35-MeV Proton Inelastic Scattering from Low-Lying States in ^{207}Pb†

W. T. Wagner, G. R. Hammerstein, G. M. Crawley, and J. R. Borysowicz
Cyclotron Laboratory and Physics Department, Michigan State University, East Lansing, Michigan 48823

and

F. Petrovich
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

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Differential cross sections for the excitation of the first four excited states in ^{207}Pb via the inelastic scattering of 35-MeV protons have been compared with microscopic-model predictions. The effects of noncentral forces in a valence orbital model have been investigated and contributions from exchange and core polarization are important. Addition of an imaginary part to the microscopic form factor was also investigated and gave the best predictions of observed transition strengths.

At present, it is widely accepted that ^{208}Pb is the best "closed-shell" nucleus and that nuclei in the Pb region offer an important test of the nuclear shell model.[1] To say that ^{208}Pb is a good "closed-shell" nucleus does not imply that it behaves as an inert core in nearby nuclei. The need for an effective charge[2] to explain $E2$ γ-transition rates in neighboring systems is evidence for the coupling of the ^{208}Pb core to the valence particles or holes. Detailed information about this coupling is essential to understanding both the structure of nuclei and the reaction mechanism in this region of the Periodic Table.

This letter examines the inelastic scattering of 35-MeV protons from low-lying states in ^{207}Pb. Inelastic scattering of 20.2-MeV protons from ^{207}Pb has been studied[3] and calculations[3-5] with a simple valence hole model and only central forces could not fit the data. At 35 MeV, any compound-nuclear effects contributing at the lower energy should be negligible. Further, the interactions used here had no adjustable parameters; this allows distinct separation of contributions from knock-on exchange, complex coupling, core polarization, and central and noncentral forces.

The differential cross sections were measured using the Michigan State University cyclotron. The 6.9-mg/cm^2-thick self-supporting target, isotopically enriched to 99.14% ^{207}Pb, was prepared by rolling. Particle detection and identification were accomplished using a position-sensitive proportional counter and back-up scintillator-phototube[6] in the focal plane of an Enge split-pole spectrometer. Comparison of the experimental elastic cross sections with the optical-model predictions using Becchetti-Greenlees[7] best-fit parameters gave the absolute normalization. This normalization is probably reliable to about ±5%. The first four excited states were clearly separated while the doublet at 2.6-MeV excitation energy was unresolved. The collective model deformation parameter, β_3, for this doublet was found to agree with a previous measurement.[8]

To explain the measured angular distributions for the scattering from the first $\frac{5}{2}^-$, $\frac{3}{2}^-$, $\frac{13}{2}^+$, and $\frac{7}{2}^-$ excited states in ^{207}Pb, initially distorted-wave Born-approximation (DWBA) calculations were made which included only the valence orbits. Figure 1 compares these theoretical results with the data, the error bars indicating statistical errors where they are larger than the symbols.

The valence calculations shown in Fig. 1(a) used a central nucleon-nucleon force and an approximate treatment of knock-on exchange.[9] For the direct amplitude, the projectile-target interaction was taken to be the two-body effective bound-state interaction (G matrix) derived from the Hamada-Johnston (HJ) potential. The use of a similar interaction, when the transition density was known from electron scattering experiments, has given a good description of inelastic scattering.[10] In these calculations, harmonic-oscillator wave functions were used with the size parameter $\alpha = 0.405$ fm^{-1} which reproduces the results of elastic electron scattering on ^{208}Pb. The optical-model parameters used were those of Becchetti and Greenlees,[7] although use of other sets gave similar results. In Fig. 1(a), only the dominant $S=0$, $L=J$ transitions are displayed. The calculations underestimate the data.

A previous study,[11] using central and tensor forces for the 20-MeV data,[3] suggested important tensor contributions in the transition to the $\frac{3}{2}^-$ state. To determine if noncentral forces could significantly improve the fits, calculations were carried out still assuming a simple valence description of ^{207}Pb and using the code DWBA70[12] which allows the use of noncentral forces and

treats exchange exactly. The central portion of the effective force was taken to be a Serber exchange mixture; the Yukawa radial shape had a 1-fm range and strength of −30 MeV for V_0. (With this even-state central interaction, results compare well with the HJ and the approximate exchange calculations as can be seen in Fig. 1(b). For the noncentral analysis the tensor and $\vec{L}\cdot\vec{S}$ potentials were taken from studies by Crawley *et al.* and Fox and Austin,[13] and by Austin.[14] The tensor force had a r^2-Yukawa radial form with a range of 0.813 fm and a strength for the $\Delta T = 1$ part of 14.6 MeV. (The $\Delta T = 0$ part was set equal to zero.) The spin-orbit force was obtained from the HJ spin-orbit force with 0.49-fm cutoff and had a radial shape given by the sum of 2 Yukawas. The parameters of the Yukawa wells were obtained by matching the r^4 and r^6 integrals of the two potentials. The strength of this spin-orbit potential agrees well with that used by Love.[15]

