Electroexcitation of Giant Multipole Resonances in ^{197}Au and ^{208}Pb between 5 and 40 MeV Excitation Energy with 90-MeV Electrons*

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Inelastic electron scattering with 90-MeV electrons shows previously observed giant resonances at excitation energies of $63A^{-1/3}$ ($E2$), $81A^{-1/3}$ ($E1$), $105A^{-1/3}$ ($E3$), and $130A^{-1/3}$ MeV ($E2$). Distorted-wave-Born-approximation analysis of additional structure at $53A^{-1/3}$ and $195A^{-1/3}$ MeV suggests a monopole assignment. Transverse contributions to the $E1$ matrix element are compatible with an electric spin-flip. Differing widths of the respective resonances in the two nuclei are explained through dynamic deformation of Au. The reduced electric transition strengths $B(EL)$ are given.

Ever since Goldhaber and Teller explained the giant dipole resonance as a collective oscillation of neutrons against protons,[1] extensions of their model have raised the question of the existence of giant resonances with other multipolarities, especially those with quadrupole and monopole characters.[2] The first experimental evidence of a giant quadrupole resonance several MeV below the giant dipole resonance was found in (e, e') experiments at Darmstadt University.[3] This was soon corroborated in the reevaluation of (p, p') data[4] at Oak Ridge National Laboratory.[5] The results were based on a model by Satchler.[6] Additional evidence was found in (e, e') experiments at Sendai University.[7] Especially significant is the (e, e') experiment of the latter group on ^{208}Pb,[8] which not only showed a splitting of the "new" resonance in this nucleus into at least three states,[9] but furthermore found two other resonances at 19 MeV ($E3$) and 22 MeV ($E2$). Each of these three resonances satisfies a large fraction of the appropriate sum rule, indicating that real giant resonances were observed. The lower $E2$ resonance $E_x = 63A^{-1/3}$ MeV is generally referred to as the isoscalar ($\Delta T = 0$) and the higher resonance at $E_x = 130A^{-1/3}$ MeV as the isovector ($\Delta T = 1$) branch of the giant quadrupole resonance.[10] Several experiments with various particles[11] have confirmed, more or less, the picture sketched above. No experimental evidence has been reported so far concerning the isoscalar and isovector monopole resonances.

The experiments reported were carried out with 90-MeV incident electrons and an overall resolution of 500 keV at the linear accelerator laboratory of the Naval Postgraduate School.[12] Comparison of the scattered electron spectra from ^{197}Au and ^{208}Pb in Figs. 1 and 2 reveals striking differences throughout the covered excitation range. The line-shape fitting procedure

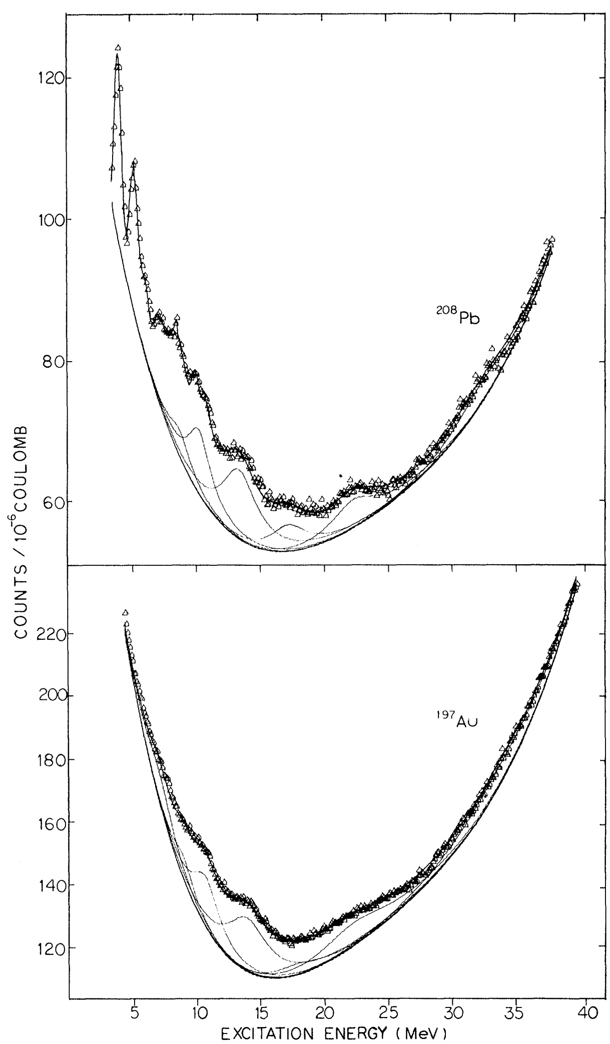

FIG. 1. Spectrum of 90-MeV electrons, scattered inelastically from Pb and Au. The fitted background which consists of the radiation tail and the machine background is shown. The counting rate is corrected for the constant momentum dispersion of the spectrometer. Thus the error increases with the excitation energy.

