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Inelastic electron scattering from ^{208}Pb at 180°

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Inelastic cross sections for 180° electron scattering from ^{208}Pb have been measured at incident energies of 40.5, 50.4, 60.3, and 75.2 MeV. Transverse electric form factors have been determined for the 3^- state at 2.614 MeV, the 5^- states at 3.198 and 3.708 MeV, the 2^+ states at 4.085 and 6.21 MeV, the 4^+ state at 4.323 MeV, and the 6^+ state at 4.422 MeV. The results for these natural parity states are compared to the predictions of an incompressible, irrotational current model, and of a particle-hole model. All transverse electric form factors show strong contributions from intrinsic magnetization currents. Transverse form factors were obtained for the proposed 1^+ state at 4.84 MeV, for the group of 1^+ states at 7.48 MeV, and for several proposed 2^- states. A search for $M1$ transition strength was made up to excitation energies of 19 MeV. The future of electron scattering as a tool for probing $M1$ strength in ^{208}Pb is discussed.

[NUCLEAR REACTIONS ^{208}Pb(e,e'), E=40.5, 50.4, 60.3, and 75.2 MeV, measured $\sigma(180°)$. ^{208}Pb deduced levels and transverse form factors. Enriched target, magnetic spectrometer.]

I. INTRODUCTION

Of the many unanswered questions about ^{208}Pb, two of the most compelling focus on the unknown transverse character of the low-lying collective states,[1] and on the whereabouts of the long-predicted but mostly unobserved magnetic dipole excitation strength.[2] In this paper are presented the results of experimental investigations into these unresolved problems using 180° inelastic electron scattering.

Much is known[1,3-6] about the longitudinal character of the low-lying, collective states of ^{208}Pb. Indeed, (e,e') data on the longitudinal cross section of the 2.614 MeV, $J^{\pi}=3^-$ state are currently more extensive than for any other nuclear excited state.[1] Conversely, little is known about the corresponding transverse cross sections, especially at low momentum transfers where data are nonexistent. The availability of such transverse data would provide a stringent test for the numerous models proposed for the structure of these states.

A long-standing problem in ^{208}Pb concerns the whereabouts of the "missing" M1 strength.[2] Theoretical estimates of the total M1 strength [B(M1)↑] vary between 20 and 50 μ_0^2 (where μ_0 denotes the nuclear magneton), considerably in excess of the presently confirmed strength[2] of approximately 8.5 μ_0^2. In simple models, the expected strength is primarily derived from the $\pi(h_{9/2},h^{-1}_{11/2})$, and $\nu(i_{11/2},i^{-1}_{13/2})$ configurations. The failure to find the predicted strength implies that the current estimates of the $\sigma_1 \cdot \sigma_2$ part of the effective nucleon-nucleon interaction may lie in serious error.

The variety of experimental searches conducted to locate M1 strength in ^{208}Pb has been reviewed by Raman.[7] Previous (e,e') measurements have been hindered either by inadequate resolution or by adverse longitudinal contamination in the measured cross sections. Even at scattering angles as far backward as 165°, longitudinal scattering is often predominant, and transverse contributions cannot be reliably determined. Moreover, in the case of the missing M1 strength, recently advanced[2,8] effective mass arguments suggest possibilities for pushing this strength to excitation energies as high as 12 MeV, in a region of exceedingly high level density. Experimental resolution of at worst a few keV is called for, a requirement well beyond present capabilities. For (e,e') measurements at 180°, however, the longitudinal cross section reaches a minimum, in effect producing a transverse pass filter." An additional advantage of 180° measurements is the minimization that occurs in the underlying continuum resulting from radiative processes.

II. EXPERIMENTAL METHOD AND DATA ANALYSIS

Measurements were performed using the high-resolution 180° electron scattering facility of the Bates Linear Accelerator. Details of this facility have been well-documented elsewhere,[9,10] so little elaboration is needed here. The targets consisted of self-supporting foils of thickness 4.50, 9.88, and 20.0 mg/cm^2, enriched to 99% in ^{208}Pb. Through the combined use of target rotation in the vacuum and a horizontally-defocussed, dispersion-matched beam spot approximately 3 mm wide and 30 mm high, average beam currents on target of up to 30 μA could be utilized without melting the target.

The incident beam energies were 30.0, 40.5, 50.4, 60.3, and 75.2 MeV. However, data obtained at the lowest energy, never previously realized at Bates, proved to be of unreliable quality and were discarded. Experimental resolutions (full width at half maximum) of no better than 50 keV were attained, because of the experimental complexities incurred with the use of the 180° system and the necessity of mounting the targets in reflection geometry. Various spectrometer acceptance solid angles up to 3.52 msr were used in order to investigate the possibility of longitudinal strength contaminating the measured cross sections. The absolute normalization of the data was established by comparison of the elastic ^{1}H(e,e) cross section to the results of extensive measurements made at Mainz.[11]

The measured spectra are shown in Fig. 1. In order to determine the cross sections represented by the observed peaks, a line shape fitting procedure described in Ref. 12 was used. Reference 12 also contains the explicit expressions to transform the measured cross sections into longitudinal and transverse (e,e') form factors. A tabulation of the data is available from PAPS depository.[13] The level energies quoted in this paper are mainly from a forthcoming compilation.[14]

III. LOW-LYING ELECTRIC TRANSITIONS

Data are presented first on transverse form factors for known electric transitions at 2.614 ($J^\pi=3^-$), 3.198 (5^-) and 3.708 (5^-), 4.085 (2^+), 4.323 (4^+), and 4.422 (6^+) MeV. As mentioned earlier, little was previously known about these form factors, especially for small values of the momentum transfer q. This arises from the inherent weakness of the transverse form factors, $F_T{}^2(q)$, which for $q\approx0.3$-1.0 fm^{-1} are typically only 10^{-3} to 10^{-2} of the corresponding longitudinal form factors, $F_L{}^2(q)$. For scattering angles close to 180°, however, longitudinal scattering is heavily suppressed. In the plane-wave Born approximation, the differential cross section near 180° is[15]

$$d\sigma(\theta\approx\pi) = \left(\frac{Z\alpha}{2E_i}\right)^2 \eta \times\left\{\left[\left(\frac{\pi-\theta}{2}\right)^2 + \frac{m^2}{E_iE_f}\right] F_L^2(q) + F_T^2(q)\right\}, \quad (1)$$

where E_i and E_f are the incident and scattered electron energies, m is the electron rest mass, Z is the atomic number, α is the fine structure constant, and η is the kinematic recoil factor. Due mainly to the effects of the finite angular acceptance of the spectrometer and multiple scattering in the target,[16] the effective scattering angle is usually 2-3° less than the geomet-

