Pure Neutron and Pure Proton Transitions in Inelastic Scattering of Pions by ^{13}C

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Differential cross sections $\sigma_{\pi^\pm}(\theta)$ for elastic and inelastic scattering of 162-MeV pions from ^{13}C were measured at momentum transfers between 0.6 and 2.1 $\hbar\cdot\mathrm{fm}^{-1}$. For two inelastic transitions, enhancement of σ_{π^-} over σ_{π^+} and of σ_{π^+} over σ_{π^-} were observed which are consistent with the values for pion scattering from free nucleons. The results are discussed qualitatively in terms of simple shell-model and weak-coupling-model configurations.

In nuclear structure physics, high-resolution and high-intensity intermediate-energy pion beams are presently being employed with increasing success. For example, recent comparative studies[1-4] of π^+ and π^- scattering at pion energies near the [3, 3] resonance yielded new information on differences between neutron and proton ground-state and transition densities. For inelastic scattering from nuclei with a neutron excess, measured[2-4] cross-section ratios $R=\sigma_{\pi^-}(\theta)/\sigma_{\pi^+}(\theta)$ range from 0.8 to 1.9. These values are not as different from unity as the ratios for pion scattering from free nucleons: $R\simeq\frac{1}{9}$ for protons and $R\simeq 9$ for neutrons at the [3, 3] resonance. This result is not unexpected for the collectively enhanced transitions in even-A nuclei on which current studies have concentrated.[2-4] Results closer to the free-nucleon values may be obtained for odd-A nuclei in transitions between single-particle states or between states which differ only by a particle-hole excitation. The ^{13}C nucleus appears particularly well suited for such a study since it shows single-particle and collective features in a number of low-lying levels.[5]

We have therefore measured differential cross sections for elastic and inelastic scattering of π^+ and π^- from ^{13}C at 162 MeV using the EPICS system[6] at the Clinton P. Anderson Meson Physics Facility (LAMPF). The target[7] was a 15-cm × 23-cm sheet of carbon, 210 mg/cm^2 thick, enriched in ^{13}C to 99%, and covered on both sides by thin (~1 mg/cm^2) Kapton foils. The energy resolution for all scattering angles was better than 300 keV (full width at half maximum).

The most striking result of this experiment is the very large value, $R\sim 9$, for the transition to a state at 9.5 MeV. This result is consistent with the free π-neutron value of 9. At angles $\theta_{\mathrm{c.m.}} \geq 50°$ and $T_\pi = 162$ MeV (momentum transfers $\geq 1\hbar\cdot\mathrm{fm}^{-1}$) we find this state quite strongly excited by π^- but so weak in π^+ scattering that it is often difficult to discriminate from the background (Fig. 1). We also observe a significant enhancement of π^+ scattering over π^- scattering for a group of states at about 16 MeV excitation. Around 21 MeV there are differences in the structure of the π^+ and π^- spectra [Figs. 1(a) and 1(b)] quite similar to results of a recent experiment[8] on ^{12}C. The centroid of this group of states is

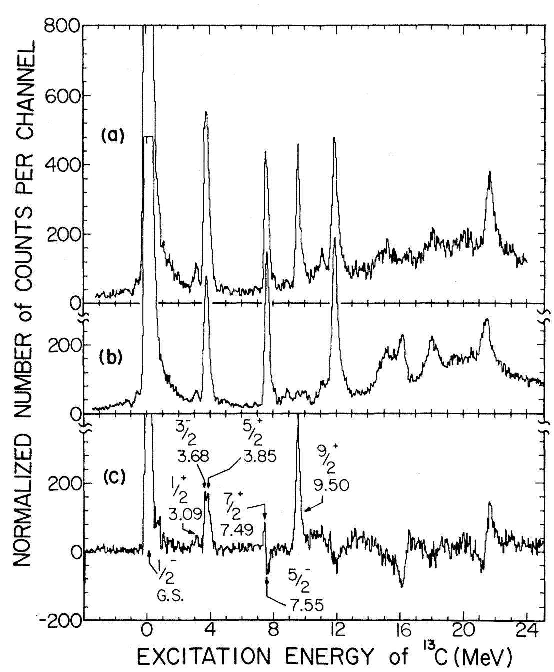

FIG. 1. Summed normalized yield spectra (a) Y_{π^-} and (b) Y_{π^+} for $^{13}C(\pi^\pm,\pi^{\pm\prime})$ at $T_\pi=162$ MeV ($\theta_{\mathrm{lab}}=62°$, 68°, 74°, 80°, 86°), and (c) difference between Y_{π^-} and Y_{π^+}.