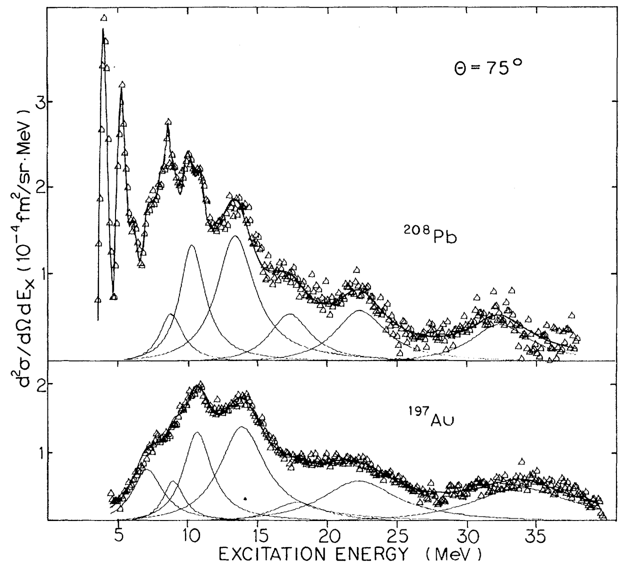

FIG. 2. Same as Fig. 1, after subtraction of the fitted background.

described by Pitthan[13] and the radiative-tail calculation described in Ref. 9 were used. The resonances shown in the Au spectrum are those required to consistently fit the measurements with 90-MeV incident electrons at angles of 60°, 75°, 90°, 105°, and 120°. The Pb spectrum was fitted by the resonances shown as well as the states which are known and have a natural width of less than 500 keV.

The difference in structure above 12 MeV can be explained by the dynamic collective model.[14] Although the ground state of Au is almost spherical, the giant dipole resonance at 14 MeV is much wider than in Pb. This broadening is due to an unresolved splitting,[15] indicating a dynamic deformation of the Au nucleus. The deformation becomes greater with higher excitation energy and leads to a greater fragmentation of strength among the different vibrational axes. It was possible to decompose each of the resonances at 18, 23, and 33 MeV in Au into two Breit-Wigner resonances. However, because of our method of fitting the background simultaneously with the resonances, the extraction of the cross sections became unreliable, so the results quoted here are obtained assuming one wide Breit-Wigner curve per resonance only.

Our experiment agrees with what is known for the 11-[9] and 22-MeV resonances.[8,16] We will therefore deal only with the other resonances. A more detailed account of all the results will be given elsewhere.[17] The final results for both nuclei as extracted from the 75° measurements are listed in Table I.

TABLE I. Comparison of results for Au and Pb as extracted from the 75° measurements. Columns 2 and 3 show multipolarity and isospin assignments assumed.

			^{197}Au						^{208}Pb					
E_x [$A^{-1/3}$ MeV]	EL	ΔT	E_x [MeV]	B(EL) [fm^{2L}] a)	Γ_{nat} [MeV]	EWSR b) [%]	SPU c)	Others B(EL)	E_x [MeV]	B(EL) [fm^{2L}] a)	Γ_{nat} [MeV]	EWSR b) [%]	SPU c)	Others B(EL)
53	E0	0	9.2	$(3.6\pm1.8)10^3$	2.2 ± 0.5	35	--	--	8.9	$(5\pm3)10^3$	1.8 ± 0.5	50	--	--
63	E2	0	10.8	$(5.2\pm1.2)10^3$	2.9 ± 0.2	77	15.5	$(8.4\pm1.6)10^3$ h)	10.5	$(6.7\pm2.5)10^3$	2.8 ± 0.3	95	21.5	$(2.6\pm0.9)10^3$ f)k) $(2.6\pm0.3)10^3$ g)k)
81	E1	1	14.0	100 ± 20 d) 50 ± 10 e)	4.5 ± 0.2	200 100	15.0 7.5	82 ± 11 d)h) 74 ± 5 i)	13.6	103 ± 20 53 ± 10	3.9 ± 0.1	205 105	16 8	64 ± 8 d)f) 71 ± 5 i)
105	E3	0 1	18.0	$(1.7\pm.8)10^5$	5.2 ± 0.7	45 30	10.0	--	17.5	$(3.2\pm1.5)10^5$	4.2 ± 0.7	90 60	17	$(1.8^{+0.6}_{-1.6})10^5$ g)
133	E2	1	23.0	$(4.6\pm1.5)10^3$	7 ± 1	95	13.5	$(6.5\pm1.4)10^3$ h)	22.5	$(4.2\pm1.4)10^3$	5 ± 1	85	14	$(3.4^{+1}_{-2})10^3$ g)
195	E0	1	33.5	$(10^{+3}_{-7})10^3$	10.5 ± 2	250	--	--	33.0	$(6.5^{+2}_{-3})10^3$	6 ± 1	150	--	--