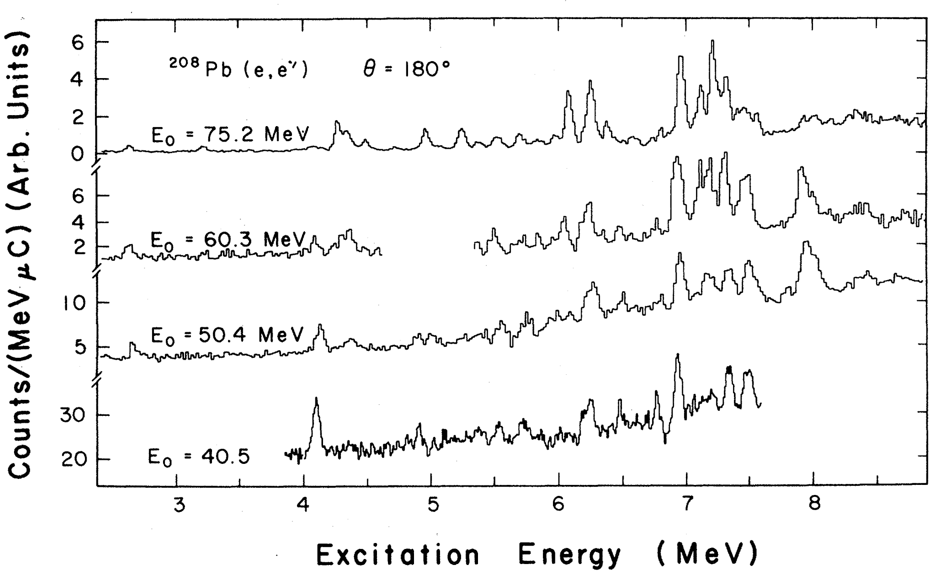

Fig. 1. Measured spectra of electrons inelastically scattered from ^{208}Pb.

rical scattering angle at 180°. Thus the kinematic suppression factor for longitudinal scattering is approximately 6×10^{-4}. Nevertheless, longitudinal contamination in the 180° data can still be appreciable. This is strikingly demonstrated in Fig. 2: Purely longitudinal elastic scattering gives rise to the strongest peak in the spectrum. Fortunately, the relative longitudinal contamination in inelastic peaks is usually much smaller.

In order to separate the longitudinal contributions from the measured cross sections, the effective scattering angle must be determined by measuring the elastic cross section. Since the ground state charge distribution is well known, the longitudinal form factor can be accurately evaluated in distorted-wave Born approximation (DWBA) using a phase-shift code. Substitution of the observed cross section into Eq. (1) then yields the effective scattering angle. Once this is known, the longitudinal contamination in the inelastic peaks can be isolated. To compute the inelastic longitudinal form factors, the Fourier-Bessel expansions for the transition charge densities given by Lichtenstadt[5] were employed. Longitudinal contamination in the measured cross sections turned out to be <20% for all the states of interest, except for the 2.614 MeV, 3^- state, where the longitudinal contribution ran as high as 50-60%. The subtraction of these components from the measured data yielded the transverse form factors shown in Fig. 3.

The separability of the longitudinal and transverse form factors implicit in Eq. (1) is strictly valid only in the plane-wave Born approximation. The wisdom of this separation for a high-Z nucleus such as ^{208}Pb is perhaps questionable. Nevertheless this separation has been made in the belief that it identifies more explicitly the role played by nuclear currents, since it is these alone which define the transverse form factors. The nature of the results being presented, where the experimental errors are often large, also argues for this approach. If one were to be concerned with the detailed comparison with sophisticated theories, then more precise results would be called for, and the separation of longitudinal and transverse form factors, as has been done here, would clearly be inappropriate.

A first step toward understanding these data may be made by using an extension of the Tassie model, which has been widely applied to the interpretation of collective, longitudinal form factors.[3] Heisenberg[1] has suggested that the total nuclear transverse current may be separated into two different components, an irrotational current and a divergenceless current

$$\bar{J}(\bar{r}) = \bar{J}_{ir}(\bar{r}) + \bar{J}_{div}(\bar{r}),$$

having the properties

$$\bar{J}_{ir}(\bar{r}) = \hbar\omega\left[\frac{2L+1}{L}\right]^{1/2} r^{L-1} \times \int_0^r r'^{1-L}\,\rho_L(r')dr'\; Y^M_{L,L-1}(\hat{r})$$

and

$$\nabla\cdot\bar{J}_{div}(\bar{r}) = 0,$$

where $\hbar\omega$ is the excitation energy and L is the transition multipolarity. The form of the current $\bar{J}_{ir}(\bar{r})$ is provided by the continuity equation when the flow of charge is assumed to be incompressible and irrotational.[17] The density $\int_0^r r'^{1-L}\,\rho_L(r')dr'$ can be interpreted as the charge which takes part