Figure 1(b) displays the results using the central-plus-noncentral forces. In the DWBA70 calculations both $S=0$ and $S=1$ transitions were included. The angular distributions are still lower than the data by factors of 3 to 6. The predictions for the $\frac{13}{2}^+$ and $\frac{7}{2}^-$ states show the most dramatic increase. For each state, the tensor contribution dominates the spin-orbit contribution; this is opposite to the results of Ref. 16, and results from the exchange character of the interaction. Calculations using Woods-Saxon wave functions give forward-angle enhancement but renormalization by factors of 2 to 6 is still needed.

It is clear from these results that a single-hole model cannot reproduce the data even though both central and noncentral forces are used. Excitations of the core are significant and were calculated using two different models. First, the phenomenological model of Love and Satchler[17] was used. The core-polarization (CP) form factor (FF) was summed coherently with the direct-plus-exchange valence FF for the $S=0$ transition of each state. The strength of the CP was chosen to give the fits shown in Fig. 2(a). In this macroscopic model, a radial matrix element of r^L relates the

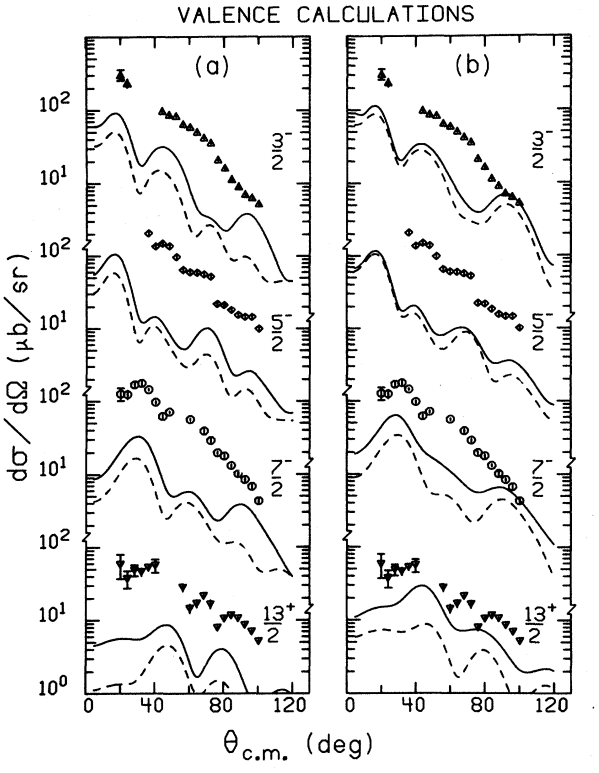

FIG. 1. Measured differential cross sections and valence orbital-model predictions. (a) The broken and solid curves give the direct and the direct-plus-exchange (DE) results, respectively, for a pure central force. (b) DE results using the code DWBA70. Central force predictions are given by the broken curve. The solid line displays calculations including noncentral interactions.

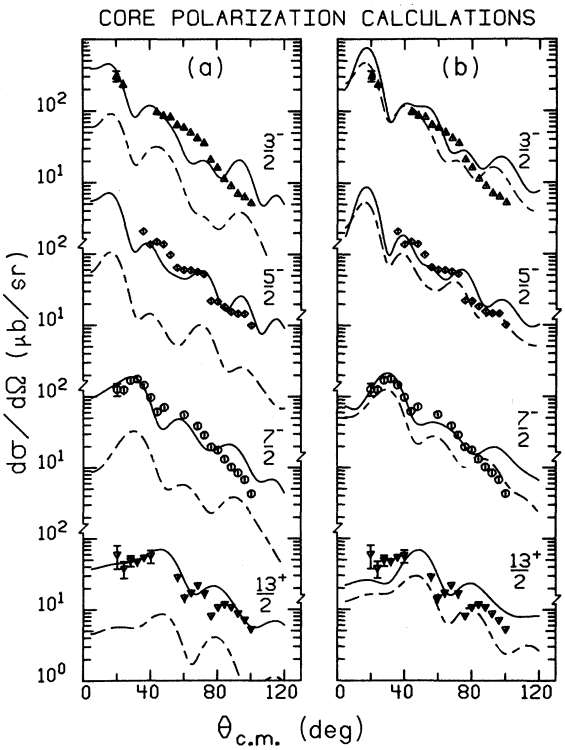

FIG. 2. Measured differential cross sections and core-polarization-model predictions. (a) The macroscopic core-polarization prediction is given by the solid line; for comparison, the broken curve shows the DE valence model. (b) The DE microscopic core-polarization results are given by the broken curve. The solid curve shows results using complex coupling.

