Coulomb-nuclear interference in pion inelastic scattering

D. S. Oakley and P. D. Kunz
University of Colorado, Boulder, Colorado 80309

C. L. Morris
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

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The energy dependence of the cross sections for the first 2^+, 3^-, and 4^+ excitations in ^{208}Pb from pion inelastic scattering at incident pion energies from $T_\pi=116$ to 291 MeV is investigated. A significant signature of Coulomb-nuclear interference is observed in the π^-/π^+ cross-section ratio.

In a recent measurement of inelastic-alpha scattering from the even zirconium isotopes, the neutron and proton contributions to collective excitations (matrix elements M_n and M_p) were deduced using an inferred interference of Coulomb and nuclear forces (CNI).[1] Pion-inelastic scattering can give a unique signature of this interference near the $\Delta_{3/2,3/2}$ resonance (at incident pion energies near 180 MeV) because of the three pion isospin components. We therefore consider what effect CNI would have on neutron and proton matrix elements extracted from pion scattering measurements, all in a collective model.

In pion scattering, the Coulomb excitation amplitude should interfere destructively with the π^+-nucleus interaction below the $\Delta_{3/2,3/2}$ resonance and constructively above it (and conversely for π^-) but at resonance, where the predominant p-wave interaction is imaginary, we expect CNI to be a small effect. Only in pion scattering should one see this unique resonance shift. Another significant feature of pion-nucleus scattering near resonance (from $T_\pi=100$–300 MeV) is that at these energies the π^- is more sensitive to the neutrons in the nucleus while the π^+ is more sensitive to the protons. This allows for the extraction of M_n and M_p from simultaneous fits to both the π^- and π^+ cross sections.[2] Even though pions are strongly interacting and do not penetrate deeply into the nuclear interior, the agreement between M_p values extracted from electron scattering, pion scattering, and gamma deexcitations is remarkably good for strong collective states.[3] In addition, the M_n and M_p values measured from pion scattering from the first 2^+ states in light $T=1$ nuclei compare well with their mirror-nuclei counterparts.[4] Because of this reliability, the extraction of matrix elements from pion scattering can be a useful tool in identifying effects such as CNI.

In order to investigate the effects of CNI on pion scattering we have performed inelastic-scattering calculations that employ the distorted-wave impulse approximation (DWIA) both with and without Coulomb excitation included. Here we use the code DWPI (Ref. 5) with a standard Kisslinger potential including a -28-MeV empirical energy shift and collective-model (Tassie) form factors, as discussed in Refs. 4, 6, and 7. The collective model is characterized by deformation parameters, β_n and β_p, which are proportional to the matrix elements M_n and M_p.

In these calculations the Coulomb term was derived by deforming a uniformly charged sphere of radius R_c and was incorporated in the transition matrix along with the nuclear form factor.[5,8] These terms have the form

$$U_{\mathrm{Coul},l}(r)=\frac{3Z_N Z_\pi e^2\beta_c}{(2l+1)R_c}f(r)\ ,$$

with

$$f(r)=\begin{cases}\left[\dfrac{r}{R_c}\right]^l, & \text{if } r<R_c\ ,\\ \left[\dfrac{R_c}{r}\right]^{l+1} & \text{if } r>R_c\ ,\end{cases}$$

where β_c is the Coulomb distortion and the Z's are the nuclear and pion charges. We have normalized β_c to the measured nuclear matrix element.[9] The results for pure Coulomb excitation were compared to DWUCK (Ref. 10) Coulomb calculations as a cross check.

The resulting calculations for the ^{208}Pb$(\pi,\pi')^{208}$Pb interaction show the expected behavior, i.e., the effect of the Coulomb excitation contribution is to change the peak of the differential cross section by about 10–20 % for the π^+ at the energies of 120 and 250 MeV and by 5–10 % for the π^-, with the respective sign changes as shown in Fig. 1. For the calculations at $T_\pi=180$ MeV the Coulomb effects are indeed seen to be negligible. If we perform the same calculation for a smaller nucleus such as ^{40}Ca, however, the effect is too small to observe at all of these energies.