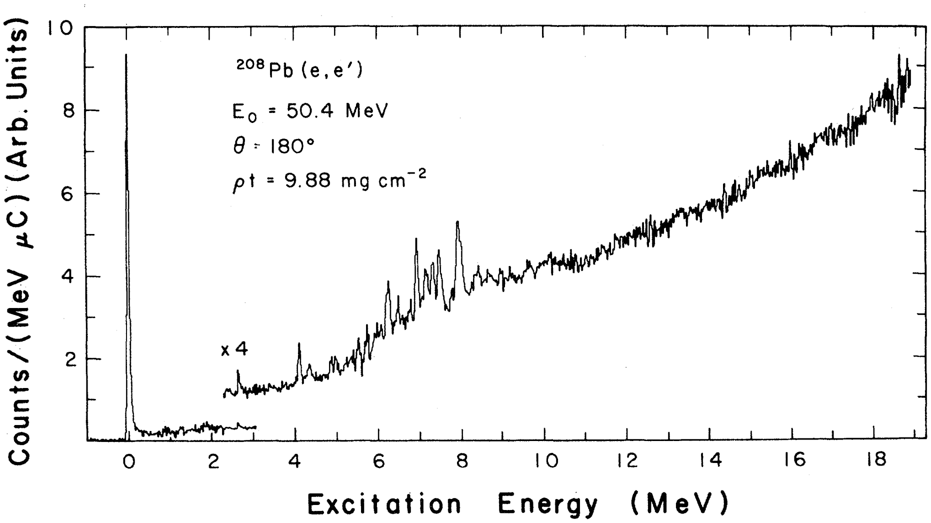

Fig. 2. Scattered electron spectrum, obtained with 50.4 MeV electrons, shows a large elastic peak and little evidence of significant sharp structure in the range E_x = 9-19 MeV.

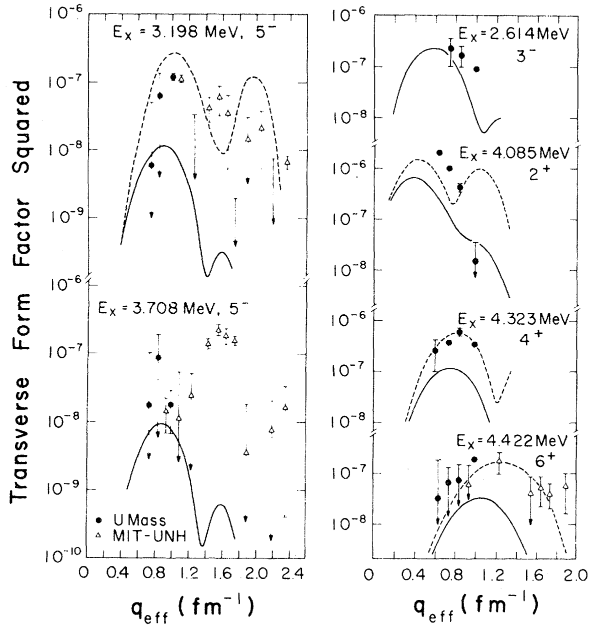

Fig. 3. Transverse (e,e') form factors for low-lying electric transitions in ^{208}Pb. In cases where no experimental datum is explicitly shown, the error bar indicates an upper limit, i.e., the measured value plus three standard deviations. The solid curves are for irrotational, Tassie-model currents. Dashed curves include, in addition, neutron magnetization currents due to predicted strong particle-hole components, as described in the text. To facilitate the comparison of measurements taken under different kinematic conditions, the data and the DWBA calculations are plotted as a function of an effective momentum transfer defined by (see Ref. 12) $q_{eff} = 1[1+(3Z\alpha/2E_iR)]$, where α is the fine structure constant, and R is the uniform density charge radius.

in the current flow. In the strict Tassie model this takes the shape of the ground state charge density; however, in this paper the example of Heisenberg[1] is followed, and the transition charge density determined by fitting[5,6] forward-angle inelastic data is utilized.

Unlike $\bar{J}_{ir}(\bar{r})$, the divergenceless current $\bar{J}_{div}(\bar{r})$ has no manifestation in longitudinal scattering.[1] Since $\bar{J}_{div}(\bar{r})$ includes all currents generated by the nucleon magnetic moments, it is expected to provide the dominant contribution[15] to the transverse electric form factor at high q. On the other hand, unless the electric transition has either a strong "spin-flip" component or the character of a rigid rotator, the low-q data should be mainly attributable to the irrotational convection current.

The form factors shown in Fig. 3 lend qualified support to these simple expectations. It may be observed, for example, that the magnitudes of the first diffraction maxima for the 2.614 MeV E3 and 3.708 MeV E5 excitations are satisfactorily accounted for by form factors derived from the irrotational Tassie model currents (continuous curves). At higher momentum transfers, however, the Tassie model considerably underestimates the data. This is very noticeable in the form factor for the 3.708 MeV state, where transverse form factors have been extracted from scattering measurements made at 160° by Lichtenstadt et al.[5,6] Even for a very collective level like the 2.614 MeV state, at q_{eff}=1.0 fm^{-1} the Tassie model prediction lies a factor of ten below the observed transverse cross section. For the 3.198 MeV E5 transition, the irrotational current model fails to describe even the first diffraction maximum. Since these states have vibrational rather than rotational character, the participation of strong intrinsic magnetization currents is inferred.

For a more quantitative estimate of the role played by magnetization currents, attention was given to the natural parity states at 4.085 (2^+), 4.323 (4^+), and 4.422 (6^+) MeV, for which theoretical structure calculations are available. As may be seen from Fig. 3, the measured data again lie well in excess of form factors calculated for irrotational, Tassie-model currents. These three levels form part of a sequence of states which has been interpreted[18] as a "quasirotational band," since the energy spacings follow rather closely the J(J+1) law. Calculations by Weber et al.[18] using a separable residual interaction model are in good agreement with the longitudinal (e,e') form factors measured for these states. Although the longitudinal form factors are determined by very collective admixtures of proton particle-hole components, the quasirotational character of these states is found by Weber et al. to arise primarily from $(2g_{9/2},1i^{-1}_{13/2})$ and $(1i_{11/2},1i^{-1}_{13/2})$ neutron configurations which provide about 75% of the wave function amplitude. These neutron excitations play no part in longitudinal excitation; however, by virtue of the neutron's intrinsic magnetization, they may be expected to contribute strongly to the transverse form factors. The corresponding electroexcitation matrix elements have been computed using the particle-hole amplitudes of Weber et al. and harmonic oscillator single particle wave functions.