[a] For the monopole $|M_{if}|^2$ (fm^4).
[b] Energy-weighted sum rule Ref. 19.
[c] Single particle units Ref. 20.
[d] Surface oscillation $\rho_{tr}(r) \sim d\rho_0(r)/dr$.
[e] Volume oscillation $\rho_{tr}(r) \sim \rho_0(r)$.
[f] Ref. 9.
[g] Ref. 8.
[h] Ref. 15.
[i] Ref. 14.
[k] Extracted from a 2-MeV-wide range only.

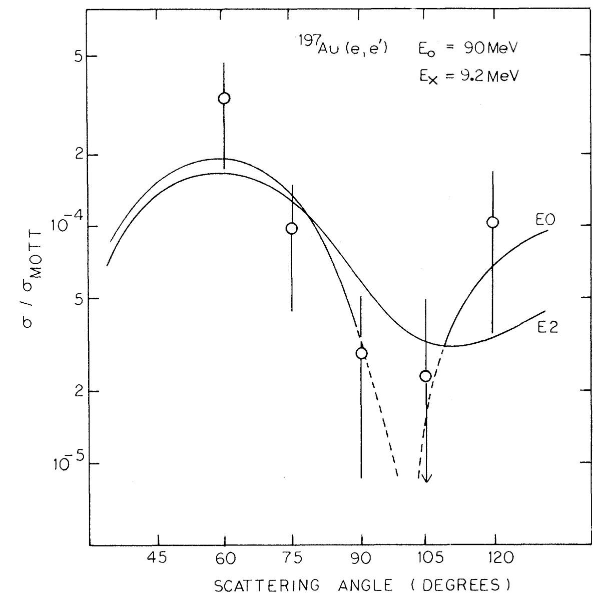

FIG. 3. Ratio of the inelastic cross section of the resonance at 9.2 MeV to the Mott cross section as a function of scattering angle. The curves show the results of DWBA calculations assuming an $E2$ or an $E0$ assignment. At 105° we did not see a resonance. The open circle corresponds to a resonance with a height of 1 standard deviation in the count rate and is, therefore, regarded as an upper limit. The error at 105° represents 1 additional standard deviation.

In Fig. 3 the ratio of the integrated cross section divided by the Mott cross section, which defines the square of the form factor, is shown for the resonance at 9.2 MeV (= $53A^{-1/3}$ MeV) and is compared to distorted-wave Born-approximation (DWBA) calculations. While for small scattering angles (low momentum transfer) $E0$ and $E2$ have the same angular dependence, they are different at the second maximum. There are, however, computational problems connected with the minimum, indicated by the dotted lines. This experiment is, nevertheless, the first experimental indication for the monopole giant resonance, and as a consequence one can obtain the value of the nuclear compressibility.[2] The evaluation was based on the usual DWBA code,[18] which was changed for the breathing mode as described by Kassis.[19]

An $E0$ resonance at $E_x = 53A^{-1/3}$ MeV would agree with experimental results in $N = 82$ nuclei, in which a resonance of $E0$ or $E2$ character was found.[13] Stronger support comes from comparison of (e, e') and (γ, n) experiments in Pb where the triplet of states at 10.2, 10.6, and 11.2 MeV is identified as being $E2$ or $E0$ on the basis of the angular distribution.[8,9] However, the $E0$ assignment is ruled out by noting[9] that the fine structure in the (γ, n) spectra[15] may be explained only if an $E2$ transition is assumed. In contrast, the resonance at 8.85 MeV has the same angular distribution as the 10.6-MeV triplet, implying either an $E2$ or $E0$ assignment, but no line is seen in the (γ, n) spectra. If this state were $E2$, a peak approximately 30 mb high, corresponding to 6 standard deviations, would have been observed in the (γ, n) spectrum. For an $E0$ assignment this fact is easily understood: The longitudinal monopole can not be excited by the pure transverse real photons.

The dipole resonance at $81A^{-1/3}$ MeV was measured with monochromatic γ rays[15] and has also been seen in (e, e') experiments.[8,9,16] Remarkable agreement has been found between the two methods.

