Inelastic Electron Scattering Studies: Cu^{63}, In^{115}, Ta^{181}, Pb^{208}, and Bi^{209}†

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Measurements were made of the cross sections for scattering of electrons of primary energies from 183 MeV to 600 MeV from Cu^{63}, In^{115}, Ta^{181}, Pb^{208}, and Bi^{209}, using high-resolution detectors. A number of $E2$, $E3$, $E4$, and two $E5$ transitions were induced with nuclear excitations up to 7 MeV. The levels excited have enhanced gamma-decay rates to the nuclear ground states. In the odd-A nuclei most of the observed transitions were to clusters of near-similar states. The results are compared in detail to studies of (p,p'), (d,d'), (α,α'), and (n,n') reactions in the same nuclei. Great similarities between these and the (e,e') are established. It is shown how the combined results can be used to determine the disposition and intensities of the levels within the clusters and how these are related to the discrete-energy core excitations in neighboring even-even nuclei. Data taken at high momentum transfer show that inelastic electron scattering continues to be dominated by excitation of collective states in disagreement with predictions based on present understanding of the process. Excitations seen in both Bi^{209} and Pb^{208} at about 5.8 MeV are identified as leading to collective states in these nuclei. They are probably $E5$ transitions although $E4$ assignments cannot be excluded. The collective states are not seen in Ta^{181} and Au^{197} in (e,e').

I. INTRODUCTION

In a previous paper[1] (hereafter referred to as I) a number of measurements were made of inelastic electron scattering cross sections for excitation of nuclear transitions of less than about 8-MeV energy. A number of collective states were excited in both odd-A and even-even nuclei. It was shown that the Born approximation analysis of the measured inelastic F^2, in the notation of I, was sufficient to extract both the multipolarities of the transitions and, by extrapolation, the rate of the corresponding gamma decay. The relatively large cross sections for excitation of $E2$, $E3$, and $E4$ transitions allowed the properties of a number of known and unknown nuclear levels to be determined. In most of the cases in which comparisons of the electron scattering results could be made with results established by other techniques it was found that the Born approximation analysis gave a good account of itself in fitting the observed F^2 and in predicting the rate and multipolarity of the corresponding gamma-ray transitions.

In the present paper we report a continuation of the program of inelastic electron scattering studies, extending the range of primary energy, momentum transfer, and nuclear excitation. We used the methods described in detail in I and preserve the notation used there.

II. EQUIPMENT AND DATA ANALYSIS

All the measurements reported here were made using the Stanford 72-in. magnetic spectrometer. The detector, similar to that described in I, was composed of 27 scintillation counters arranged in two blocks in the focal plane of the spectrometer. For each counter $\Delta p/p=0.067\%$. The scintillator dimensions were 3/16 in.×3/8 in.×1 in. Each scintillator was bonded to a Lucite light pipe which was in turn cemented to a 3/4-in. end-window photomultiplier. The multiplier outputs were integrated and amplified using transistorized preamplifiers having 60 Mc/sec band widths[2] whose outputs were taken 300 ft to the electronic equipment described in I. Each of the blocks of counters was backed by a liquid fluorochemical Čerenkov counter, using FC 75, viewed by two 6810-A photomultipliers. The output of each Čerenkov counter passed to a fast transistorized discriminator whose output drove coincidence circuits also driven by the signals from the scintillation counters ahead of the Čerenkov counter.

One of the blocks of counters contained 18 scintillators closely spaced. The second contained 9 scintillators spaced 3/16 in. apart. The positions of the scintillators were determined optically and were checked by a series of calibration runs. The remainder of the electronics was essentially that of I.

A thin (0.0106 radiation length) carbon target was used to determine the efficiencies of the various elements of the scintillation array. Absolute cross sections were determined by comparison with the scattering of electrons from the free protons in a polyethylene target matched in carbon content to the carbon target. The data reduction procedure, including the application of the bremsstrahlung and Schwinger corrections, has been described[3] and a typical corrected and uncorrected proton calibration peak is shown there. In all of the present measurements the spread of primary beam energy was in the range from 0.07% to 0.2% and the uncertainty in the determination of scattered electron momenta, from all effects combined, was from 0.16% to 0.30% depending in large measure on the thicknesses of the targets used.

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[1] H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian, Phys. Rev. 123, 923 (1961). Referred to in the text as I.

[2] H. W. Kendall, Ann. Rev. Nucl. Sci. 9, 349 (1959).

[3] H. W. Kendall and I. Talmi, Phys. Rev. 128, 792 (1962).

Graphical techniques were used to display the measured F^2 for discrete nuclear transitions and to determine the fitting parameters β_λ. From the measured transition energies and the corresponding values of λ and β_λ we found the value of the local wavelength correction, Γ_{sp} (the Weisskopf single-particle gamma-ray rate), Γ_m (the measured rate), and the value of $B(E\lambda)$, the reduced transition rate, appropriate to a gamma transition $j=\lambda$ to $j=0$, a nuclear spin change associated with a transition in an even-even nucleus. A $B(E\lambda)$ calculated in this manner is equivalent to $B_{\text{ph}}(E\lambda)$ for an odd-A nucleus in which the valence-nucleon core interaction is insufficient to split the excited state (based on a deformed core) into a resolved multiplet. The use of $B_{\text{ph}}(E\lambda)$ is discussed in I and, in more detail, by Alder *et al.*[4] The M.I.T. Laboratory for Nuclear Science LGP-30 digital computer was used in making these calculations. One of the objects of the present investigation was to study transitions in nuclei in which the multiplets were so broadened that the weak-coupling description would be inappropriate. The expressions for Γ_m include statistical factors from the known ground-state and excited-state spins. For the cases in which we observe great splitting (especially in Cu^{63}) there are unfortunately no measurements of the excited state spins available and we are unable to reduce the uncertainties in the Γ_m and other measured quantities that are consequent on our lack of knowledge of the statistical factors. For the sake of simplicity we have treated all the transitions as if they occurred in even-even nuclei. The cases for which this is adequate are pointed out below.

The study of inelastic transitions in odd-A nuclei is more difficult than in even-even nuclei for several reasons. The collective excitations as observed in the inelastic spectra are rarely as prominent as with even-even nuclei and the levels may be split into multiplets whose study requires very high energy resolution. High resolution demands not only a narrow energy spectrum from the accelerator but also very thin targets. Both result in low counting rates. In the observed spectra there usually appears to be an enhanced background of what are presumably weak excitations of closely spaced single-particle states. The sum of these difficulties generally results in cross-section measurements whose uncertainties are considerably greater than for corresponding even-even targets. The uncertainties are not always assessable with precision because statistical fluctuations in part of an observed spectra may have a very great effect on neighboring lower energy portions of the same spectra, after corrections are applied, as a consequence of propagation of errors through the radiative correction program. Although we investigated this propagation for a number of spectra our computational facilities were not adequate to allow us to treat the determination of uncertainties in a detailed manner for all the cases of interest. On the basis of these studies we have estimated the uncertainties in the measured F^2 resulting from statistical fluctuations in the data of the uncorrected spectra and their propagation through the correction program. These uncertainties, expressed as standard deviations, are shown on the curves of the F^2 and in the tables of numerical results. It will be seen that they are in general greater than those reported in I for even-even nuclei.

The results of the measurements are shown in Table I. This table gives, for each target nucleus, ϵ, the energy of the transition excited, λ, the determined multipole order of the (assumed electric) transition, and β_λ, the relevant Born approximation fitting parameter as determined by experiment. In addition we give Γ_{sp}, the single particle (Weisskopf) estimate of the decay rate for the corresponding γ decay, Γ_m, its measured value deduced from the β_λ, $G=\Gamma_m/\Gamma_{sp}$, the γ-ray enhancement, and $B(E\lambda)$ in units of $e^2(\text{fermi})^{2\lambda}$. The Γ_m and Γ_{sp} are computed assuming each transition occurs in an even-even nucleus, i.e., a $j=\lambda \rightarrow j=0$ transition. The table also includes information from a variety of inelastic nuclear scattering reactions that bears on the present results. This information is discussed in succeeding sections.

The assumption that we excite electric transitions most strongly for the conditions of the present experiment has been studied by Walecka[5] and is known to be a good assumption.

III. DISCUSSION OF THE RESULTS

A. Introduction

A number of the nuclei studied in the present experiment have been studied in inelastic (p,p'), (α,α'), (n,n'), or (d,d') reactions. See I for references concerning the earlier proton and alpha reaction data, Cohen and Price,[6] for deuteron data, and Saudinos, *et al.*[7] for recent α-reaction data. A number of (n,n') studies are referred to in the Nuclear Data Sheets.[8]

For the most part these various reactions appear to excite collective states of a variety of configurations. However, in the interpretation of the results it is rarely possible to make multipole assignments for the observed transitions nor can even the relative parities of the ground and excited states always be determined in ways that are free from ambiguity.

In I it was shown that the (e,e') reaction also leads to excitation of predominantly collective states. In the present experiment we have studied a number of odd-A nuclei all of which have been studied by one or more of

[4] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).

[5] D. J. Walecka, Phys. Rev. **126**, 653 (1962).

[6] B. L. Cohen and R. E. Price, Phys. Rev. **123**, 283 (1961).

[7] J. Saudinos, R. Beurtey, P. Catillon, R. Chaminade, M. Crut, H. Faraggi, A. Papineau, and J. Thirion, Compt. Rend. **252**, 96 (1961).