The results of combining the contributions of the irrotational and neutron magnetization currents are represented in Fig. 3 by the dashed curves. Without access to detailed model predictions, there exists some uncertainty concerning the relative phase of the irrotational and magnetization terms. The two amplitudes have been added (constructive interference), since this is what the data clearly demand. In each of the three cases the neutron magnetization is found to provide the dominant contribution to the transverse form factors. Good agreement with the data is obtained for the

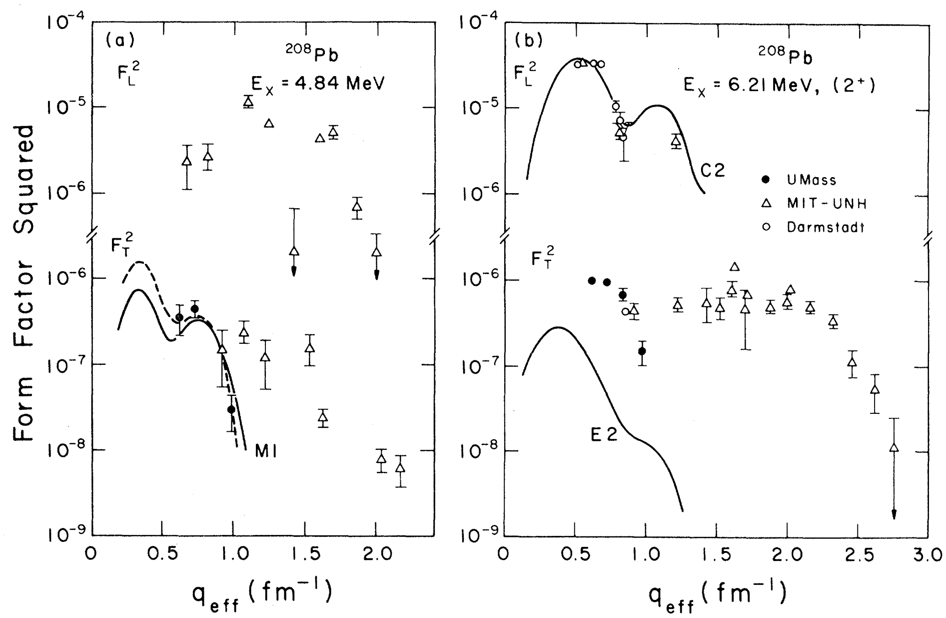

Fig. 4. Separated longitudinal and transverse form factors for transitions in ^{208}Pb. (a) Results for peak observed at 4.84 MeV and comparison with two theoretical M1 curves. (b) The longitudinal form factor of the 6.21 MeV excitation seems to be well described by a curve reproducing the q dependence of the 4.09 MeV E2 transition. The transverse E2 curve is for an irrotational current only.

4^+ and 6^+ levels, but not for the 4.085 MeV, 2^+ state. Given the character of these states, one may consider form factor enhancement due to rigid rotator currents. Except for the 2^+ state, the data can be explained without recourse to such motion. Recent theoretical work suggests that the contribution of rigid rotator currents to transverse form factors is small.[19,20]

It is almost certain that a similar explanation exists also for the observed enhancement of the E5 form factors over the irrotational flow predictions. The structure[5] of 5^- states in ^{208}Pb is believed to be not as collective as, for example, the 2.614 MeV 3^- level; the character of these states may be defined by one or a few dominant particle-hole configurations, which can be expected to have large magnetization amplitudes. For example, random phase approximation (RPA) calculations[6] suggest that the structure of the 5^- state at 3.198 MeV is dominated by the $\nu(2g_{9/2},3p_{1/2}^{-1})$ configuration with an amplitude of 0.874. The relevant dashed curve in Fig. 3 shows the result of combining this particle-hole term in opposite phase with the irrotational flow current. It is seen that, even in destructive interference, the neutron magnetization contribution is more than sufficient to account for the observed strength of the first diffraction maximum. In fact, the RPA particle-hole amplitude of 0.874 appears too large, unless it happens that remaining small admixtures in the transition matrix element coherently combine to cancel some of the $\nu(2g_{9/2},3p_{1/2}^{-1})$ strength.

To conclude this section, brief mention is made of a relatively strong state appearing at 6.21 MeV in the measured spectra. Weber et al.[18] have predicted the existence of a 2^+ state at this energy. This state displays both longitudinal and transverse character and has been given a tentative 2^+ assignment by Frey.[21] Fig. 4 shows that the longitudinal form factor is well fitted by a curve reproducing the q dependence of the 4.086 MeV, 2^+ state. From the forward-angle results of the Darmstadt[21] and the M.I.T.-New Hampshire[5,6] groups, the strength of the 6.21 MeV state is estimated as $B(E2)\uparrow = 505 \pm 37\ e^2\mathrm{fm}^4$. As shown in Fig. 4, there now exists a considerable pool of data on the transverse part of this form factor as well.

IV. SEARCH FOR *M*1 EXCITATION STRENGTH

The motivation for seeking out the ^{208}Pb magnetic dipole strength has been comprehensively justified in the literature.[2] In the simplest shell model picture only two low-lying 1^+ states can be constructed, arising from the $\pi(h_{9/2},h_{11/2}^{-1})$ and $\nu(i_{11/2},i_{13/2}^{-1})$ configurations, as shown in Fig. 5. Based on currently accepted single-particle energies, these two basis states are nearly degenerate, and appreciable mixing may therefore be expected. Accordingly, the wave functions for the two mixed 1^+ states may be written as

$$\psi(1^+,\Delta T=0) = A\ \pi(h_{9/2},h_{11/2}^{-1}) + \sqrt{1-A^2}\ \nu(i_{11/2},i_{13/2}^{-1}), \quad (2a)$$

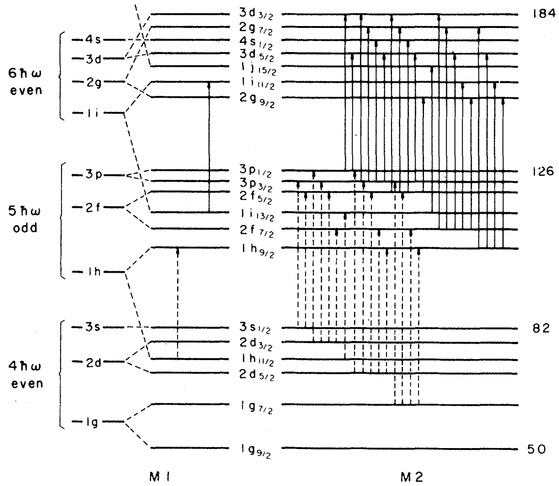

Fig. 5. Single-particle M1 and M2 excitations in ^{208}Pb. The full and dashed arrows respectively signify neutron and proton transitions.

$$\psi(1^+,\Delta T=1) = \sqrt{1-A^2}\ \pi(h_{9/2},h_{11/2}^{-1}) - A\nu(i_{11/2},i_{13/2}^{-1}) . \quad (2b)$$

In principle, inelastic electron scattering should provide an explicit means of determining the structure of the states, since the (e,e') form factor is sensitive to the parameter A, as well as to the isoscalar ($\Delta T=0$) or isovector character ($\Delta T=1$) of a particular transition.