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shifted towards lower excitation energy in the π^+ spectra in comparison with the π^- spectra as is apparent in the difference spectrum [Fig. 1(c)].

We prefer to represent the differences between the cross sections σ_{π^-} and σ_{π^+} by the parameter $A=(\sigma_{\pi^-}-\sigma_{\pi^+})/(\sigma_{\pi^-}+\sigma_{\pi^+})$ rather than by the ratio $R=\sigma_{\pi^-}/\sigma_{\pi^+}$. Values of A obtained at the maxima of the differential cross sections are presented in Fig. 2. For the 9.5-MeV state $A=+0.8\pm0.2$, consistent with a pure neutron excitation. For a state or a group of states at $E_x\simeq16$ MeV, $A=-0.6\pm0.2$ indicating an almost pure proton excitation. For other states the values of A range from about -0.4 to $+0.4$, more in line with previously observed enhancement factors. [The ratio $R=1.86\pm0.16$ for $^{18}O(2^+)$ (Ref. 2) corresponds to a value of $A=+0.30\pm0.04$.]

Of the "single-neutron states" of ^{13}C known[9] from $^{12}C(d,p)$ we resolve the weakly excited $\frac{1}{2}^+$ state at 3.09 MeV and obtain $A=0.3\pm0.1$. The $\frac{5}{2}^+$ state at 3.85 MeV was not fully resolved from the $\frac{3}{2}^-$ state at 3.68 MeV but we estimate cross sections from peak fitting and derive $A=0.4\pm0.1$. These values of A are only about one-half of the free-neutron value indicating sizable contributions from the protons or from more complex reaction mechanisms.

At forward angles ($\theta_{c.m.}\leq50°$) the unresolved triplet at 7.5 MeV is expected to be dominated by the transition to the collective $\frac{5}{2}^-$ state (7.55 MeV). This state and the $\frac{3}{2}^-$ state at 3.68 MeV are often interpreted as a weak-coupling doublet obtained by coupling a $p_{1/2}$ neutron to the first excited 2^+

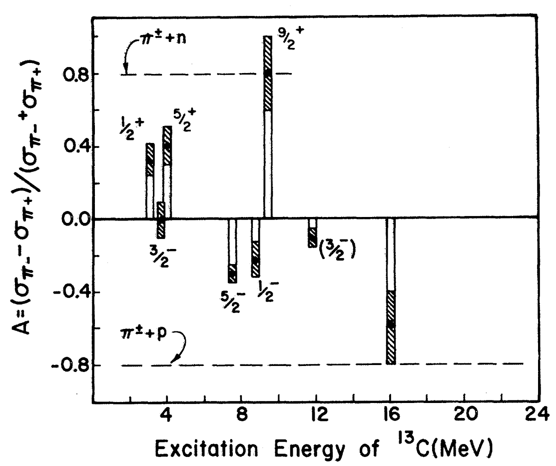

FIG. 2. Values of $A=(\sigma_{\pi^-}-\sigma_{\pi^+})/(\sigma_{\pi^-}+\sigma_{\pi^+})$ from $^{13}C(\pi^\pm,\pi^{\pm\prime})$ at 162 MeV at the maxima of the differential cross sections. Broken horizontal lines: values of A for $\pi^\pm+n$ and $\pi^\pm+p$.

