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Excitation of Unnatural-Parity States in ^{12}C by 800-MeV Polarized Protons

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Cross sections and analyzing powers have been measured for 800-MeV proton inelastic transitions to unnatural-parity states in ^{12}C. Data for the 15.11-MeV 1^+, $T=1$ state are well explained by a distorted-wave impulse-approximation calculation based on proton-neutron charge-exchange cross sections. Negative analyzing powers were observed for the first time at 800 MeV, for the 12.71-MeV 1^+, $T=0$ state. Values of A_y appear to be characteristic of the isospin transfer, and support isospin assignments for states at 18.3 and 19.4 MeV.

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Recent nucleon-nucleon experiments suggest that spin-dependent terms in the proton-proton scattering amplitude are significant around 800 MeV,[1] yet previous evidence for excitation of unnatural-parity states in inelastic proton scattering in this energy region is scant.[2,3] These levels with parity $(-1)^{J+1}$ require a spin transfer, ΔS, of 1; first-order excitation of such states thus depends entirely on the spin-dependent terms. Here we report differential cross sections to low-spin unnatural-parity states in ^{12}C which are comparable in magnitude to those observed at much lower energies. In addition, large negative values of the analyzing power, A_y, have been seen for the first time at 800 MeV; the magnitude of A_y appears characteristic of the isospin transfer.

Angular distributions of $d\sigma/d\Omega$ and A_y were measured with the 800-MeV polarized beam at the Clinton P. Anderson Meson Physics Facility with use of the High Resolution Spectrometer. Scattered particles were detected in an array of drift chambers and scintillation detectors that have been described previously.[4] Energy resolution was generally about 120 keV. Data in several angle bins were summed to give an angular resolution of 0.34° for most of the data shown. Absolute cross sections accurate to ± 15% were determined by comparison with previous elastic scattering data for ^{12}C.[4] The transverse polarization of the beam was monitored continuously with a hydrogen polarimeter; it averaged about 0.75.

A spectrum taken at 2.3° with a spin-down incident beam is shown in Fig. 1. With the exception of the highly collective 4.44-MeV 2^+ state, the unnatural-parity transitions to the states at 12.71 MeV ($1^+, T=0$) and 15.11 MeV ($1^+, T=1$) dominate the spectrum. The two strong states at 18.3 and 19.4 MeV are also apparently unnatural-parity transitions. A state at 19.4 MeV has been identified in electron scattering as a 2^-, $T=1$ state.[5] States at these energies observed in pion scattering have been tentatively assigned 2^-, $T=0$ and 2^-, $T=1$, respectively, but with considerable isospin mixing.[6] Many other states have also been observed in this energy region.[7] At larger angles, the ^{12}C spectrum is dominated by natural-parity states.

The angular distributions for the two 1^+ states are noticeably different from each other, as shown in Fig. 2. Both, however, ar similar to the corresponding data at 122 MeV.[8] The absolute cross sections for the two states are each within a factor of 2 of the 122-MeV values; the 800-MeV values are mostly larger. For the $T=1$ state, A_y is close to zero (as it is also for the $\Delta T=1$, $\Delta S=1$ transition in ^6Li measured in the same experiment). The $T=0$ state, however, has a significantly negative A_y at small momentum transfer, in contrast to the uniformly positive

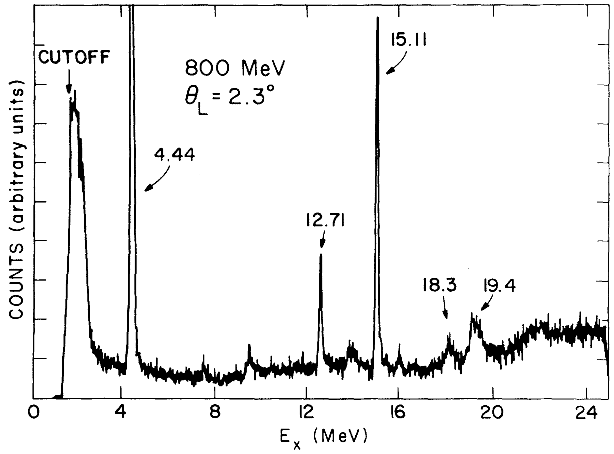

FIG. 1. Small-angle spectrum of the reaction ${}^{12}C(p, p')^{12}C$. An electronic cutoff was used to suppress the elastic peak at the left-hand side.