A detailed appraisal of the status of the M1 strength in ^{208}Pb has been given by Raman.[7] The relatively well-established M1 strength of ≈ 8.5 μ_0^2 is shared between 35 states clustered in the 7.25-7.82 MeV region, and the less well-established strength, also of ≈ 8.5 μ_0^2, is shared by 7 states in the 8.22-9.40 MeV region. The strong fragmentation is attributed to mixing of the two 1p-1h configurations with configurations of the 2p-2h type. Notwithstanding this observed fragmentation, it is expected that the structure of the low-lying 1^+ states should be given dominantly by the doorway $\pi(h_{9/2},h_{11/2}^{-1})$ and $\nu(i_{11/2},i_{13/2}^{-1})$ amplitudes. The main portion of the well-established M1 strength in ^{208}Pb is in fact found between 7.40 and 7.55 MeV with a total B(M1)↑ value of 6.0 μ_0^2 from radiative neutron capture measurements.[7,22] For the same region, threshold photoneutron studies[23] suggest a somewhat lower integrated M1 strength of 4.4 μ_0^2. We tentatively identify a peak observed at 7.48 MeV in the 180° (e,e') spectra of Fig. 6b with this concentration of M1 strength.

The form factor values corresponding to this peak are shown in Fig. 7a. Also included are the results of measurements by the Darmstadt group,[21] as well as photon-point values derived from the radiative neutron capture[22] and threshold photoneutron[23] measurements. Three different model predictions are depicted, two of which, the pure (A=0) proton (π^*) and the pure neutron (ν^*) transitions, employ the effective operators suggested by Knüpfer et al.[24,25] The third calculation, for complete isovector mixing ($A=1/\sqrt{2}$) of the 1p-1h proton and neutron configurations, employs bare nucleon charge and magnetic moment values. By normalizing the various calculated curves to the measured data, a range of B(M1)↑ values of 14 to 26 μ_0^2 is obtained. This model dependence of the deduced B(M1)↑ value arises even for incident electron energies as low as 40 MeV. The corresponding 180° momentum transfer places the measurements in a region located beyond the first diffraction maximum in the form factor, a region sensitive to nuclear structure details. Hence, the q range of the existing (e,e') data is too high to permit the extraction of model-independent B(M1)↑ values.

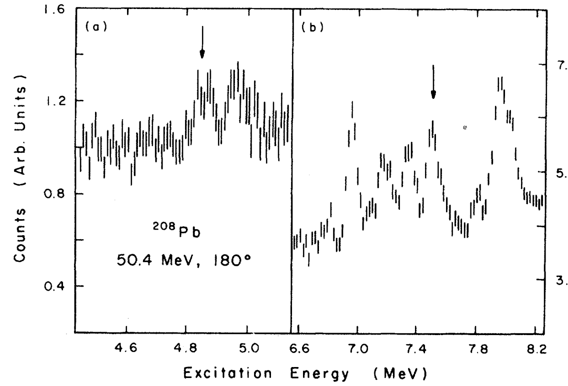

Fig. 6. Detail of an inelastic electron spectrum showing candidate M1 peaks at 4.84 and 7.48 MeV.

The stark disagreement of the (e,e') B(M1)↑ value with 5.2 μ_0^2, the average strength derived from (n,γ) and (γ,n) experiments, is even more instructive. It turns out that any admixture of the two 1p-1h configurations underestimates the (e,e') data by at least a factor of 2.5 when normalized to B(M1)↑ = 5.2 μ_0^2. As shown in Fig. 7b, slightly better results are obtained if the effective operators suggested by Knupfer et al. are used; however, the level of disagreement remains striking. Several possible sources for this discrepancy will now be discussed.

Firstly, attention is drawn to the Darmstadt measurements of Frey[21,25] indicated in Fig. 7a. These data were obtained at angles forward of 180°, but have been DWBA-corrected by us to correspond to the form factor values that would have been obtained for pure M1, 180° scattering. The two 141° points and the 165° measurement at $q = 0.46\ \mathrm{fm}^{-1}$ are seen to lie well above the trend of the 180° data, disclosing the existence of longitudinal transition strength in this excitation region. Following a more detailed analysis, Frey ten-