state of ^{12}C. At forward angles the 3.68-MeV state is almost equally excited by π^+ and π^- ($A\simeq0$) but the 7.5-MeV triplet is a factor of 2 more strongly excited by π^+ than by π^- ($A=-0.3\pm0.1$). [At larger angles ($\theta_{c.m.}\gtrsim50°$) the 7.5-MeV triplet is nearly equally excited by π^+ and π^-.] The different values of A for the weak-coupling states imply a state dependence of the blocking of the quadrupole strength of ^{12}C by the extra neutron. This can be understood in terms of the major components of the wave functions in simple j-j coupling. If the excited core (2^+, $T=0$) consisted of only a $(p_{3/2})^{-1}(p_{1/2})^{+1}$ one-particle, one-hole (1p-1h) structure, the addition of a $p_{1/2}$ neutron would generate 2p-1h states with $J^\pi=\frac{1}{2}^-$, $\frac{5}{2}{}_1^-$, $\frac{3}{2}{}_2^-$, and $\frac{5}{2}^-$. The isospin structure of the $\frac{1}{2}^-$, $\frac{3}{2}{}_2^-$, and $\frac{5}{2}^-$ states would be such that only protons could be involved in the transition. Apparently the "collective" $\frac{5}{2}^-$ state at 7.55 MeV has a large component of 2p-1h structure leading to the observed π^+ enhancement. Clearly the excited core is not a pure $[(p_{3/2})^{-1}(p_{1/2})^{+1}]_{2^+}$ state (1p-1h) and the experimental value of A for the $\frac{5}{2}^-$ state ($A=-0.3\pm0.1$) is smaller than the free-proton value. Thus neutrons must also be involved in the transition. The $\frac{3}{2}{}_1^-$ state can be reached by both proton and neutron excitations even if the core were a pure 1p-1h state. Still, the experimental value of $A\simeq0$ requires additional neutron contributions since the simple 1p-0h to 2p-1h transitions would favor proton excitations.

The spin and parity assignment, $J^\pi=\frac{3}{2}^-$, for the 9.5-MeV state is quite uncertain.[5,10-14] In low-energy electron scattering no $M1$ strength could be detected.[10] Two- and three-particle-transfer reactions[11,12] quite strongly suggest a high-spin state at this energy and recent high-energy electron-scattering data[13] yield $J^\pi=\frac{9}{2}^+$. A $\frac{7}{2}^+$ and a $\frac{9}{2}^+$ state have been predicted around this energy by Lane[15] and later by several other authors (e.g., Baker[16] and Jäger *et al.*[17]) as members of a weak-coupling multiplet based on a $d_{5/2}$ neutron coupled to the first excited 2^+ state in ^{12}C. Such a structure is consistent with the extremely small neutron width from $^{12}C+n$ elastic scattering[14] and the preferential decay of the 9.5-MeV state in ^{13}C or its mirror at 9.0 MeV in ^{13}N by neutron or proton emission, respectively, to the 2^+ state in ^{12}C (see references in Ref. 12). The wave function of the $\frac{9}{2}^+$ member of the weak-coupling multiplet has a very large overlap with the wave function of a $\frac{9}{2}^+$ state at about 9.5 MeV predicted by the intermediate-coupling model (Ref. 18). A $\frac{9}{2}^+$ state of similar structure was also found close to 9.5 MeV in a shell-model calculation.[19]

We remark that an inelastic transition to the $[(2^+, T_0=0)\otimes(d_{5/2})]_{1/2^+,\ldots,9/2^+, T=1/2}$ weak-coupling states should involve mainly neutrons. The ground state (g.s.) of ^{13}C may be represented by a mixture of p-shell $(m+1)$-particle, m-hole states $(m=0, 1, 2)$. If we assume the excited ^{12}C(2^+) to be a mixture of p-shell n-particle, n-hole states $(n=1, 2, 3, 4)$ with $T_0=0$, the weakly coupled $d_{5/2}$ nucleon can only be a neutron. This means that only the promotion of a p-shell neutron to the $d_{5/2}$ shell can contribute to the transition if the g.s. and the multiplet states are connected by a single-particle operator. Thus the strong π^- enhancement for the 9.5-MeV state and the $\frac{9}{2}^+$ assignment from electron scattering[13] suggest that this state is the the $\frac{9}{2}^+$ member of the multiplet. The $\frac{7}{2}^+$ member[20] is probably the 7.59-MeV state of the unresolved triplet at 7.5 MeV. The π^+ enhancement of the 7.5-MeV triplet is observed only at forward angles ($\lesssim 50°$). At larger angles ($\gtrsim 50°$) the $\sigma_{\pi^+}(\theta)$ and $\sigma_{\pi^-}(\theta)$ are quite similar. This may be due to relatively large contributions from the $\frac{7}{2}^+$ state which should be enhanced in π^- scattering like the 9.5-MeV state.