[8] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

TABLE I. Results of the inelastic electron scattering studies. The first column gives the energies of the inelastic peaks expressed in terms of the nuclear excitation in MeV. λ is the multipole assignment and β_λ the fitting parameter found from analysis of the measured F^2. Γ_{sp} is the Weisskopf single-particle gamma-ray rate assuming a radius $r=1.2A^{1/3}$ fermis. Γ_m is the measured value computed from the value of β_λ. The enhancement G is Γ_m/Γ_{sp}. Γ_{sp}, Γ_m, and G have been computed assuming that the transitions occur in even-even nuclei. Except in Pb^{208} there is no information available concerning the excited state spins of any of the levels observed here. $B(E\lambda)$ are the reduced transition rates in units of $e^2(\text{fermi})^{2\lambda}$. The exponent of ten is given, for each entry, after the comma. Thus $(3,10)=3\times10^{10}$. The uncertainties given in columns 3 through 7 are standard deviations based on statistical uncertainties in the measured spectra after propagation through the radiative correction program. In earlier papers[a] we have quoted additional 30% uncertainties arising from uncertainties in the theoretical analysis. More recent comparisons of Γ_m's with values measurements by other techniques indicate this value is conservative. It should probably be closer to 20%. It is not included in the uncertainties in the table. Column 8 lists the transitions excited by (α,α'), (p,p'), or (d,d') reactions that we believe are identified with those excited by the present (e,e') studies. Branching ratios for these excitations are not available nor are the results entirely consistent between the different techniques. The comparisons between heavy-particle and the electron scattering data are discussed in detail in the text. We are grateful to D. Blum for pointing out some small numerical errors in reference 1 of the text for the Γ_m and G for Pb^{208}. They are here corrected.

Transition energy (MeV)	λ	β_λ	Γ_{sp} (sec^{-1})	Γ_m (sec^{-1})	G	$B(E\lambda)$	Transition energies (high resolution)	Remarks
Copper-63								
1.20±0.20	2	(2.5±0.5, −2)	(4.7,10)	(4.02±0.8, 11)	8.5±1.8	(6.6±1.4, 2)	{1.01[b] 1.41[b]	0.6 MeV $E2$ unobserved in (e,e')
2.60±0.15	3	(2.2±0.33, −2)	(1.13,8)	(7.6±1.1, 8)	6.7±1.0	(1.14±0.17, 4)	2.53[b] 2.53[c]	
3.6	3	(3.5±0.7, −2)	(1.1,9)	(1.18±0.23, 10)	10.6±2.0	(1.82±0.3, 4)	{3.43[b] 3.52[c] 3.82[b] 3.89[c]	{More than one state excited in (e,e'). A 4.47-MeV $E3$ transition not observed in (e,e')
5.5 ±0.2	4	(1.9±0.47, −2)	(3.24,6)	(1.73±0.43,7)	5.3±1.3	(1.97±0.49,5		
7.5 ±0.2	3	(8.3±2.5, −3)	(1.88,11)	(4.75±1.4, 11)	2.5±0.75	(4.31±1.3, 3)		}Multipole assignment uncertain
7.5 ±0.2	4	(1.6±0.48, −2)	(5.3,7)	(2.4±0.72, 8)	4.5±1.4	(1.66±0.5, 5)		
Indium-115								
1.10±0.25	2	(2.1±0.63, −2)	(6.8,10)	(1.26±0.38, 12)	18.5±5.5	(3.18±0.95, 3)	{1.11[c] 1.14[d] 1.19[c] 1.48[d]	{The (e,e') results for this group of levels had large background subtractions.
2.21±0.1	3	(2.4±0.36, −2)	(1.2,8)	(2.17±0.33, 9)	18.0±2.7	(1.02±0.15, 5)	{2.06[c] 2.17[c] 2.49[c] 2.15[d] 2.43[d]	{The (e,e') results consistent with equal excitation of 2.15 MeV and 2.43-MeV levels.
Tantalum-181								
3.60±0.25	4	(7.8±3.9, −3)	(1.2,6)	(1.1±0.6,7)	9.3±4.6	(5.7±2.8, 6)	Broad peak ~3.5 MeV[d]	
Lead-208								
2.60	3	(1.7±0.5, −2)	(1.23,9)	(3.60±1.1, 10)	29±8.7	(5.4±1.6, 5)	2.61[e] 4.0[d]	}See reference 1 of text
4.30	4	(1.9±0.6, −2)	(8.6,6)	(2.29±0.7, 8)	27±8.1	(2.4±0.7, 7)	4.33[e] 4.3[d]	
5.8 ±0.25	5	(6.2±1.8, −2)	(3.9,4)	(2.44±0.7, 5)	8.0±2.4	(3.08±0.92, 6)	{5.4[d] 5.7[d]	Similar level (levels) in Pb-206, Pb-207
Bismuth-209								
2.60								{See reference 1 of text for data on these levels
4.30								
5.9 ±0.25	5						5.4[d] broad	Data on this level are limited. See text.

[a] See references 1 and 3.
[b] See reference 7. (α,α') studies
[d] See reference 6. (d,d') studies
[c] See reference 19. (p,p') studies
[e] See reference 22. (d,d') high resolution

the inelastic nuclear reactions. In general the bombarding energies in these heavy-particle reactions are at least an order of magnitude lower than that required for useful (e,e') studies, and hence, it is far easier to resolve excitation of closely spaced nuclear states. In the succeeding parts of this section we discuss the results of the (e,e') studies in Cu^{63}, In^{115}, Ta^{181} and the pair of nuclei Pb^{208} and Bi^{209}, and compare the results in detail with the results of the high-resolution data from the heavy-particle studies.

B. Copper-63

The study of Cu^{63} by the (e,e') technique was suggested by the results of Thirion and his collaborators[7] using inelastic scattering of 44-MeV alpha particles to excite this nucleus to a number of different states. Using the phase rule discussed theoretically by Lemmer, de-Shalit, and Wall,[9] and by Blair[10] they were able to identify two clusters of states, one of about three odd-parity states at approximately 1 MeV and a second of four even-parity states, at approximately 3.8 MeV. The ground state of Cu^{63} has odd parity. Data on nearby even-even nuclei strongly suggest that these clusters represent the analogs, in this odd-A nucleus, of the 2^+ and 3^- states seen, for example, in Ni^{64}, Ni^{62}, Ni^{60}, Ni^{58}, and a number of others. The broadening of the even-even core excitation into a multiplet may be thought of, in some cases, as a consequence of the interaction of the odd number of valence nucleons with the core. See the theoretical treatments of the general problem by Raz,[11] and by de-Shalit[12], and the discussions of the weak-coupling model applied to Cu^{63} by Tamura and Choudhoury,[13] and Lawson and Uretsky.[14] It is of considerable interest, then, to determine if each of these clusters in Cu^{63} does indeed contain states of similar

[9] R. Lemmer, A. de-Shalit, and N. Wall, Phys. Rev. **124**, 1155 (1961).

[10] J. S. Blair, in *Proceedings of the International Conference on Nuclear Structure, Kingston* (University of Toronto Press, Toronto, 1960).

[11] B. James Raz, Phys. Rev. **120**, 167 (1960).

[12] A. de-Shalit, Phys. Rev. **113**, 547 (1959); **122** 1530 (1961).

[13] T. Tamura and D. C. Choudhoury, Phys. Rev. **113**, 552 (1959).

[14] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957).

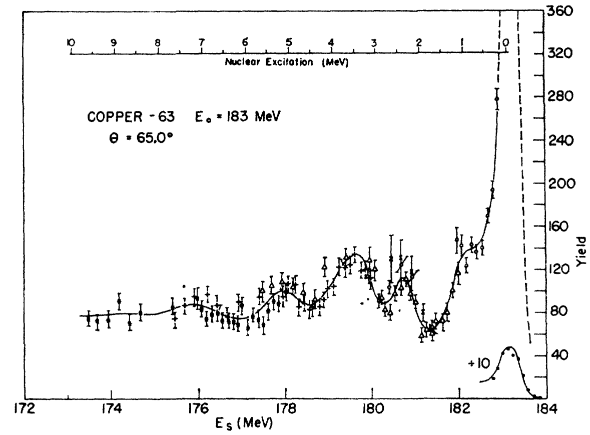

FIG. 1. Spectrum of 183-MeV electrons scattered at 65° (laboratory angle) from Cu^{63}. The data include five runs with the 27-channel detector discussed in the text. The data have been corrected for the varying efficiencies of the different channels and normalized to the same integrated beam current. The smooth curve is a visual fit to the data. The error bars shown are standard deviations arising from counting statistics. Schwinger and bremsstrahlung corrections have not been applied.

parity and more important, to see if each state in a cluster is reached by a transition from the ground state of similar multipole order. In addition, measurements of the corresponding γ-ray transition rates would allow specification of the enhancements of these rates compared to single-particle estimates and shed light not

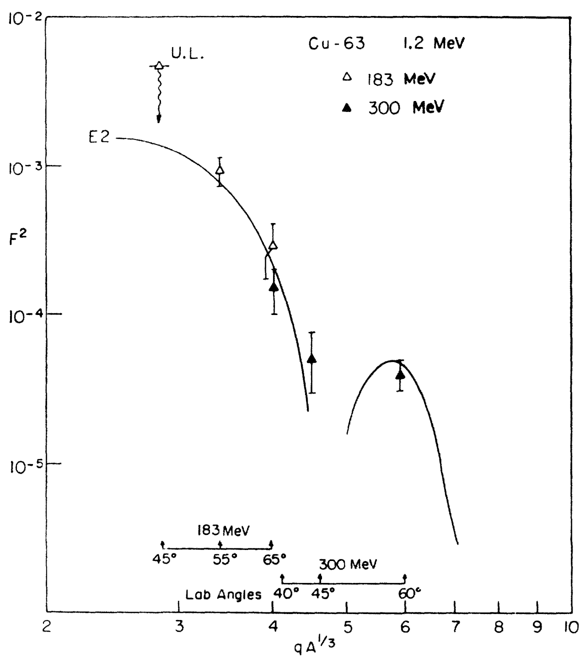

FIG. 2. F^2 for the inelastic scattering of electrons from Cu^{63} exciting the 1.2-MeV state. Data are shown for two primary electron energies: 183 MeV and 300 MeV. The abscissa is $qA^{1/3}$, where q is the momentum transfer in reciprocal fermis and A is the mass number. The 300 MeV has had the local wavelength correction applied so it may be compared directly with that taken at 183 MeV. A theoretical $E2$ prediction is shown using parameters selected in the manner described in reference 1 of the text. See text for a discussion of the several unresolved transitions that are presumed to contribute to these data.