This experiment shows reasonable agreement in the angular distribution between experiment and DWBA calculations for the two forward angles, but exhibits deviations for the backward angles, an effect already found in $N = 82$ nuclei.[13] We tried to explore the nature of the dipole oscillations by assuming volume and surface oscillations separately in the DWBA calculations. The results in terms of sum-rule exhaustion favor a volume oscillation (Table I). Then, however, our results are 30% smaller than the (γ, n) experiments.

There may be two reasons for this: (1) The (γ, n) measurements must be corrected for the contributions of the isovector $E2$ resonance to the integrated cross section. (2) Inelastic electron scattering at forward angles measures only the longitudinal matrix element $B(C\lambda)$. The continuity equation yields $B(C\lambda) \approx B(E\lambda)$, where $B(E\lambda)$ is the transverse electric matrix element, which is the main part of the quantity measured in γ absorption. There is, however, another possible contribution to the total transverse matrix element, namely, the electric spin-flip contribution.[9,13] Following Ref. 13 we found a 20–30% contribution to the total $B(E1)$ value possible, which would solve both problems: the difference in sum-rule exhaustion between (e, e') and (γ, n) and the increase of the cross section at backward angles in (e, e').

For the resonances at 18 MeV we extracted an $E3$ matrix element.[8] Backward-angle measurements in Au suggest an additional $M2$ contribution.

No resonance has been reported up to now at 33 MeV. The angular distribution in Au exhibits $E0$ (or $E2$) character. Thus this resonance might be the isovector monopole state, proposed by Ref. 10. However, the great width in Au together with the fact that it is located at the end of our measured excitation range makes an accurate assignment very difficult.

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[1]M. Goldhaber and E. Teller, Phys. Rev. 74, 1046 (1948).

[2]H. Überall, *Electron Scattering from Complex Nuclei* (Academic, New York, 1971).

[3]R. Pitthan and Th. Walcher, Phys. Lett. 36B, 563 (1971), and Z. Naturforsch. 27a, 1683 (1972).

[4]H. Tyrén and Th. A. J. Maris, Nucl. Phys. 4, 637 (1957), and 6, 446 (1958) and 7, 24 (1958).

[5]M. B. Lewis, Phys. Rev. Lett. 29, 1257 (1972); M. B. Lewis and F. E. Bertrand, Nucl. Phys. A196, 337 (1972).

[6]G. R. Satchler, Nucl. Phys. A195, 1 (1972).

[7]S. Fukada and Y. Torizuka, Phys. Rev. Lett. 29, 1109 (1972).

[8]M. Nagao and Y. Torizuka, Phys. Rev. Lett. 30, 1068 (1973).

[9]F. R. Buskirk, H. D. Gräf, R. Pitthan, H. Theissen, O. Titze, and Th. Walcher, Phys. Lett. 42B, 194 (1972), and in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Pacific Grove, California, 1973,* edited by B. L. Berman, CONF-730301 (Lawrence Livermore Laboratory, Livermore, Calif., 1973).

[10]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1972), Vol. 2; T. Suzuki, Nucl. Phys. A217, 182 (1973).

[11]A. Moalem, W. Benenson, and G. M. Crawley, Phys. Rev. Lett. 31, 482 (1973); K. A. Snover, K. Ebisawa, D. R. Brown, and P. Paul, Phys. Rev. Lett. 32, 317 (1974); L. L. Rutledge, Jr., and F. C. Hiebert, Phys. Rev. Lett. 32, 551 (1974).

[12]R. W. Berard, F. R. Buskirk, E. B. Dally, J. N. Dyer, X. K. Maruyama, R. L. Topping, and T. J. Traverso, Phys. Lett. 47B, 355 (1973).

[13]R. Pitthan, Dissertation, Darmstadt University, 1972 (unpublished), and Z. Phys. 260, 283 (1973).

[14]M. Danos and W. Greiner, Phys. Rev. 134, B284 (1964).

[15]A. Veyssière, H. Beil, R. Bergère, P. Carlos, and A. Lepretre, Nucl. Phys. A159, 561 (1970).

[16]Y. Torizuka *et al.*, private communication.

[17]X. K. Maruyama, F. R. Buskirk, E. B. Dally, J. N. Dyer, and R. Pitthan, to be published.

[18]S. T. Tuan, L. E. Wright, and D. S. Onley, Nucl. Instrum. Methods 60, 70 (1968).

[19]N. I. Kassis, Technical Report, Institut für Kernphysik der Universität Mainz, 1969 (unpublished).

[20]R. A. Ferrell, Phys. Rev. 107, 1631 (1957); J. Weneser and E. K. Warburton, in *The Role of Isospin in Electromagnetic Transitions,* edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969).

[21]S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data A 2, 347 (1966).