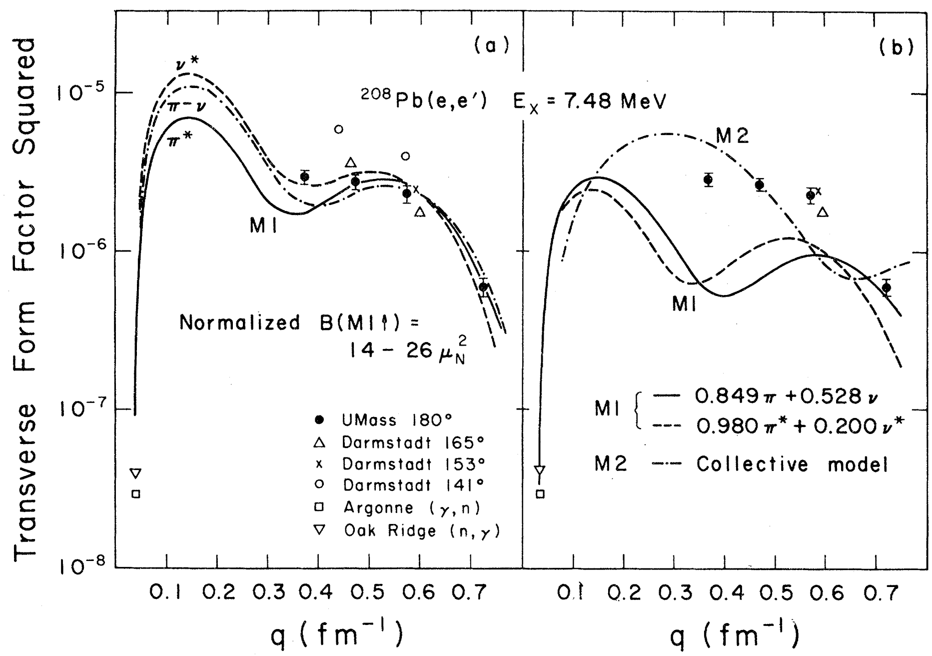

Fig. 7. Transverse (e,e') form factors for ^{208}Pb states in the region E_x = 7.50 - 7.55 MeV. The data are compared to theoretical curves computed using harmonic oscillator radial wave functions and the two simplest single-particle excitations, $\pi(h_{9/2}, h^{-1}_{11/2})$ and $\nu(i_{11/2}, i^{-1}_{13/2})$. Asterisked curves denote the use of effective operators proposed by Knüpfer et al. (Refs. 24 and 25). (a) Normalization of the calculated curves to the (e,e') data leads to a B(M1)↑ value that is inconsistent with that given by (γ,n) and (n,γ) measurements. (b) On the other hand, the data are poorly fitted by the M2 q dependence calculated using the collective model. In this case the M1 curves are normalized to the photon-point measurements. The abscissa here is q and not q_{eff} as in other figures.

tatively assigned longitudinal strength to possible 1^- and 3^- levels near 7.5 MeV. Indeed, neutron capture measurements[7] have provided ground state radiation widths for several 1^- states in this vicinity. These 1^- and 3^- states will have associated transverse components which will augment the 180° cross section. The magnitude of this enhancement may be assessed by comparison with the cross sections observed for other, more clearly defined 1^- and 3^- states. In fact, the transverse electric strength in definite and probable E1 and E3 excitations is observed to be very weak. Using for reference, known states[7,21] at 5.512, 5.525, and 6.620 MeV, it is estimated that less than 20% of the transverse cross section measured for the 7.48 MeV peak is electric in nature. According to this comparison, it therefore seems unlikely that contaminant transverse electric strength could account for the unexpected enhancement of the 7.48 MeV peak.

Secondly, Frey[21] has proposed that the bulk of the transverse strength in the 7.48 MeV peak has M2 character on the basis of similarities observed with a presumed 2^- doublet at 8 MeV. The 180° data do not support this suggestion. As shown in Fig. 7b, these data are not well fit by a theoretical curve that satisfactorily describes the observed low-q behavior of proposed M2 states.

A third point of conjecture concerns higher-lying M1 excitations of $2\hbar\omega_0$ character. RPA calculations, performed by Speth et al.[26] predicted such states to be concentrated in the 18-22 MeV region; however, a subsequent experimental search[27] of this excitation range revealed little significant structure. It was then demonstrated that many of the predicted $2\hbar\omega_0$ levels undergo appreciable shifts to lower excitation energies when pi- and rho-meson exchanges are considered.[28] Thus it is conceivable that M1 strength in the 7.5 MeV region includes large $2\hbar\omega_0$ admixtures. Since the radial dependences of the $2\hbar\omega_0$ transition densities are quite different from those of the low-lying 1p-1h excitations, such mixing would modify considerably the shape of the expected M1 form factor, and could, in principle, produce a q dependence consistent with both the electron scattering and the photon point data.

Further evidence for the admixture of $2\hbar\omega_0$ configurations into the 7.5 MeV cluster of 1^+ states may also be indicated by recent ^{208}Pb(p,n)^{208}Bi measurements[29] at 0°. Petrovich, Love, and McCarthy[30] have demonstrated how forward-angle (p,n) cross sections may be combined with radiative transition probabilities to separate convection current and spin current contributions in isovector M1 excitations. This procedure has recently been extended[31] to enable separation of the spin and orbital contributions to the 7.5 MeV M1 strength in ^{208}Pb, which is accessible by both the isovector and the isoscalar operators. Comparison of the 0° (p,n) measurements[29] with the B(M1)↑ value deduced from (n,γ) and (γ,n) work leads to two possible results[31]:

$$|\rho^{s1}(q=7.5\ \text{MeV}/c)| = 0.8 \pm 0.2,$$

$$|\rho^{\ell\pi}(q=7.5\ \text{MeV}/c)| = 1.1 \pm 0.5 \text{ or } 2.6 \pm 0.5,$$

for the isovector spin and proton orbital current transition densities, respectively. The two densities are constrained to have opposite signs, implying a strongly destructive interference between spin and orbital currents at the photon point $q=\hbar\omega$.

The deduced transition densities may now be compared with nuclear model predictions. For example, for a pure isovector ($A=1/\sqrt{2}$) transition between the two spin-orbit partners represented in Eq. (2b), one obtains $\rho^{s1}=-1.10$ and $\rho^{\ell\pi}=+0.27$. Thus, the purely isovector model does not seem tenable since it cannot account for the large proton orbital current indicated by the comparison of the (p,n) data with the experimental B(M1)↑ value. Of all the various possible admixtures of the two simplest 1p-1h configurations, the maximum calculated orbital current density corresponds to the pure proton transition represented by $\pi(h_{9/2},h_{11/2}^{-1})$. In this case, $\rho^{s1}=-0.89$ and $\rho^{\ell\pi}=0.38$. Unfortunately, the enhancement obtained in $\rho^{\ell\pi}$ is insufficient to permit easy reconciliation with either of the alternative experimental values.

Thus, the comparison of the 0° (p,n) data with the measured B(M1)↑ value seems to suggest the same conclusion as the combined (e,e'), (n,γ), and (γ,n) analysis. The M1 strength in the 7.5 MeV region of ^{208}Pb can only be very crudely described as a simple admixture of the two low-lying single-particle excitations. In particular, the large collective orbital current indicated by the analysis implies that $2\hbar\omega_0$ and higher-lying components are participating in some coherent fashion. The proposed low-q, destructive interference between the enhanced convection current and spin current warrants further investigation. It may offer a partial explanation of why M1 transition strength is not readily observable in (e,e') measurements on heavy nuclei.