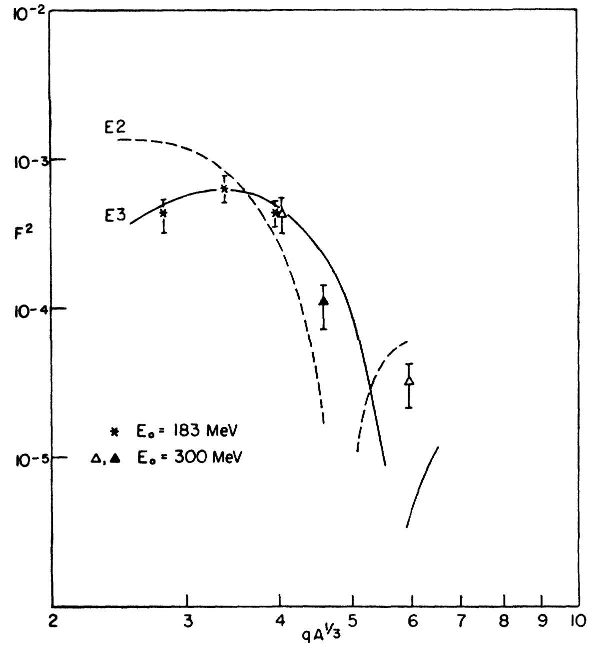

FIG. 3. F^2 for the inelastic scattering of electrons from Cu^{63} exciting the 2.6-MeV state. An $E3$ fit to the data is shown and, for comparison, an $E2$ prediction. As far as is known, this is a transition to a discrete state (cf. caption for Fig. 2).

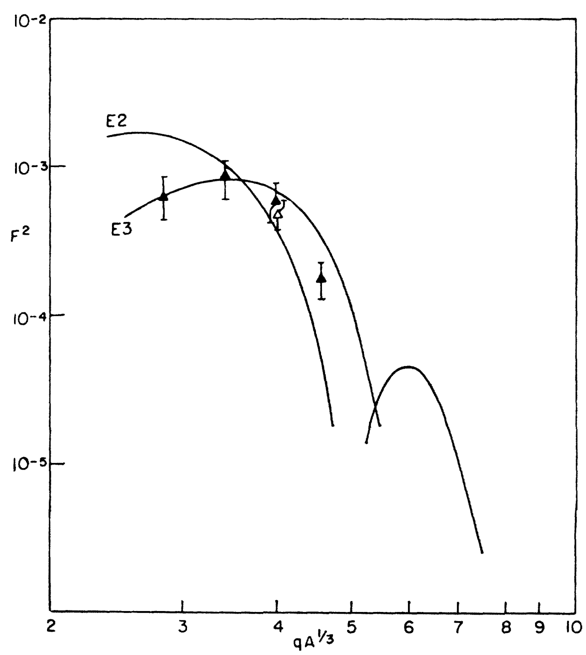

FIG. 4. F^2 for the inelastic scattering of electrons from Cu^{63} exciting the 3.6-MeV level. It is presumed, on the basis of arguments discussed in the text, that these data include unresolved transitions of about equal intensities to states at 3.43 and 3.82 MeV (cf. caption for Fig. 2).

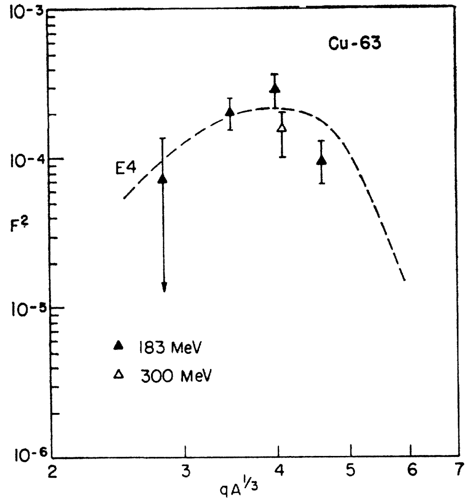

FIG. 5. F^2 for the inelastic scattering of electrons from Cu^{63} exciting the 5.5-MeV level. An $E4$ prediction is shown (cf. caption for Fig. 2).

only on the extent to which enhanced ground-state decay rates were correlated with enhanced inelastic alpha-particle cross sections but also on the collective nature of the levels involved.

We have measured the inelastic cross sections for scattering of electrons from Cu^{63} of primary energy 183, 300, and 600 MeV for scattering angles in the range from 31° to 65° in the laboratory. Typical results are shown in Fig. 1 which shows the spectrum of 183-MeV electrons scattered through a laboratory angle of 65°. Five inelastic transitions are seen in these data. With the exception of the 7.5-MeV transition, they were

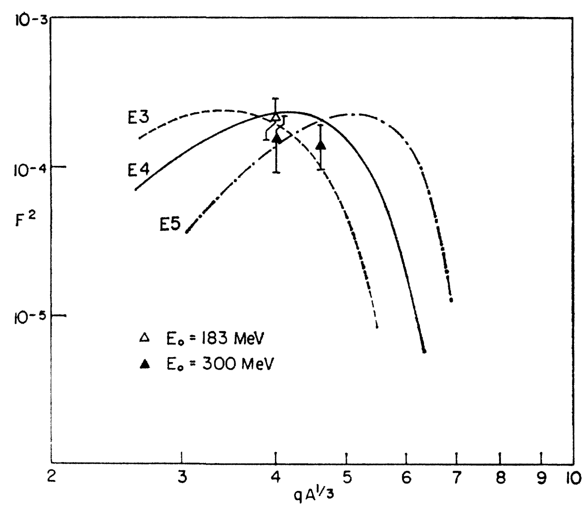

FIG. 6. F^2 for the inelastic scattering of electrons from Cu^{63} exciting the 7.5-MeV level. $E3$, $E4$, and $E5$ predictions are shown. The fact that we fail to see the transition except over a narrow range of q argues that an $E4$ assignment, which peaks at these values of q, is the most likely. Neither of the other two assignments are excluded by the data (Cf. caption for Fig. 2).

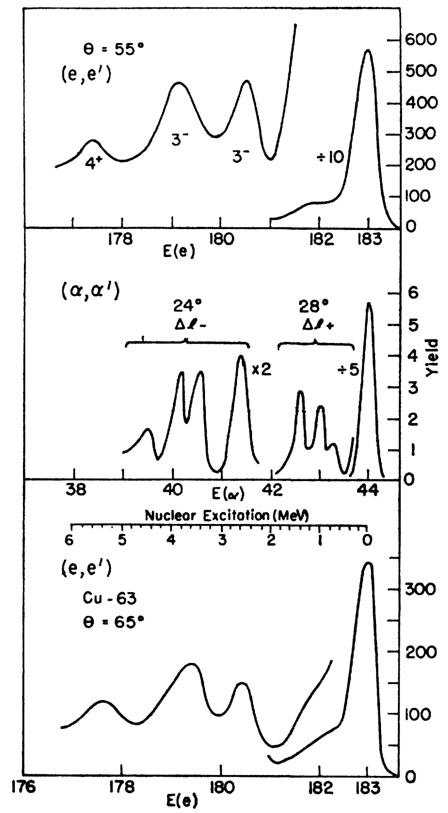

FIG. 7. Qualitative comparison of the energy spectra of 183-MeV electrons scattered at 55° and 65° and of 44-MeV alpha particles scattered at 28° and 24° from a Cu^{63} target. The abscissas are such that nuclear excitations, increasing to the left, are the same for all spectra. The yields are in arbitrary units. The alpha-particle data have been taken from Saudinos *et al.* (reference 7). The electron data, from the present work, have had the Schwinger and bremsstrahlung corrections applied. The multipole assignments for the transitions, from the electron scattering F^2, are shown on the top curve. An $E2$ assignment is made for the transition at about 1.2 MeV. The parity changes during the transitions induced by the alpha particles are shown in the center plot.

observed in all the 183-MeV runs and in most of the 300-MeV runs. The peaks are seen with a resolution that is considerably worse than what was obtained by the Saclay group[7] and a number of discrete transitions seen by them are observed here unresolved. The F^2 for the five transitions observed here are shown in Figs. 2 through 7. The predictions of the best theoretical fits to these data are shown also. The displays of the F^2 and the theoretical predictions are given in the same manner as those in I.

A qualitative comparison of some of the (α,α') results and data from 183-MeV electron scattering is shown in Fig. 7. A quantitative comparison between the inelastic spectra from these two vastly different reactions is not extremely useful; Fig. 7 is intended to show only qualitative similarities. The figure compares the inelastic spectra for two angles of electron scattering and, for the alpha reactions, excitation of an odd-parity multiplet observed at scattered alpha angle of 28° and an even parity multiplet, observed at 24°. The momentum transfers for all the data are roughly comparable. We see that within the uncertainties in the (e,e') data resulting from the lower resolution the (e,e') reaction appears to be exciting the same sets of states. This is a conclusion reached by similar series of comparison in In^{115}, Ta^{181}, Au^{197}, Pb^{208} (all discussed in the present paper) and in Ni^{58}, Co^{59}, and V^{51} (to be published[15]). In the present case this is supported by noticing that the unresolved excitation seen in (e,e'), which corresponds to the odd-parity states seen by the Saclay group at 0.69, 1.01, and 1.41 MeV, is observed at a mean energy of 1.20 MeV. These states are unmistakably reached by $E2$ transitions and are, hence, states of odd parity. The same states are also strongly excited by the (d,d') reaction.[16] The multipole assignment is made on the basis of the observed F^2 for the transition, shown in Fig. 2. The 0.69-MeV transition is not observed in the (e,e') studies. It is expected to be masked by the elastic peak. If we treat the observed yield as arising from a sum over all members of an $E2$ multiplet in the sense of the treatment of Kendall and Talmi[17] of the weak coupling approximation (whose validity in the present case is questioned in part IV of this paper) we find a value of $B(E2)=(6.6\pm1.4)\times10^2e^2F^4$ and an enhancement $G=8.5$ for the corresponding sum of the γ transitions from the states. Whether or not the weak coupling description is valid we are able to conclude that these 1.01-MeV and 1.41-MeV states are in fact the analogs of the fast $E2$ transitions in neighboring even-even nuclei in the sense that their mean energy and enhancements are similar.