To relate these results to experiment we have compared existing pion-inelastic-scattering data for the first 2^+, 3^-, and 4^+ states in ^{208}Pb to the above calculations. The $T_\pi=116$ MeV data were collected with the pion spectrometer at Schweizenisches Institute für Nuklearforschung and the remaining data were measured using the Energetic pion channel and spectrometer at Los Alamos Meson Physics Facility at incident pion energies of 120, 180, 250, and 291 MeV.[6,11–13]

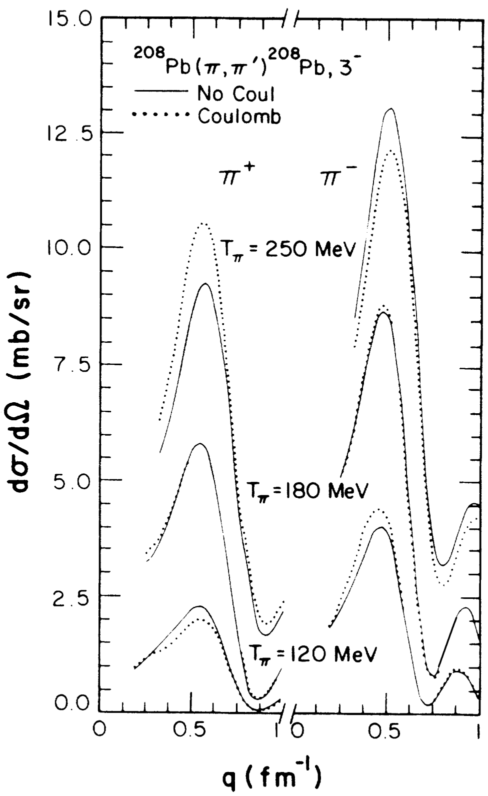

FIG. 1. Comparisons of $L=3$ DWPI ^{208}Pb$(\pi,\pi')^{208}$Pb Tassie-model calculations with (solid lines) and without (dotted lines) Coulomb excitations included. These particular calculations give matrix-element values of $M_n=1194$ $e\,\mathrm{fm}^3$ and $M_p=777$ $e\,\mathrm{fm}^3$, yielding a hydrodynamic ratio of $M_n/M_p=1.54$. The relative neutron versus proton (π^- vs π^+) strength changes systematically with energy when Coulomb excitations are included.

The resulting angular-distribution shapes were accurately reproduced by the DWPI calculations. With no Coulomb excitation, however, the magnitudes of the cross sections could not be reproduced without making the deformation parameters energy dependent. Being proportional to the nuclear matrix elements, these deformation parameters are not expected to vary with energy. Furthermore, no such variation has been observed from pion scattering to low-lying collective states of light- and medium-mass nuclei, as confirmed by a study of the calcium isotopes at several energies near resonance.[14] This energy dependence is shown in Fig. 2 and Table I, where the extracted matrix-element ratios which give the best fit to the data are displayed as a function of energy. The trend here is that the neutron contribution drops relative to the proton contribution when the beam energy is increased. When Coulomb terms are included, however, β_p (M_p) must be raised to fit the below-resonance (116–120 MeV) data and lowered for the above-resonance (250–291 MeV) data, with the reverse for M_n. Again, at 180 MeV the Coulomb effects are small. As shown in the table and figures, this 10% effect in the cross sections is enough to account for most, if not all, of the observed energy dependence. With the Coulomb effect included the ratios of deformations, and hence the matrix-element ratios extracted for the first 2^+, 3^-, and 4^+ states, are energy independent within the uncertainties. Comparison of the DWIA calculations to the 120- and 250-MeV data is presented in Ref. 6. The errors in the matrix elements presented here are only statistical and were derived in a manner to be consistent with Ref. 6.