Another point of contention regarding the M1 strength in ^{208}Pb is the relatively weak [B(M1)↑ ≈ 1.2 μ_0^2] 1^+ state calculated by Vergados[32] at 5.45 MeV. It has been noted that the isoscalar nature of this state renders it insensitive to theoretical conjectures such as effective mass arguments.[2] The nearest experimental claim for this crucial state belongs to Swann,[33] who carried out a comparison between self-absorption and scattering results, and concluded that there were two unresolved (<3 keV) levels (1^+ and 1^-) at 4843 keV, each with ground state radiation widths of 2.8 eV [B(M1)↑ ≈ 5.8 μ_0^2]. It is known through (α,α'γ) measurements[34] that a definite 1^- state exists at this energy, but the 1^+ state has not been conclusively shown to exist. Two new measurements have addressed this problem. The resonance fluorescence experiment of Biesot and Smith[35] using plane-polarized photons can effectively excite only one member of the postulated doublet. Their results favor a 1^+ assignment for this member, although a 1^- possibility is not excluded. Chapuran et al.,[36] on the other hand, have essentially repeated Swann's measurements, and have found no compelling reasons to invoke such a doublet.

The present (e,e') data acquired at 180° with 40.5 and 50.4 MeV electrons do reveal a small peak at 4.84 MeV as shown in Fig. 6a. Comparison of our points with the more forward angle data of Lichtenstadt[5] in Fig. 4 indicate that this peak has both longitudinal and transverse character, and therefore must accommodate an electric transition. There is no a priori reason to suspect, however, that the transverse form factor may not also include the superimposed contribution from a (purely transverse) magnetic excitation.

Because the 4.84 MeV peak is relatively weak, the derived form factors are rather sketchy. Nevertheless, an upper limit to possible M1 strength may be assessed by comparing the low q transverse data with two of the theoretical curves shown in Fig. 7. This procedure yields an upper bound of 2.5 μ_0^2, less than half of the strength proposed by Swann.[33] Recalling, however, that even the most successful of the theoretical descriptions overestimated the M1 strength in the 7.48 MeV peak by a factor of ≈ 2.5, the deduced upper limit may be considered generous, especially since the transverse electric strength that must exist in compliance with the finite longitudinal cross section observed for the 4.84 MeV peak has been neglected.

The total M1 strength in ^{208}Pb becomes highly uncertain if it is as highly fragmented as demonstrated[7,22] by the cluster of 35 states in the 7.25-7.82 MeV region. In this region, the total strength carried by 35 states is less than 8.5 μ_0^2 with no single state carrying more than 1.6 μ_0^2. In other energy regions, similar experimental sensitivities have neither been attained, nor are likely in the near future. The theoretical problem posed by the existing measurements lies less in the total strength than in the absence of strong 1^+ states predicted by all RPA calculations.[37-40] It has been suggested[2,8,28] that these early calculations erred in employing unperturbed particle and hole energies, and that appreciable strength should be found at substantially higher excitation energies than previously foreseen. If so, the fragmentation should become even more severe and difficult to measure. Even though strong 1^+ states are no longer expected, a search was made for them up to excitation energies of 19 MeV. As shown in Fig. 2, no evidence was found above 9 MeV for narrow structure comparable in magnitude to the 7.48 MeV peak.

V. MAGNETIC QUADRUPOLE (*M*2) TRANSITIONS

In contrast to the M1 case where the simple single-particle model identifies only two low-lying 1^+ states, the same model predicts a multitude of M2 excitations, as shown in Fig. 5. A priori, it is then expected that the M2 spectrum will show a high degree of collectivity arising not only from the intermixing of the 1p-1h basis states, but also from mixing with the 2p-2h excitations which appear to play a vital role in fragmenting the M1 strength. Calculations made in RPA by Ring and Speth[37] predict the strongest 2^- state to lie at 7.5 MeV with a B(M2)↑ value of 9380 $\mu_0{}^2\text{fm}^2$, which is half the total expected M2 strength.

The only existing information on M2 transitions in ^{208}Pb comes from previous (e,e') measurements.[25,41] Based on comparison with the RPA calculations, Frey et al.[25] identified eight 2^- states between 6.428 and 8.008 MeV with a total B(M2)↑ strength of 8510 ± 750 $\mu_0^2\text{fm}^2$. Figure 8 shows the data available on the four most easily resolved of the proposed M2 transitions. The present 180° data lie in good agreement with measurements made at more forward angles. Thus the results are consistent with the purely transverse character expected of magnetic transitions.

A comparison is made not only to the predicated RPA form factor, but also to the q dependence obtained from a phenomenological collective model in which the M2 current density is defined by[42] $j(r) \sim d\rho(r)/dr$, where $\rho(r)$ is the simple two-parameter Fermi representation of the ground state charge distribution of half-density radius 6.412 fm, and skin-thickness 2.47 fm. The two contrasting models yield M2 form factors which follow a similar q dependence as far as the first diffraction minimum at $q_{eff} \approx 0.9\ \text{fm}^{-1}$. However, as Fig. 8 indicates, the two calculations diverge at this point, with neither accounting for the enhanced high q cross sections measured by Lichtenstadt et al.[5,6]

Table I shows B(M2)↑ transition strengths deduced using only data below the first diffraction minimum, where the theoretical description seems adequate. Note that the collective model gives values approximately 55% in excess of the RPA results. This discrepancy further underlines the model dependence in the reduced transition probabilities extracted from incomplete or statistically imprecise (e,e') data. In this case the model uncertainties may carry even more far-reaching consequences, as will be discussed in the following section.