A state at 2.6 MeV is clearly identified with the 2.53-MeV level excited by alpha particles. The F^2 shown in Fig. 3 identifies the transition as $E3$, and thus the parity change is in agreement with the earlier negative assignment. The parity of the levels is thus even.

A broad cluster of states at 3.6 MeV is again well fitted by an $E3$ assignment. The energy quoted is the mean of the value found from the four spectra in which it was observed. The uncertainties in the shapes of the peaks preclude any attempt to extract a branching ratio for excitation of the 3.43- and 3.82-MeV positive-parity levels seen in the α studies, but it is quite clear from the observed width that more than one state is being excited. Indeed the shapes of the observed spectra are such that one might conclude that there is some weak excitation of the 4.47-MeV odd-parity state needed to complete the comparison with the alpha excitation. The uncertainties are large, however, and a definite conclusion is unwarranted.

In addition to observing states previously seen following alpha excitation we observed an $E4$ transition at 5.5 MeV, whose F^2 is shown in Fig. 5, and a transition at 7.5 MeV. The latter was observed over such a narrow range of momentum transfer that no reliable multipole assignment could be made. In Table I we have computed the γ-ray parameters on the assumption the transition is either $E3$ or $E4$. These are assignments suggested by similar excitations in nearby nuclei. If either one is correct the γ rate is not substantially enhanced.

Several conclusions can be drawn from the results discussed here. The first is that electron excitation appears to excite the same states as alpha excitation. We notice also that, qualitatively, the relative excitation of the different members of the multiplets is the same for both processes. For example, the ratio of excitation cross sections in (e,e') for the 2.60-MeV state to the sum of the 3.43- and 3.82-MeV states is $11/18=0.63$. The same ratio for the alpha process is 0.56. Although the uncertainty in the (e,e') number is probably greater than 20%, this, in addition to our failure to observe clearly the 4.47-MeV level, weakly excited in (α,α'), lends additional support to our arguments.

An immediate consequence of the above remarks is that we find the alpha process to have correctly assigned the parities of the observed states. With the support of the (e,e') analysis of the Cu^{63} levels the near identities of the number, position, and intensities of the states excited by (α,α') in Cu^{63} and Cu^{65} (see curves 2a and 2b of reference 7) argue that the negative-parity states in Cu^{65} at about 1.2 MeV and the even parity ones at about 3.5 MeV are reached by $E2$ and $E3$ transitions.

The scattering of 600-MeV electrons from Cu^{63} was

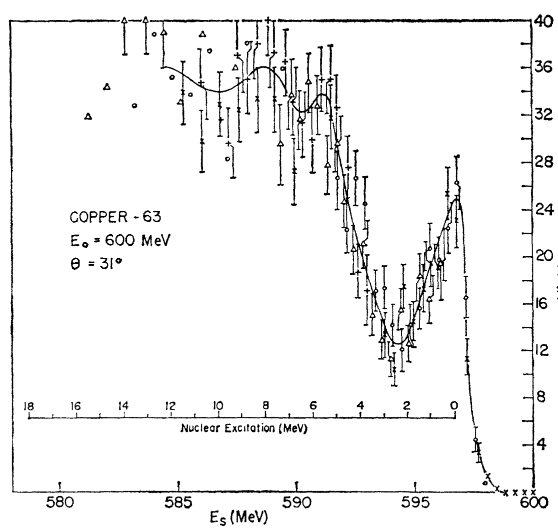

FIG. 8. The spectrum of 600-MeV electrons scattered at 31° from Cu^{63}. The energy resolution is about 0.2% for these data. The $E2$ transitions observed at lower momentum transfers contribute to the asymmetric shape of the elastic peak. By analogy with the results of scattering electrons from Pb^{208} (see Fig. 17) under similar conditions and from Ni^{58} at slightly greater momentum transfer [H. Kendall (to be published)] we conclude the large rise in yield at about 5-MeV excitation arises from excitation of $E4$ transitions we are here unable to resolve.

[15] H. W. Kendall, Inelastic Electron Scattering Studies: V^{51}, Ni^{58}, Co^{59}, Bi^{209} (to be published).
[16] J. L. Yntema, B. Zeidman, Phys. Rev. Letters 2, 309 (1959).
[17] Equation (6) of reference 3.

studied at a laboratory angle of 31°. The spectrum of scattered electrons is shown in Fig. 8. This run did not show any resolved discrete nuclear transitions. These and similar data from Ta^{181} and Pb^{208} nuclei are discussed in part IV.

C. Indium-115

Electron scattering from In^{115} was studied at laboratory angles from 45° to 70° using electrons of 183-MeV primary energy. Two inelastic peaks only were observed. The largest was at (2.21±0.1) MeV and was seen to consist of excitation of more than one level. Although in two of the runs it appeared that with our resolution we might be capable of observing structure in the peaks, small fluctuations in the operation of the equipment prevented us from actually carrying this out. The 2.21-MeV peak was always observed to be about 700 keV wide at half maximum when the elastic peak width was 400 keV. The second peak was observed on the bremsstrahlung tail of the large elastic peak. It was difficult to observe this particularly at the lower momentum transfers where the elastic peak was very large. The best estimate of its energy was 1.1 MeV, but different runs gave results which differed by as much as 150 keV. No other important transitions were observed. Two representative inelastic spectra are shown in Figs. 9 and 10, and the F^2 for the elastic and two inelastic transitions are shown in Figs. 11 and 12.

Indium-115 has been studied by a variety of techniques. Reference 8 gives a number of references on (n,n'), $(n,n'\gamma)$, (p,p'), (γ,γ'), $(\alpha,\alpha'\gamma)$, (p,p'), and (d,d') studies. See also the paper of Johnson and Smith[18] and

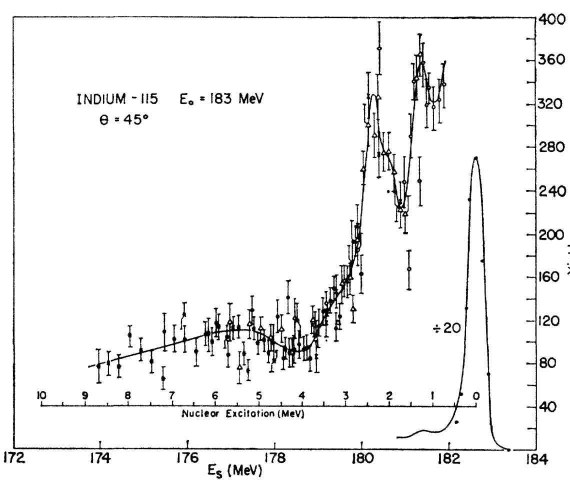

FIG. 9. In this and the succeeding figure, we show spectra of 183-MeV electrons scattered inelastically from In^{115} at laboratory angles of 45° and 50°. A change in energy resolution (about 25%) between the two curves accounts for the differences between the sharpness of the peaks. The width of the 2.1-MeV transition is clearly visible. The present figure shows the scattering at 45° (cf. caption to Fig. 1).

[18] O. E. Johnson and W. G. Smith, Phys. Rev. **116**, 992 (1959).

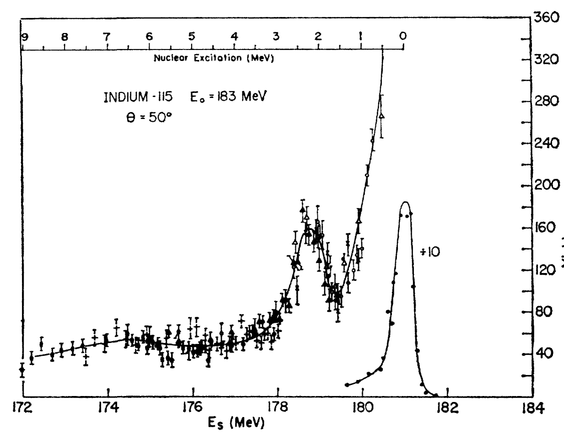

FIG. 10. Spectrum of 183-MeV electrons scattered from In^{115} at 50° (cf. caption to Fig. 9).

references 6–16 in it. The (p,p') work of Cohen and Rubin[19] and the (d,d') work of Cohen and Price[6] deserve special mention. Comparison of the present data with some of the results in these latter two references shows clearly that the (p,p') and (d,d') reactions are exciting the same states as the electron scattering. Comparison spectra similar to Fig. 7 are shown in Fig. 13. In addi-

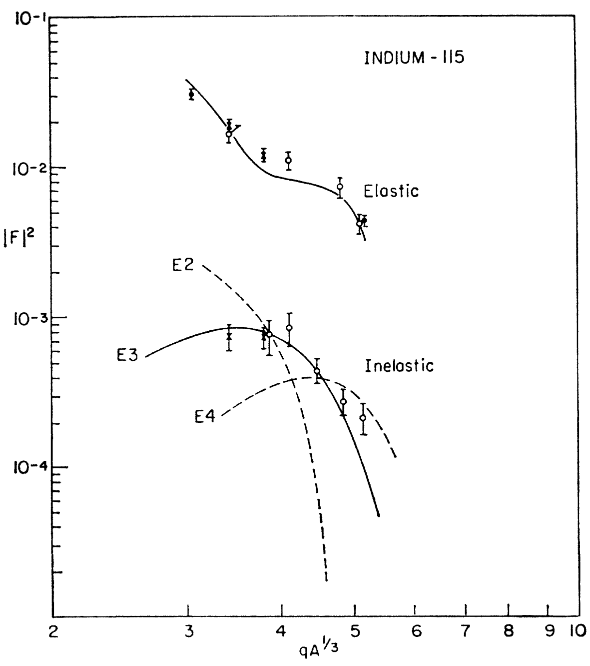

FIG. 11. F^2 for the scattering of electrons from In^{115}. F^2 for elastic and the 2.1-MeV nuclear excitation are shown. The theoretical prediction for the elastic scattering (solid line) is taken from the comparison of theory and experiment of Crannell *et al.*, reference 20; the present elastic data supplement the measurements of that paper. An $E3$ prediction for the 2.1-MeV transition is shown. Arguments given in the text suggest that these inelastic data arise primarily from two unresolved transitions of about equal intensities to levels at 2.15 and 2.43 MeV.