TABLE I. e_{eff} and ϵ_p obtained using the macroscopic model (Ref. 15) and microscopic model described in the text.

State	LSJ	Exp [a] e_{eff}	Macroscopic e_{eff}	Macroscopic ϵ_p	Microscopic e_{eff}	Microscopic ϵ_p
$3p_{3/2}$	202	0.75	0.74	2.08	0.87	2.05
$2f_{5/2}$	202	0.93	0.95	2.69	0.85	2.24
$2f_{7/2}$	404	···	0.61	2.53	0.78	1.99
$1i_{13/2}$	707	···	0.43	2.76	0.41	1.77

[a] From Ref. 2.

CP strength to the effective charge[17]; these matrix elements were calculated using Woods-Saxon wave functions in a well of radius $1.2A^{1/3}$ fm, diffuseness 0.70 fm, spin-orbit strength of 25 MeV, and depth adjusted to give the correct binding energy. Expressed as $\langle r^L\rangle/(1.2A^{1/3})^L$, these matrix elements have values of 0.625, 0.722, 0.778, and 0.716, in order of excitation energy. Table I displays the values of e_{eff}, the effective charges extracted from the CP strength, and ϵ_p. If σ_{CP} and σ are the total integrated cross sections with and without CP admixtures, $\sigma_{\text{CP}} = \epsilon_p{}^2\sigma$. The tabulated experimental e_{eff} are obtained assuming the neutron-hole model. The model e_{eff} is consistently smaller than the effective charges obtained at 20 MeV,[3] a discrepancy probably due to exchange contributions which are more important at 20 MeV and which were not included in the lower-energy calculations. For the $\frac{13}{2}^+$ level, this CP model cannot give the needed forward-angle enhancement.

Second, CP effects were calculated with a completely microscopic model. Admixtures of one-particle–two-hole core excitations in each state were determined using first-order perturbation theory. The CP wave function, $|j\rangle_{\text{CP}}$, for a state of spin j was given by

$$|j\rangle_{\text{CP}} = |j\rangle + \Sigma A(j'Jj)|(j'J)j\rangle,$$

the sum running over j' and J. The ket $|j\rangle$ denotes a valence state of spin j corresponding to the appropriate neutron hole. $|(j'J)j\rangle$ refers to a component of total spin j resulting from the coupling of a neutron hole of spin j' to a particle-hole core state with angular momentum J. The amplitude of a particular component is given by

$$A(j'Jj) = -\langle(j'J)j|V|j\rangle/\Delta E,$$

where the energy denominator $\Delta E = E_j - E_{j'} - E_J$. The energies for the orbitals were taken either from the zero-deformation Nilsson scheme or from experiment. There were 19(13) particle and 10(12) hole proton (neutron) orbits included in the calculation. Harmonic-oscillator wave functions with $\alpha = 0.405$ fm^{-1} were used. The coupling potential, V, was the Kallio-Kolltveit force.[18] Similar treatments[5,19] in this mass region have given encouraging results.

Distorted-wave calculations using these CP wave functions are displayed in Fig. 2(b). Only contributions from $S=0$ amplitudes were included and only central forces were used. The broken curve gives the results for the direct-plus-approximate exchange calculations. In each case the experimental strength is underestimated. Table I gives e_{eff} and ϵ_p for these CP calculations. Here, e_{eff} was obtained from the proton-CP electromagnetic transition rates and the neutron-hole model values. The agreement with the experimental values is quite good. Unfortunately, numerical limitations prevented calculations including noncentral forces. However, it is estimated that the retardation of the $S=1$ amplitudes from CP is sufficient to cancel any increase in these amplitudes arising from the tensor force. This assertion should be checked more carefully for the $\frac{13}{2}^+$ excitation.

The solid curve in Fig. 2(b) shows results using a complex FF. The imaginary portion of the collective vibrational model FF was added to the approximate-exchange microscopic CPFF. Each deformation parameter, β_L, was obtained by fitting to the data; statistical weighting of the initial- and final-state spins was included. In order of excitation energy, the values of β_L were 0.037, 0.039, 0.038, and 0.038. The approximate exchange FF was used since the β_L's are scaled by the data and thus include some exchange effects. As seen in other instances,[5,16,20] introduction of complex coupling improves the agreement. CP wave functions also give the best fit to the 20-MeV experimental results when complex coupling is used.[5]

In summary, using realistic interactions with noncentral components and accounting for exchange effects, calculations reproduce only 20–50% of the observed inelastic cross sections when simple neutron-hole wave functions are used. A macroscopic core-polarization description is consistent with lower-energy results. A microscopic core-polarization model, with central forces, predicts cross sections slightly lower than those observed. Addition of an imaginary portion to the real microscopic CPFF gives the best fits. The importance of noncentral forces in this CP description remains to be investigated.

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