Since we assume the $2^+\otimes d_{5/2}$ configuration to be excited by a one-step process (primarily by the promotion of one of several $p_{3/2}$ neutrons to the $d_{5/2}$ shell), the transition can proceed by an orbital angular momentum transfer ΔL of at most 3. Thus the minimum total angular momentum transferred to the target, $\Delta J=4$, for the $\frac{1}{2}^- \to \frac{9}{2}^+$ transition, is obtained by a spin flip of the neutron. The shape of the angular distribution for the $\frac{9}{2}^+$ state has the appearance of a $\Delta L=5$ transition which we obtained from a spin-nonflip distorted-wave impulse-approximation (DWIA) calculation using the code[21] DWPI with a complex collective form factor. However, angular distributions for spin-flip transitions are known[22] to peak at larger angles than spin-nonflip transitions of the same ΔL. In fact, our qualitative arguments are being confirmed by recent microscopic DWIA calculations of Lee and Kurath[23] which use intermediate-coupling model wave functions[18] for the g.s. and the lowest $\frac{9}{2}^+$ state. These calculations give a good fit to our data for the state at 9.5 MeV with $\Delta L=3$ and $\Delta S=1$.

States of a $2^+\otimes d_{5/2}$ configuration can also be obtained by coupling a $d_{5/2}$ particle to a 2^+, $T_0=1$ state of the core resulting in isospins $T=\frac{1}{2}$ or $T=\frac{3}{2}$. The isospin coupling coefficients for the $T=\frac{1}{2}$ states are such that the protons should be involved in the transition more strongly than the neutrons and for the $T=\frac{3}{2}$ states neutrons and protons would be expected to contribute more equally. We suggest that the π^+ enhanced state (or group of states) at 16 MeV contains components of the $T=\frac{1}{2}$ multiplet states.

In summary, the inelastic scattering of π^+ and π^- on ^{13}C yielded a number of striking results. Two transitions were found to be consistent with pure neutron and pure proton excitations. Qualitative arguments were presented to explain these data as transitions to states of principally $2^+\otimes d_{5/2}$ weak-coupling structure. The weak transitions to the "single-neutron states" at 3.09 and 3.85 MeV were only moderately enhanced in π^- scattering suggesting significant proton particle-hole components in the wave functions or sizable contributions from two-step processes. The excitation of the $[2^+\otimes p_{1/2}]_{3/2^-, 5/2^-}$ weak-coupling states showed a state dependence of the blocking of the quadrupole strength of the ^{12}C core. Finally, a difference in the structure of π^- and π^+ spectra at about 21 MeV was observed, similar to results[8] for $^{12}C+\pi^\pm$, indicating isospin mixing between $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states. The experimental angular distributions and calculations will be presented in a forthcoming publication.

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[1]J. P. Egger *et al.*, Phys. Rev. Lett. 39, 1608 (1977).
[2]S. Iversen *et al.*, Phys. Rev. Lett. 40, 17 (1978), and Phys. Lett. 82B, 51 (1979).
[3]C. Lunke *et al.*, Phys. Lett. 78B, 201 (1978).
[4]C. L. Morris *et al.*, in Proceedings of the Second International Conference on Meson-Nuclear Physics, Houston, Texas, 5–9 March 1979 (unpublished).
[5]F. Ajzenberg-Selove, Nucl. Phys. A268, 1 (1976).
[6]H. A. Thiessen and S. Sobottka, Los Alamos Scientific Laboratory Report No. LA-4534-MS (unpublished), and references therein.
[7]Kindly provided by Dr. R. Macek of group MP-13, Los Alamos Scientific Laboratory.
[8]C. L. Morris *et al.*, to be published.