[19] B. Cohen and A. Rubin, Phys. Rev. **111**, 1568 (1958).

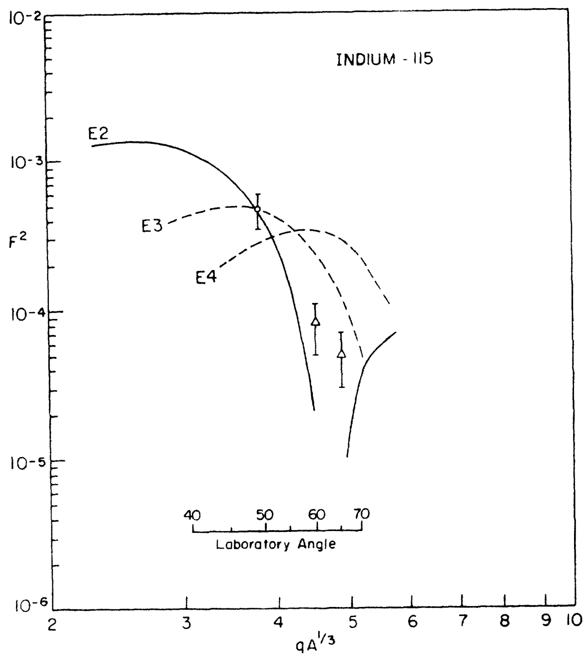

FIG. 12. F^2 for the 1.2-MeV transition in In^{115}. The energy of this transition could not be determined very accurately because of background from the tail of the elastic peak.

tion to the spectrum of deuterons scattered using an energy resolution of 80 keV Fig. 13 also shows the (d,d') spectrum with the resolution artificially broadened to 450 keV. This is about 10% greater than that employed in the present (e,e') work. The similarities between the (d,d') and (e,e') excitations as shown in this figure are very great.

The width and mean energy of the group of states excited by (e,e') is in nearly quantitative agreement with the consequences of assuming equal excitation of two levels at 2.49 and 2.15 MeV. The states are excited equally both in (d,d') and (p,p'). In addition to determining the energies of the observed peaks we are able to make an $E3$ assignment for the transition to these two states and to determine that the $B(E3)$ for the sum of the two transitions is enhanced by a factor of about 18. These results confirm the conjecture made by Cohen and Price[6] that these levels constitute the "anomalous" octupole states.

We make a less unambiguous $E2$ assignment for the transition we observe at 1.1 MeV. The total $B(E2)$ for this is also enhanced by about a factor of 18. It is clear however, from the systematics of first excited states of even-even nuclei and the multiplets seen at similar energies in nearby odd-A nuclei that this $E2$ assignment is very likely the correct one.

The combined information from our measurements and the very high-resolution data of Cohen and his collaborators establishes the following results. The fast $E3$ transition seen in even-even nuclei has its counterpart in In^{115}. The effect of the odd number of valence nucleons is, in this nucleus, to split the transition into two approximately equal strength transitions 340 keV apart with a mean excitation energy of 2.1 MeV. Although the spins of these states are unknown the states both can de-excite to the ground state by emission of $E3$ photons with rates which are greatly enhanced over single-particle rates.

A similar situation appears to prevail for the levels at about 1 MeV. We clearly excite one or more of these but were unable to measure the width of the multiplet because of masking by the elastic peak. The mean position of the cluster is in agreement, within the experimental uncertainties, with the results of Cohen.[6,19] The $E2$ assignment and the observed enhancement of the

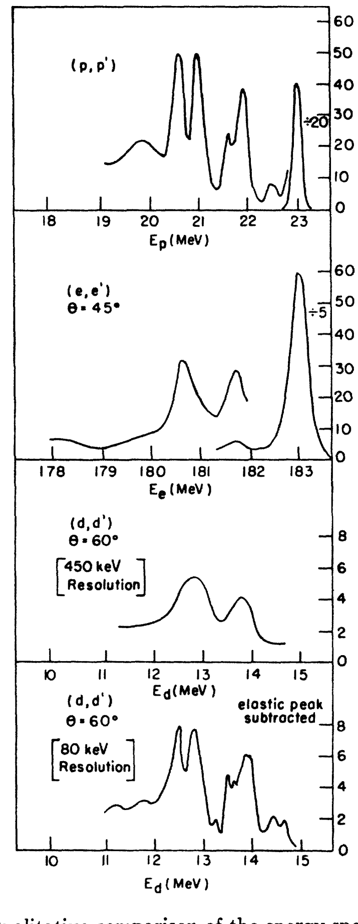

FIG. 13. Qualitative comparison of the energy spectrum of 183-MeV electrons scattered at 45° from In^{115} with the spectrum of 15-MeV deuterons and 23-MeV protons scattered at 60° and 90° respectively, from the same target nucleus. The proton data are from Cohen and Rubin (reference 19), and the deuteron data from Cohen and Price (reference 6). The elastic peak has been subtracted from the latter data. The (d,d') data are shown with 80-keV resolution and with the resolution artifically increased to 450 keV. Comparisons of the heavy-particle data with seven other inelastic (e,e') spectra indicate that the electron scattering populates the states at 2.15 and 2.43 MeV with roughly equal intensities. The uncertainties in the (e,e') data of this figure are such that this conclusion is consistent with these data also. Radiative and Schwinger corrections have been applied to the (e,e') spectra.

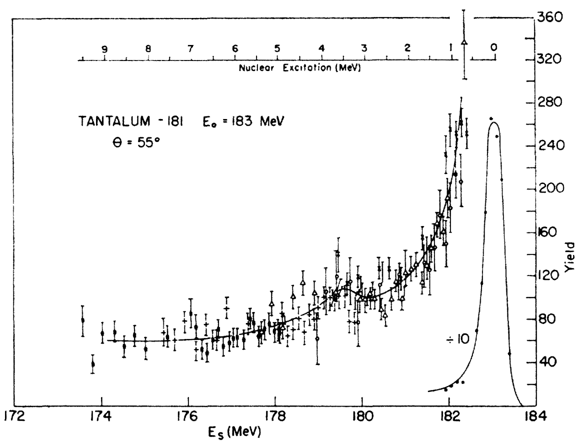

FIG. 14. Spectrum of 183-MeV electrons scattered at 55° from Ta^{181}. The contribution of the bremsstrahlung tail from the elastic peak to the region of the inelastic peak at 3.6 MeV is evident (cf. caption to Fig. 1).

$B(E2)$ plus the absence of other strong excitations in a nucleus such as In^{115} in this energy range argue that, as in Cu^{63} and the other transitions in In^{115}, the (e,e') data are again complementing the heavy-particle information and that there is strong evidence that the valence nucleons contribute to split the $E2$ core excitation.

There showed in the inelastic electron spectra evidence for other weak transitions being induced in In^{115}. There were no strong transitions observed and unambiguous data on the weaker ones are lacking. There appeared to be no transition analogous to the fast $E4$'s seen in Ni^{58} (reference 1). If they exist in this nucleus they are certainly much weaker than in Ni^{58}.

The elastic scattering of electrons from In^{115} has been studied in detail both theoretically and experimentally.[20] In Fig. 11 we show the comparison of the present elastic results with the best fit to the earlier relative and absolute data.[20] It is seen that in the region of the diffraction dip there is a slight disagreement between theory and experiment. A minor change in the details of the assumed ground-state charge distribution would be sufficient to remove the discrepancy. As the elastic scattering computer codes are no longer available we have not been able to carry out this analysis.

D. Tantalum-181

There are only the most meager data on the collective states of strongly deformed nuclei for excitations above 3 MeV. Cohen and Price[6] have investigated Ta^{181} with the (d,d') reaction. As in similar (p,p') studies the strong anomalous states seem to disappear. Either they are weakly excited or their strength is distributed among a large number of widely spaced levels which do not stand out as a group when excited.

We studied Ta^{181} by (e,e') using electrons of primary energy 183, 300, and 600 MeV, in an effort to search all accessible ranges of momentum transfer so as to be sensitive to $E2$, $E3$, and $E4$ transitions. With the exception of a weak 3.6-MeV transition seen over a reasonably wide range of momentum transfer and a 5.6-MeV transition so weak we are unable to confirm its existence with any confidence, the search gave wholly negative results (see Figs. 14, 15, 16, and 17).