VI. CONCLUDING DISCUSSION

The nature of our results is to raise, rather than answer, questions about the magnetic dipole states in ^{208}Pb. This arises mainly from two experimental difficulties: the inability to achieve the required fine energy resolution, and the failure to measure to very low momentum transfers. As noted at the outset, the

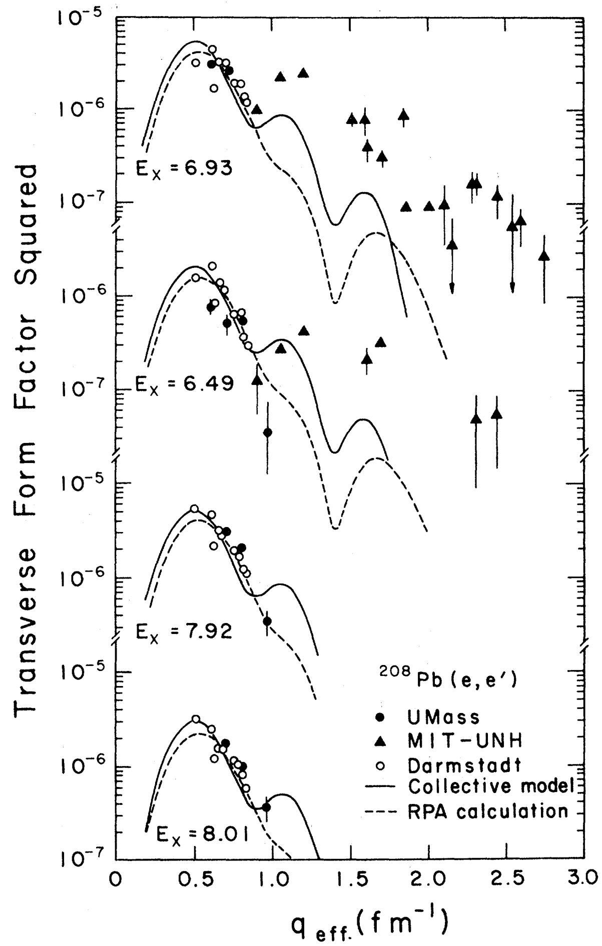

Fig. 8. Transverse form factors deduced for ^{208}Pb transitions exhibiting M2 character.

TABLE I. Experimentally deduced transition probabilities for ^{208}Pb transitions exhibiting M2 character. The two sets of values correspond to the different q-dependences predicted by the RPA and collective models.

E_x (MeV)	B(M2)↑ ($\mu_0{}^2\text{fm}^2$) RPA	Collective
6.48	1018	1596
6.93	2582	3985
7.92	2541	4010
8.01	1453	2310
	Sum = 7594	Sum = 11901

states of interest exist in a region of high level density. It is known, for example, that at least eight states contribute[7] strongly to the 7.48 MeV peak discussed in Section IV.

It is emphasized, however, that fine resolution alone would be insufficient to satisfy the basic requirements of an interpretable (e,e') experiment. Coulomb distortion effects and the large nuclear radius of ^{208}Pb combine to shift the diffraction structures of low-multipole form factors to small momentum transfers. For example, if the predicted q dependences shown in Fig. 7 are approximately correct, our measurements scarcely touch upon the first diffraction maximum, and are therefore confined to a region that is sensitive to model uncertainties. As a result, little can be deduced regarding the character or strength of low-multipole transitions.

In order to measure weak transverse cross sections to small momentum transfers, low incident electron energies must be used. For the case in point, it is necessary to produce and detect electrons of energy $\lesssim$10 MeV. However, at such energies, the radiation tail rises sharply, severely degrading the signal-to-background ratio. Therefore, although it would seem advantageous to measure at 180°, where the radiation tail is minimized, inspection of Fig. 1 suggests that, even at 180°, the unwieldy magnification of the radiation tail may well become a limiting factor.

One possible solution to this problem, involving the use of an e^+ beam, has been considered by Heisenberg and Papanicolas.[43] For positrons, Coulomb distortion of the incident and scattered waves by the high-Z nucleus serves to push the inelastic form factors to higher q, rather than to lower q, as occurs with electrons. Thus the first diffraction maximum of the M1 form factor could be conveniently surveyed at moderate incident beam energies, where the elastic radiation tail is more manageable. The present limitation on the use of this technique is that the e^+ fluxes typically provided by existing facilities are about three orders of magnitude less intense than the ≈ 1 μA average current that would be required to complete the M1 measurements within a reasonable time span.

In view of the foregoing discussion, it is debatable that (e,e') experiments will ever solve such problems as determining the distribution of low-multipole magnetic strength in ^{208}Pb. Perhaps this particular problem will be more profitably addressed by using coincidence techniques with high duty-factor electron beams.

To some extent, the difficulties experienced in the interpretation of the present measurements are exacerbated by the lack of a more firmly-rooted theoretical understanding. For example, if the predicted q dependence of the M1 form factor was unequivocal, 1^+ states could be more confidently identified. At the same time it is the theoretical dubiety which motivates further experimental studies.

The interpretation of the proposed M2 transitions is also qualified by theoretical uncertainties. It has been argued that the multiplicity of possible M2 excitations might be expected to produce a high degree of collectivity. Recent RPA calculations by Heisenberg[44] deny this conclusion, suggesting that the 1p-1h basis configurations mix very little and consequently yield a spectrum of relatively pure single-particle excitations. As a result, the predicted M2 form factor shapes may vary strikingly from excitation to excitation, making the identification of M2 transitions rather problematical. The RPA calculations also predict that low-multipole electric transitions can also retain a high proportion of single-particle character. Therefore, a relatively pure neutron excitation with small longitudinal cross section might be mistakenly identified as a magnetic transition.

The outlook for the measurement of the low-lying electric transitions is much more encouraging. These states are well resolved, and the ability to determine both the longitudinal and transverse form factors provides a comprehensive test for nuclear models. In this experiment, there were several examples of states having intrinsic characters defined by one or a few dominant neutron particle-hole configurations. Transverse electron scattering probes these components directly, whereas longitudinal scattering is sensitive only to minor proton particle-hole fragments in the wave function.

It has been shown, in addition, that the irrotational convection currents expected in the collective, liquid-drop picture succeed only in describing the transverse electric form factors at very low momentum transfers. Intrinsic magnetization currents are primarily responsible for the transverse electric form factors measured in this experiment. Convection current contributions can be studied more clearly in self-conjugate nuclei, where there exist transitions proceeding solely by the isoscalar operator.[15] Obviously, more detailed theoretical investigations are required. It is to be hoped that the increasing availability of transverse form factor measurements will stimulate more endeavors in this direction.

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