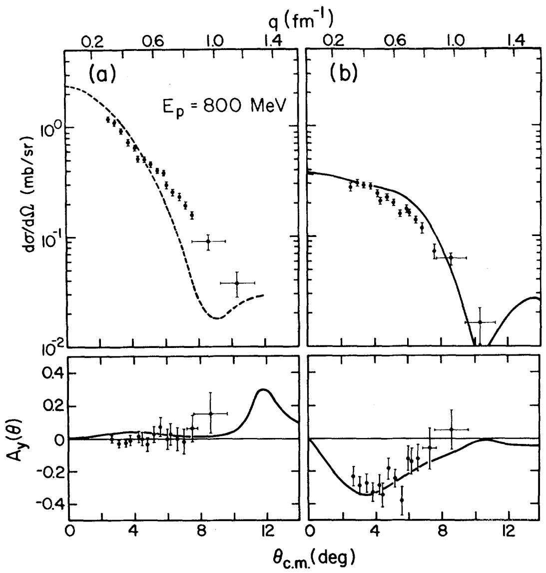

FIG. 2. Cross sections and analyzing powers for the (a) 15.11-MeV and (b) 12.71-MeV states of ${}^{12}C$. The curves are distorted-wave calculations described in the text.

values of A_y previously observed at this energy for natural-parity transitions. Analyzing powers at 122 MeV are very different from these.[9]

Theoretical interpretation of these data is appropriately based upon the impulse approximation (IA) as formulated by Kerman, McManus, and Thaler.[10] This method has enjoyed considerable success in the description of the elastic scattering of 800-MeV (Ref. 4) and 1.04-GeV (Ref. 2) protons. Here the interaction between the projectile and the target nucleons is assumed to be the free nucleon-nucleon (N-N) interaction. The scattering amplitude in the N-N center-of-mass (c.m.) system can be written

$$M(q) = A(q) + B(q)(\vec{\sigma}_j\cdot\hat{n})(\vec{\sigma}_j\cdot\hat{n}) + C(q)(\vec{\sigma}_i+\vec{\sigma}_j)\cdot\hat{n} + E(q)(\vec{\sigma}_i\cdot\hat{q})(\vec{\sigma}_j\cdot\hat{q}) + F(q)(\vec{\sigma}_i\cdot\hat{Q})(\vec{\sigma}_j\cdot\hat{Q}), \quad (1)$$

where $\vec{q}=\vec{k}-\vec{k}'$, $\vec{Q}=\vec{k}+\vec{k}'$, and $\vec{n}=\vec{k}\times\vec{k}'$.

The subscripts i and j refer to incident and target nucleons, respectively, and $\vec{k}$ and $\vec{k}'$ are incident and outgoing momenta. Each of the complex amplitudes $A(q)$, etc., is isospin dependent: $A(q) = A_0(q) + A_1(q)\vec{\tau}_i\cdot\vec{\tau}_j$.

Unfortunately, the spin-dependent amplitudes are poorly known above 500 MeV; hence the IA cannot be applied directly. An indirect approach for the 15.11-MeV state is suggested by the fact that the spin and isospin transfer are appropriate for one-pion exchange (OPE). Now it is well known that the forward-angle behavior of the $p(n,p)n$ charge-exchange (CE) reaction (backward-angle n-p scattering) can be largely accounted for by OPE, although there is still debate over the correct description of the peak at $q=0$.[11] A close connection between the CE reaction and the reaction ${}^{12}C(p,p')^{12}C(15.11$ MeV) at small q therefore seems plausible. In terms of the invariant amplitudes of Eq. (1), the cross section for the CE reaction may be written

$$d\sigma/d\Omega_{CE} = 4[|A_1|^2 + |B_1|^2 + 2|C_1|^2 + |E_1|^2 + |F_1|^2]. \quad (2)$$

A similar form for the IA cross section for the (p,p') excitation of the 15.11-MeV state is obtained if a zero-range approximation in coordinate space is made[12]:

$$d\sigma/d\Omega_{15.11} = [|B_1|^2 + |C_1|^2 + |E_1|^2 + |F_1|^2]I^2(q), \quad (3)$$

where $I(q)$ is a distorted-wave integral which includes the nuclear transition density. Equations (2) and (3) differ only in their dependence on A_1 and C_1. The spin-independent amplitude $A_1(q=0)$ can be reasonably estimated from the known differences between $p+p$ and $n+p$ total cross sections; it contributes less than 15% of the CE cross section at 0°. The spin-orbit term C_1 does not contribute at all at 0°; the present A_y data are consistent with other evidence[13] that $C_1(q)$ is small at larger q as well (see discussion of the A_y data below). Thus the known CE cross sections as a function of q can be used in (3) to replace the unknown N-N amplitude factor with the result $d\sigma/d\Omega(q)_{15.11} = \frac{1}{4}[d\sigma/d\Omega(q)_{\rm CE}]I(q)^2$.