Strongly deformed nuclei exhibit much weaker diffraction structure in their elastic F^2 than do spherical nuclei. The elastic electron scattering process in Ta^{181} has been studied both experimentally and theoretically and the results given in reference 21. Essentially nothing is known concerning the consequences of the permanent deformation in altering the Born approximation treatment of inelastic scattering and we are extremely hesitant about drawing conclusions based on the analysis of the F^2 for the 3.6-MeV transition. The statistical uncertainties introduced by the very large background subtractions combined with our lack of

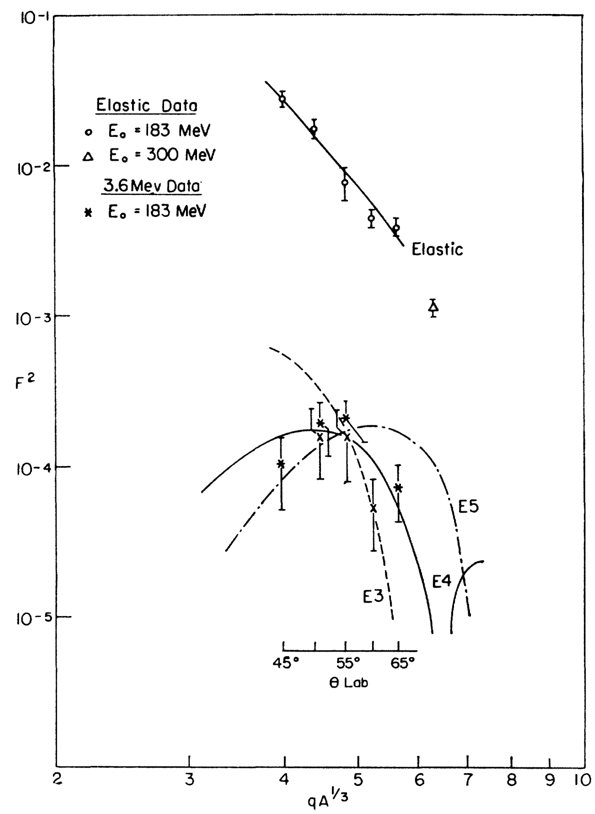

FIG. 15. The measured F^2 for the 3.6-MeV transition in Ta^{181}. An $E4$ fit to the data is shown. The uncertainties in the analysis of the data from this deformed nucleus are very great and we are reluctant to draw quantitative conclusions from the fit to the data. See especially the remarks in the text (cf. caption to Fig. 2). Some representative elastic data are shown also.

[20] H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian, Phys. Rev. **121**, 283 (1961).

[21] B. Downs, D. Ravenhall, and D. Yennie, Phys. Rev. **106**, 1285 (1957).

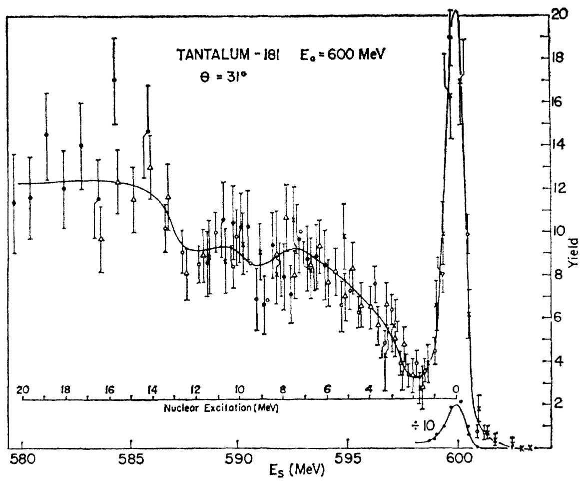

FIG. 16. Spectrum of 600-MeV electrons scattered at 31° from Ta^{181}. See the caption to Fig. 8 and the discussion in part IV of the text.

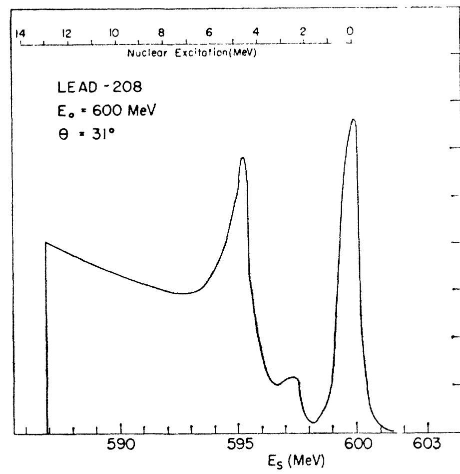

FIG. 18. The data of the preceding figure with radiative and Schwinger corrections applied (cf. caption to Fig. 17).

knowledge of even a qualitative response of the theory to the introduction of a permanent ground-state deformation are the primary sources of this reserve. However, if the deformation of the nucleus is not regarded as altering the predictions then the data suggest an $E4$ assignment for the 3.6-MeV transition, and if, in addition, the ground state is assumed to have spin zero so we can make a definitive, albeit incorrect, assignment of the excited-state spin then the gamma ray completely de-exciting the nucleus from this state has a rate enhanced by about a factor of 9. This result is equivalent to the enhancement of $B_{\mathrm{ph}}(E4)$ if we assume we are observing all members of the multiplet associated with a vibrational state.

The state in question is weakly excited by inelastic deuteron scattering and apparently by the (p,p') reaction (see Fig. 9 of reference 19). We conclude that the correlation between heavy-particle and electron induced excitations continues to hold in the present circumstances and that the very strong $E3$ and $E4$ transitions seen in the Pb region are indeed much attenuated in

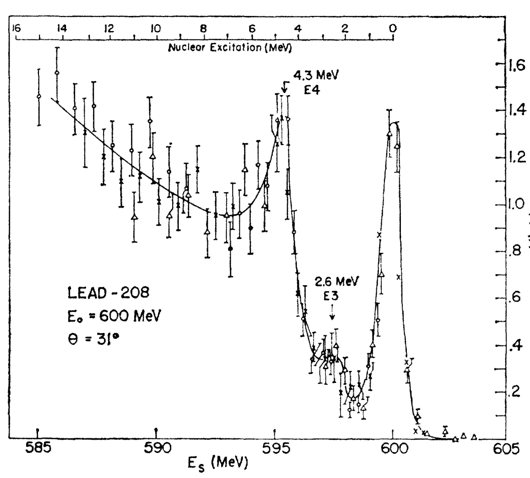

FIG. 17. Spectrum of 600-MeV electrons scattered at 31° from Pb^{208}. In addition to the elastic peak the 2.6-MeV $E3$ transition and 4.3-MeV $E4$ transition are seen. The increase in the $E4$ excitation probability compared with the $E3$ (as compared with lower q measurements) is consistent with the predictions of the theory based on these assignments. The spectrum indicates that both transitions cannot be $E3$'s of comparable strength. See caption of Fig. 8 and the text for more complete discussion of these data. The succeeding figure shows these data with radiative and Schwinger corrections applied.

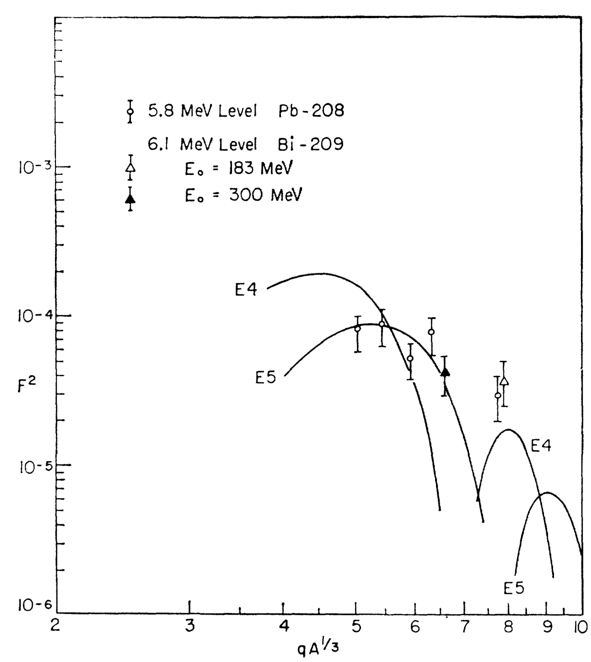

FIG. 19. F^2 for the 5.8-MeV levels in Pb^{208} and Bi^{209}. $E4$ and $E5$ fits are shown. Although the $E5$ assignment is the better of the two in the region of the principal diffraction maxima the $E4$ probably cannot be excluded by the data. The observed F^2 does not have a distribution similar to the known $E4$ states in these nuclei (cf. Fig. 21).

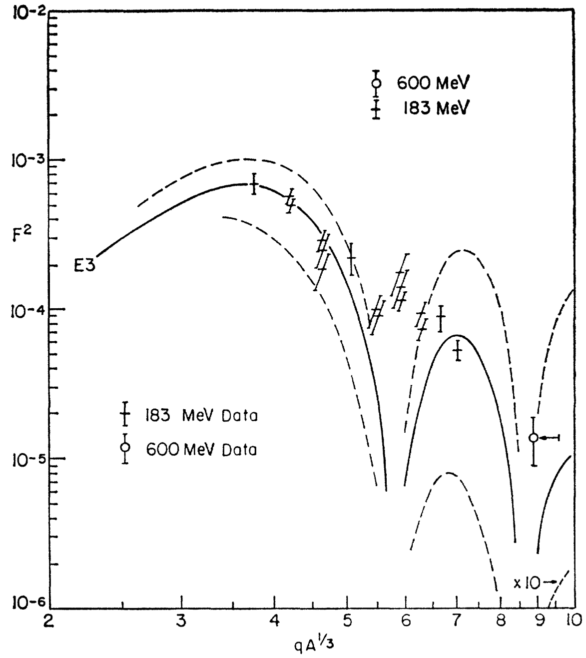

FIG. 20. F^2 for the 2.6-MeV $E3$ transition in Pb-208. The 183-MeV results and the inelastic $E3$ predictions (solid line) are from reference 1 in the text. To illustrate the great sensitivity the theory has to the details of the diffuseness of the nuclear surface, we show (upper dashed curve) the prediction based on a nuclear model having a uniform density out to $r=1.2A^{1/3}$ fermi and zero outside. The transition charge density is a delta function at r. The lower curve uses the model assumed for the solid curve but with the ratio of edge thickness to radius appropriate to $A=60$ instead of 208. The 600-MeV data have had the local wavelength correction applied. The direction and magnitude of the correction is shown by the horizontal arrow.