The resulting energy-averaged ratio of M_n/M_p extracted for the first 3^- state is 1.79. Although this exceeds the value of 1.54 expected for the collective model, it is consistent with that extracted from medium-energy proton scattering, where these values range from 1.49 to 1.72.[15,16] The 116- and 291-MeV values are not included in these averages because of the large uncertainties involved.

In conclusion, we see that Coulomb excitation of the low-lying collective states in ^{208}Pb is significant in pion-elastic scattering above and below the $\Delta_{3/2,3/2}$ resonance. Furthermore, we have explicitly seen the predicted energy dependence of such an interaction which, when included, interferes destructively with the $\pi^+(\pi^-)$-nucleus potential below (above) the delta resonance and constructively above (below) it. Inclusion of Coulomb excitation gives, within the uncertainties, energy-independent matrix-element ratios of M_n/M_p for the first 2^+, 3^-, and 4^+ states in ^{208}Pb.

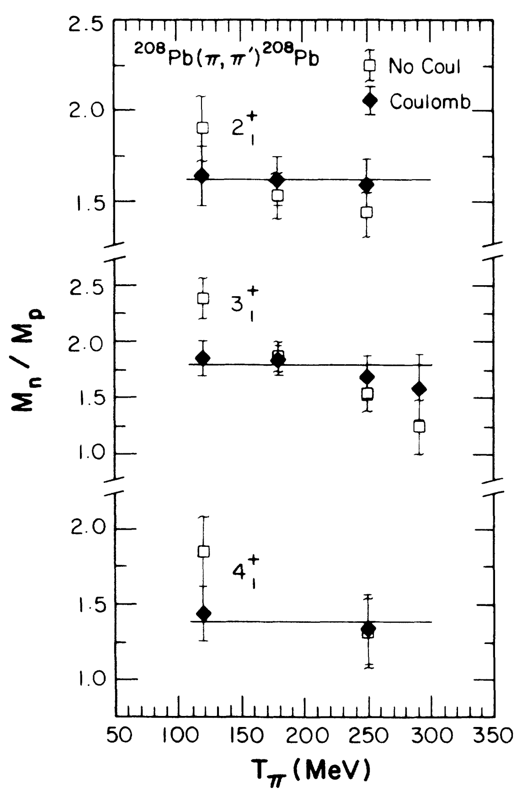

FIG. 2. Comparison of matrix-element ratios, M_n/M_p, extracted with and without Coulomb effects included. These ratios are plotted as a function of incident pion lab energy for the first 2^+, 3^-, and 4^+ states in ^{208}Pb.

TABLE I. Neutron and proton multipole matrix elements extracted for ^{208}Pb from this work with and without Coulomb effects included. Data are from Refs. 6, 11, 12, and 13.

State (J^{π})	E_x (MeV)	T_{π} (MeV)	M_n/M_p [a]	M_n/M_p [b]
3^-	2.61	116	2.04(0.35)	1.59(0.28)
3^-	2.61	120	2.38(0.18)	1.85(0.14)
3^-	2.61	180	1.86(0.13)	1.83(0.13)
3^-	2.61	250	1.54(0.16)	1.68(0.18)
3^-	2.61	291	1.24(0.24)	1.58(0.30)
3^-	2.61	average[c]		1.79(0.09)
2^+	4.09	120	1.90(0.18)	1.64(0.16)
2^+	4.09	180	1.53(0.12)	1.61(0.13)
2^+	4.09	250	1.44(0.13)	1.59(0.14)
2^+	4.09	average		1.62(0.08)
4^+	4.32	120	1.85(0.23)	1.44(0.18)
4^+	4.32	250	1.31(0.23)	1.33(0.23)
4^+	4.32	average		1.39(0.15)

[a]No Coulomb excitation.
[b]Values with Coulomb excitation included.
[c]Average of 120, 180, and 250 MeV only.

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