. Lett. 39, 1188 (1977).

[14] C. Olmer, M. Mermaz, M. Buenerd, C. K. Gelbke, D. L. Hendrie, J. Mahoney, D. K. Scott, M. H. Macfarlane, and S. C. Pieper, Phys. Rev. C 18, 205 (1978).

[15] J. G. Cramer, R. M. DeVries, D. A. Goldberg, M. S. Zisman, and C. F. Maguire, Phys. Rev. C 14, 2158 (1976).

[16] D. C. Kocher and R. L. Auble, Nucl. Data Sheets 19, 494 (1976).

[17] D. H. Youngblood, J. M. Moss, C. M. Rozsa, J. D. Bronson, A. D. Bacher, and D. R. Brown, Phys. Rev. C 13, 994 (1976).

[18] G. R. Satchler, Nucl. Phys. A195, 1 (1972), and private communication.

Charge-State Dependence of the Coulomb Explosion of 10-MeV OH^+

A. Breskin, A. Faibis, G. Goldring, M. Hass, R. Kaim, Z. Vager, and N. Zwang
Physics Department, Weizmann Institute of Science, Rehovot, Israel
(Received 9 August 1978)

A molecular OH^+ beam has been produced in a Pelletron accelerator. The Coulomb explosion of 10-MeV OH^+ in thin carbon foils was studied by measuring energy and angular distributions of protons in simultaneous coincidence with the emerging oxygen charge states. A simple model of effective charge illustrates the use of such coincidence measurements to provide information about the electronic screening of moving ions in a solid, and about the formation of emergent charge states.

Much interest has been recently focused on studies of the Coulomb explosion which occurs when a molecular ion impinges on a thin target.[1-4] After the molecule enters the foil, the "explosion" can be considered to occur in two distinct stages. Within a very short time ($\ll 1$ fsec) the