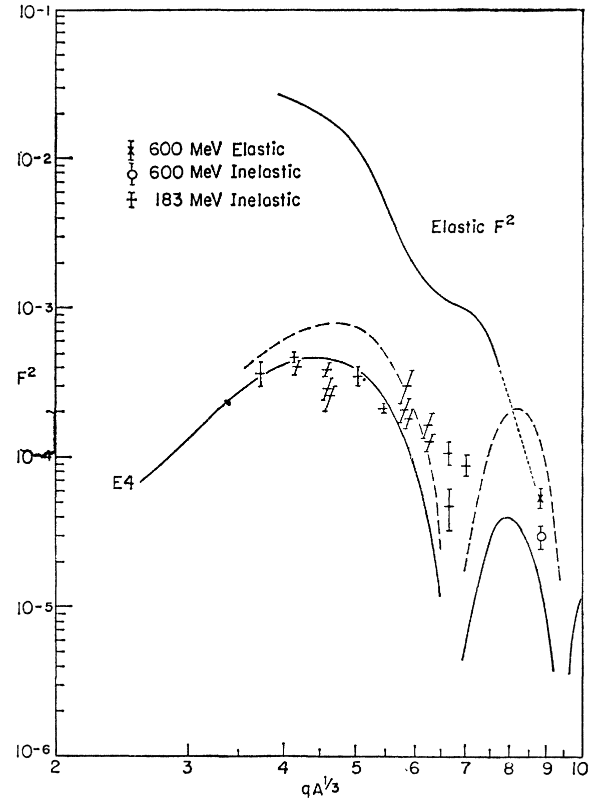

FIG. 21. Elastic and 4.3-MeV inelastic F^2 for Pb^{208}. The inelastic data and predicted $E4$ F^2 are from reference 1 of the text. See also caption to Fig. 20. The elastic F^2 (solid line) is also from reference 1 but has been corrected for a normalization error made there. It is a visual fit to the data and is indistinguishable from the observed elastic F^2 for Bi^{209}. The extrapolation (small dashes) is a visual fit to the earlier F^2 and the new elastic point taken at 600 MeV. The inelastic F^2 (dashed curve) is the prediction from the assumption that the transition charge density is a δ function at $r=1.2A^{1/3}$ (fermis). The 600-MeV data have had the local wavelength correction applied.

the region of permanent deformations. A less intensive study of the scattering of electrons from Au^{197} gives a similar result including the correlation with the results of a (p,p') study. These results for gold are briefly discussed in the succeeding part of this paper and a comparison of the (e,e') and (p,p') excitation of gold is shown in Fig. 22.

E. Lead-208 and Bismuth-209

A substantial part of the inelastic scattering experiments reported in I consisted of the study of the scattering of 183-MeV electrons from Pb^{208} and Bi^{209}. In the present work we have extended the range of momentum transfer studied in the case of Pb^{208} in order to determine at the higher momentum transfers that the F^2 for the 4.3-MeV 4^+ excitation does in fact exceed the F^2 for the 2.6-MeV 3^- excitation as predicted by theory and hence to remove the remaining ambiguity in the $E4$ assignment. The results of the present measurements are shown in Figs. 17–22. Some older unpublished data were evaluated in order to locate the transitions in these nuclei observed by Cohen and Rubin[19] at about 5.6 MeV. The similarities between the (p,p') and (e,e') studies of these nuclei has been discussed in I. In Fig. 22 we show the comparison of spectra for the excitation of Pb^{208} for (p,p') and (e,e') reactions. The (e,e') data are taken from unpublished data of the authors of I. The particular parameters of the (p,p') measurements were not such as to accentuate both the excitation of the 2.6-MeV and the 4.3-MeV level. It is, however, clear that they are both being excited as is a broad level at about 5.6 MeV. A level energy (5.8 ± 0.2) MeV is seen in (e,e') in Pb^{208} at a primary energy of 183 MeV, at angles of 55°, 60°, 65°, 70°, and 90°. The measured F^2 are shown in Fig. 19. The gamma-ray rate enhancement is about 8 (cf. Table I).

Scattering of 300-MeV electrons from Bi^{209} at 31° and 45° showed a level at (6.2 ± 0.3) MeV at the larger angle but only an upper limit for excitation of the state at 31°. A level at (5.9 ± 0.2) MeV had been observed in 183-MeV electron scattering at 55°, 60°, 75°, and 90° but the quantitative data for all but the last point are no longer available. The measured F^2 extracted from the 300-MeV 45° point, appropriately corrected for the

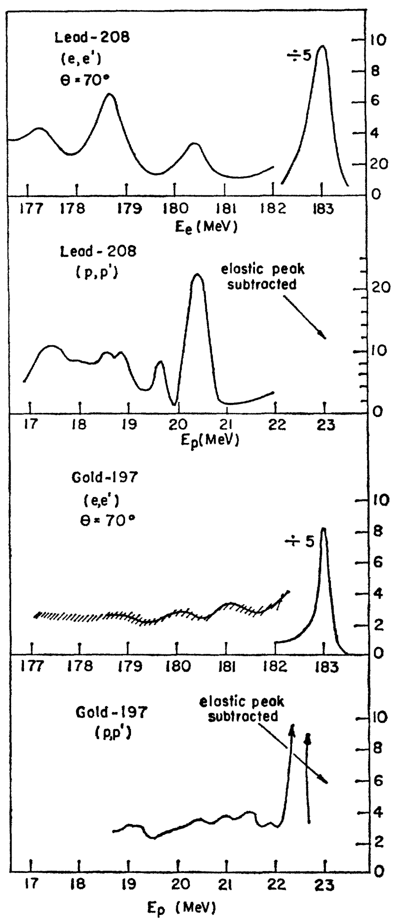

FIG. 22. Qualitative comparison of the spectra of 183-MeV electrons scattered at 70° from Pb^{208} and Au^{197} with the spectra of 23-MeV protons scattered at 90° from the same targets. The proton data are from the reference in the caption of Fig. 13. The proton data and, separately, the electron data were taken under the same conditions. The (e,e') data from Au^{197} have uncertainties about as large as shown by the hatching. Qualitatively neither $(e.e')$ nor (p,p') excite strong transitions of energy greater than one or two MeV in Au^{197} yet they both do in Pb^{208}. A strong transition seen in Au^{197} in (p,p') at about 0.5 MeV may be masked by the elastic peak in the (e,e') data.

local wavelength, is shown also in Fig. 19. The 183-MeV data for the 5.8-MeV transition in Pb^{208} are fitted by an $E5$ assignment. The Bi^{209} points are in agreement with the $E5$ predicted F^2. An $E4$ F^2 does not fit the Pb^{208} data particularly well but probably cannot be excluded on consideration of the known uncertainties in the theory applied.

Scattering of 600-MeV electrons from Pb^{208} at 31° shows excitation of the 2.6-MeV and 4.3-MeV levels (see Fig. 17). As expected the $E4$ transition has substantially greater cross section than the $E3$. The peaks ride on a background that appears to be an extension of the envelope of the quasi-elastic scattering peak. Figure 18 shows the data with the Schwinger and bremsstrahlung corrections applied. The poorer energy resolution at this point did not allow us to observe the 5.8-MeV transition. An upper limit on the F^2 for the transition at this primary energy and angle does not conflict with the $E5$ assignment.

The $E5$ states in Pb^{208} and Bi^{209} have their analog in both Pb^{207} and Pb^{206} (reference 19), in the region between 5 and 6 MeV. If our assignment is correct, then the common level represents the third member of the collective excited-state spectrum common to those nuclei, a conclusion supported by the measured value of G. The other two members are reached by the 2.6-MeV $E3$ transition and the 4.3-MeV $E4$ transition. The values of G and Γ as determined from experiment for the $E5$ transition have an exceedingly strong dependence on our assumptions concerning the outermost parts of the nucleus. As there is essentially no information, theoretical or experimental, on collective $E5$ excitations in such a nucleus to which we can compare our results it would be particularly useful to have further studies of these levels by other techniques.

The F^2 for the elastic, the 2.6-MeV, and the 4.3-MeV transitions in Pb^{208} are shown in Figs. 20 and 21. The 183-MeV data displayed are from I as are the predicted F^2. The 183-MeV data showed that there are apparently no diffraction dips observed in the inelastic data. This failure to reproduce even in part the predictions of the Born approximation near the Born zeros is observed with much lower Z targets. The present 600-MeV data are consistent with the filling-in of the Born zero (for the 2.6-MeV point) and (for the 4.3-MeV point) with the accuracy of the predicted F^2 based solely on the 183-MeV data. To illustrate how surprising this continued agreement is, at high q, in view of the great sensitivity of the theory to the diffusenesss of the nuclear surface we have compared the above predictions with those that arise (a) from assuming no diffuseness of the surface and (b) with a surface parameter characteristic of $A=60$ rather than $A=208$ (see Figs. 20 and 21). Assumption (a) is equivalent to assuming the transition charge distribution is a delta function at $r=1.20A^{2/3}$ (fermis). These predictions differ by factors of from 50 to over 100 in the range of $qA^{1/3}$ about 9.