[9]S. E. Darden et al., Nucl. Phys. A208, 77 (1973).
[10]G. Wittwer et al., Phys. Lett. 30B, 634 (1969).
[11]N. Anyas-Weis et al., Phys. Rev. 12C, 201 (1974).
[12]C. H. Holbrow et al., Phys. Rev. C 9, 902 (1974).
[13]D. I. Sober, private communication.
[14]W. Galati et al., Phys. Rev. C 5, 1508 (1972).
[15]A. M. Lane, Rev. Mod. Phys. 32, 519 (1960).
[16]F. C. Barker, Nucl. Phys. 28, 96 (1971).
[17]H. U. Jäger et al., Nucl. Phys. A171, 16 (1971).
[18]S. Cohen and D. Kurath, Nucl. Phys. 73, 1 (1965); D. Kurath, private communication.
[19]D. J. Millener and D. Kurath, Nucl. Phys. A255, 315 (1975).
[20]The locations of the $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ members of the multiplet are uncertain.
[21]R. A. Eisenstein and G. A. Miller, Comp. Phys. Commun. 11, 95 (1976).
[22]G. E. Walker and E. Siciliano, private communication; C. Olmer et al., Phys. Rev. Lett. 43, 612 (1979).
[23]T.-S. H. Lee and D. Kurath, private communication.

Static Polarization Effects in the Nucleus-Nucleus Potential

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This letter presents a study of a simple way to relax the frozen-configuration assumption in the calculation of the real part of the nucleus-nucleus potential. The proposed model allows the thickness of the surface layer of each nucleus to vary from the outer side to the interacting side giving rise to polarized shapes which simulate a neck formation. The result is compared to other potentials available in the literature.

The calculation of the nucleus-nucleus potential starting from an energy-density formalism is very convenient when simplifying assumptions about the density of the composite system are made. A common starting point is the frozen-configuration assumption or the sudden approximation[1-5] according to which the density of the whole system is taken as the sum of the asymptotic individual densities at any separation distance between the interacting nuclei. In practice such a simplification allows one to calculate the interaction potential between any pair of nuclei once the densities are known.

In this Letter I propose a way to relax the frozen-configuration assumption by trying to maintain the simplicity of the calculations. Under mutual influence the nuclei deviate from their spherical shape and I try to describe this polarization effect by a gradual change of the surface layer thickness from an equilibrium value a_0 at the outer side to a value a at the interacting side of each nucleus. This value is found by minimizing the potential with respect to a at each separation distance s_0 between the surfaces, with

$$s_0 = R - R_1 - R_2, \tag{1}$$

where R is the distance between the centers of the nuclei, and R_1 and R_2 are the nuclear radii. In this way I extend the formalism of Ref. 4 according to which one defines the nucleus-nucleus potential $\tilde{V}(s_0,a)$ as the difference between the binding energy of the composite system at s_0 and the binding energy of the nuclei separated at infinity. The Skyrme-interaction density functional[6] is used to calculate the binding energies. For the composite system the density is taken as the sum of the individual densities and the kinetic energy densities of the composite system and of the individual nuclei are described by the Thomas-Fermi approximation. The advantage of these approximations is that the Skyrme-interaction energy density H reduces to an algebraic function of the densities ρ_1 and ρ_2 only. Then the potential can be written as the volume integral

$$\tilde{V}(s_0,a) = \int [H(\rho_1{}^a + \rho_2{}^a) - H(\rho_1{}^{a_0}) - H(\rho_2{}^{a_0})]\, dv. \tag{2}$$

The parameter a_0 is the equilibrium value of the surface layer thickness for an individual nucleus. As Skyrme-interaction parameters I have chosen the set[6] SII which gives for a semi-infinite slab $a_0 = 0.48$ fm and $E_{\rm surf} = 22.38$ MeV/fm^2 when the Thomas-Fermi approximation is used for the kinetic energy density as defined in Ref. 6. At infinity the densities ρ_1 and ρ_2 are described by

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