The strong collective excitations seen in lead and bismuth do not persist as one moves to somewhat lower mass numbers. The results from Ta^{181}, discussed above, bear this out as do a number of spectra measured using targets of Au^{197} bombarded with 183 MeV electrons. Measurements were made at 50°, 60°, 70°, and 80°. No excitations were observed. Although by no means as through a search for weak transitions was made as in Ta^{181} it was clear that no excitations exist similar to those seen in Pb^{208}. As in Ta^{181} the correlation with the results of the (p,p') studies is very high. Figure 22 shows comparison of (p,p') and (e,e') spectra for both Pb^{208} and Au^{197}. The (p,p') data and, separately, the (e,e') data were taken under identical conditions and hence may be directly compared. Inelastic deuteron scattering measurements from Pb^{206}, Pb^{207}, Pb^{208}, and

Au^{197} using high-energy resolution[22] have yielded results which are again very similar to the (p,p') and (e,e') measurements. Gold shows no strong excitations in the range from about 0.7 MeV to over 4 MeV, while under the same conditions the 2.61-MeV state in Pb^{208}, a 2.65-MeV level in Pb^{207}, and levels at 2.68 and 2.71 MeV in Pb^{206} are very strongly excited.

Continuing theoretical studies[23] of the structure of the collective states in Pb^{208} still fail to explain their configurations and lifetimes on the basis of particle-hole interactions. In particular it is expected that the high gamma-decay rates observed can only be understood by using a great number of particle-hole configurations to describe the states.[23,24]

IV. CONCLUSIONS AND SUMMARY

The study of odd-A nuclei undertaken in the present work was intended in part to determine the multipole assignments and gamma-ray rates for those levels that are excited strongly by the scattering of high-energy electrons and to compare these results with the excitation of the same and other levels by inelastic scattering of heavy particles. We have found a strong correlation between the different techniques not only as to the particular levels excited but even, where reasonably precise comparisons are possible, including relative intensities. Comparisons with (p,p'), (α,α'), and (d,d') have shown not only that these reactions excite those states strongly which have enhanced gamma-decay rates to the ground state but that where such states appear to be absent none of the reactions including (e,e') are able to excite any discrete states with large probability. In addition, in all the cases investigated in which assignments of excited-state parities relative to the ground states have been made by analysis of heavy-particle excitation studies these assignments were verified by explicit multipole assignments from the (e,e') results. Among the examples in odd-A nuclei cited in the present work were collective excitations observed as single levels within the experimental resolution (see the remark below concerning Bi^{209}) and others in which clusters of states were seen that were so widely split that even individual transitions could be resolved (e.g., in Cu^{63}).

We have not made detailed comparison with the results of (n,n') reactions primarily because the experimental techniques available are not able to yield data of high energy resolution and at the same time make definitive relative parity assignments over a wide range of excitation. We should mention, however, that the (n,n') reaction appears to have the property, in common with the other reactions discussed here, of exciting predominantly collective states. This is documented well by references in the Nuclear Data Sheets[8] for In^{115}, Co^{59}, and Bi^{209}. Unpublished data of Day[25] show that the strongest excitations observed in Bi^{209}, Pb^{207}, and Pb^{208} using incident neutrons of 4.1 MeV are at 2.6 MeV. (See I for the studies of the collective states in Co^{59}).

There have not been many studies based on precise experimental information concerning core deformations in even-even and nearby odd-A nuclei: There are some cases in which a well-defined core excitation may be weakly coupled to a valence nucleon configuration; Co^{59}, In^{115}, or Bi^{209} may be examples. There are certainly others for which such a description is inadequate. Studies[3] of the low-energy $E2$ transitions in V^{51} bear this out and it is likely that the great widths of the multiplets in Cu^{63} and Cu^{65} imply violation of the necessary conditions for a weak-coupling description.[14] The results of Day[25] show that the widths of the expected 2.6-MeV multiplets in the odd-A nuclei Pb^{207} and Bi^{209} are not extremely great: more precise data are expected to be available soon. That there are interactions between the core and the valence nucleons is known for $A=209$ by studies of the ground-state quadrupole moment of Bi^{209}. It is altered by a factor of two as a consequence of the interaction of the extra proton and the nuclear surface.[26,27] The present studies combined with the results of the high-resolution heavy-particle excitations provide a number of well documented cases of such multiplets. The (e,e') results show that the states comprising a multiplet all decay to the nuclear ground state by fast electric transitions of common multipole order. In a number of cases (see I for several examples) the (e,e') results identify an analogous single fast transition of the same energy and multipole order in nearby even-even nuclei. The heavy-particle reactions complement this information by providing data on the disposition and relative excitation cross sections for the different levels of the multiplet. The combined results evidently represent a body of information that is very sensitive to the properties of the nuclear surface and its interaction with the valence nucleons. Table I includes the energies of each of the states, seen in high-resolution nucleon scattering, that we identify as belonging to the multiplets excited by the (e,e') reaction. Branching ratios from these high-resolution data are not presently available.

There is some theoretical understanding of the mechanisms of the (p,p') and similar reactions that give rise to strong excitations of collective states. See especially the recent work of Tamura and Terasawa[28] and the detailed study of Pinkston and Satchler.[29] It is expected

[22] R. K. Jolley, E. K. Lin, and B. L. Cohen, Phys. Rev. **128**, 2292 (1962).

[23] W. J. Pinkston Shell Theory and Pb^{208}: II (to be published). See reference 1 for references to earlier calculations.

[24] J. Sawicki, Phys. Rev. **126**, 2231 (1962).

[25] R. B. Day (private communication). We appreciate permission to quote these unpublished results.

[26] T. Tamura and T. Udagawa, Collective $E3$ and $E4$ Transitions and the Effective Charge (to be published).

[27] V. N. Guman, Zh. Eksperim. i Teor. Fiz. **41**, 800 (1961) [translation: Soviet Phys.—JETP **14**, 574 (1962)].

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that the electron scattering mechanism should excite collective nuclear levels preferentially at low values of the momentum transfer in the same way that the (p,p')-type reactions do. This follows from the remark that, for low q, the transition matrix elements for nuclear excitation, are, within constant factors, just the matrix elements for the corresponding gamma-ray decays and the electron scattering cross sections then must exhibit the same enhancement as the gamma-decay rates. At high momentum transfers there is no reason to expect such behavior, in fact, quite the opposite. The expansion of the (e,e') matrix element in powers of qr, where r is the nuclear radius, whose leading term is so closely related to the gamma decay, is entirely invalid at the highest values of qr reached in experiments of the present type. [For example, for the data of Fig. 18, the value of qr is about 9.] The interaction of the incident electron with the protons in the target nucleus is clearly weak as is seen not only from the values of the e,p scattering cross sections but also by the demonstrated and somewhat surprising success of the Born approximation in analyzing the present class of measurements. Electron scattering cross sections are primarily sensitive to nuclear structure over distances of order $1/q$ and it is remarkable that the single-particle excitations do not become increasingly important relative to the collective excitations. The strong collective excitations involve the correlated motions of a fairly large number of particles over distances which, for $Z\approx 82$, are of the order of ten fermis. One does not expect the excitation of such states, for $1/q\simeq 0.8$ fermi, using a weakly interacting probe, to give rise to cross sections that dominate the scattered electron spectrum at low nuclear excitation. Yet Fig. 18 convincingly shows that this is indeed the case. The correlation between $B(E2)$ and the inelastic (e,e') cross sections should begin to be less apparent for q greater than its value at the first diffraction maximum.

Figures 8, 16, 17, and 18 show the spectra of electrons scattered from Cu^{63}, Ta^{181}, and Pb^{208} at the highest momentum transfers at which the elastic and inelastic F^2 have been measured. Each was taken at a primary electron energy of 600 MeV at a laboratory scattering angle of 31°. The momentum transfer for each is 1.63 $(\text{fermi})^{-1}$. The lead data, discussed above, show prominent peaks corresponding to excitation of the collective states. The tantalum data, Fig. 16, show no prominent structure: a result that lends additional confirmation to our earlier conclusions concerning the absence of distinct vibrational states in this type of nucleus. The copper data, Fig. 8, although no discrete transitions are resolved, show that the fast $E2$ transitions are being excited and, in addition, the $E4$'s at 5.5 MeV. The spectrum is quite similar to several taken in Ni^{58} in which similar collective states at similar excitation energies were strongly excited.[14] We regard the structure shown in Figs. 8, 17, and 18 as indicating the continued dominance of the collective states in nuclear excitation by high momentum transfer electron scattering.

The above remarks apply to the inelastic heavy-particle scattering results also although in those reactions there is a much stronger interaction between the incident particle and the nucleus. The decrease in the correlation between the gamma enhancements and the excitation cross sections should occur for these processes for somewhat greater values of q. The difference in the interaction strengths between the heavy particle and the electron reactions is reflected directly in the differential cross sections for excitation. For the (p,p') and (e,e') comparison data for In^{115} shown in Fig. 13 the differential cross sections for inducing the 3^- transitions to the two levels at approximately 2.1 MeV are $\sim$0.6 mb/sr and 0.01 mb/sr, respectively. The ratio of the cross sections is about 60. For excitation of the 2.6-MeV level in Pb^{208} the ratio for the data of Fig. (22) is estimated to be about 5000.

Now the qualitative characteristics of inelastic electron scattering are well understood and with the Born approximation analysis we can extract useful quantitative results whose uncertainties have been determined by comparison with results from other techniques and found not to be very great. On the basis of the remarks above,[30] however, we must conclude that this present method of analysis can only be regarded as an empirically justified procedure for extracting values of λ and Γ_m. One would expect both single-particle and collective states to be excited at high momentum transfer but the continued correlation of the cross sections with the corresponding gamma-ray enhancements should not persist to high values of q. Why the (e,e') reaction continues to excite preferentially long-range correlations in the nucleus at high momentum transfer remains a puzzle.

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[30] See the remarks of Kurt Gottfried, in Proceedings of The International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, Italy, September 3–8, 1962 (to be published).