Calculations of $I(q)$ were performed with a version of the code[14] DWBA-70 modified for use with medium-energy protons.[15] The Cohen-Kurath[16] wave functions with harmonic-oscillator radial forms ($\alpha = 0.513$ fm^{-1}) were used to describe the transition density of the 15.11-MeV state. Electron-scattering data indicate that these are appropriate for the lwo-q region explored here.[17] A Yukawa potential of range 0.1 fm was used to simulate the zero-range interaction. The predicted cross section is shown by the dashed line in Fig. 2(a). Given the approximate nature of the calculation, it is apparent that the $p(n,p)n$ data account extremely well for the cross section of the 15.11-MeV state.

The nearly constant $q=0$ cross section of the CE reaction over a wide energy range[11] suggests that the $\Delta T = 1$ interaction varies little with energy. In qualitative agreement with this prediction cross sections for the 15.11-MeV state at $E_p = 122$ MeV (Ref. 8) are similar to those measured here. The strength of the $\Delta S = 1$, $\Delta T = 1$ interaction at 800 MeV measured in terms of the $q=0$ t matrix is 120 MeV fm^3 (in the N-N c.m. system). This is very close to the central OPE value of 124 MeV fm^3. However, a calculation with a OPE potential reproduces the present data only when the tensor interaction is reduced by ~40%.

Unfortunately, there are no comparable guidelines for understanding the cross section of the 12.71-MeV state. Simple meson exchange or N-N reactions do not yield the appropriate mixture of amplitudes for this transition. Interactions appropriate for ~140-MeV (Ref. 18) and 1.04-GeV (Ref. 2) protons have been tried but do not yield reasonable results for the 12.71-MeV data at 800 MeV. Thus we have adopted a purely phenomenological approach; the N-N interaction has been adjusted to fit the data for the 12.71-MeV state. The analyzing-power data are a very important constraint in determining the parameters of an effective interaction. In the plane-wave IA for a pure $\Delta L = 0$, $\Delta S = 1$ transition $A_y d\sigma/d\Omega$ is given by

$$A_y d\sigma/d\Omega = 2\,\mathrm{Re}(B^*C).$$

For higher ΔL transfer and for mixed-ΔL transitions the expression is somewhat more complex, but the dependence of $A_y d\sigma/d\Omega$ on $\mathrm{Re}(B^*C)$ remains.[10] In the distorted-wave IA we have found that the qualitative features of the plane-wave expression remain; large values of A_y are produced only when $\mathrm{Re}(B^*C)$ is large. Spin-orbit coupling in the optical potential has a very small effect. This may be seen in the OPE calculation of A_y for the 15.11-MeV state, where $C_1 = 0$ was assumed [solid line in Fig. 2(a)].

The results of the phenomenological calculation for the 12.71-MeV state with the Cohen-Kurath wave functions are shown in Fig. 2(b). The effective N-N interaction was constructed in the following manner. A real spin-orbit potential consistent with present knowledge of C_0 and an imaginary spin-spin potential are required to produce a large negative A_y. A tensor potential is needed to account for the shape of $d\sigma/d\Omega$ and A_y. The ranges chosen (0.4 fm) are consistent with the range of forces which contribute to the excitation of the 12.71-MeV state at lower energies.

The plane-wave expression for A_y coupled with the distinctly different measured values for the two 1^+ states suggests that A_y for small q may be used as a signature of the isospin transfer in other unnatural-parity transitions. The A_y data shown in Fig. 3 then tend to confirm the assignments of the 18.3-MeV ($T=0$) and 19.4-MeV ($T=1$) states.[6] A DWBA calculation with the interaction determined from the data for the 12.71-MeV state yields reasonable agreement with A_y and $d\sigma/d\Omega$ for the 18.3-MeV state. The configura-

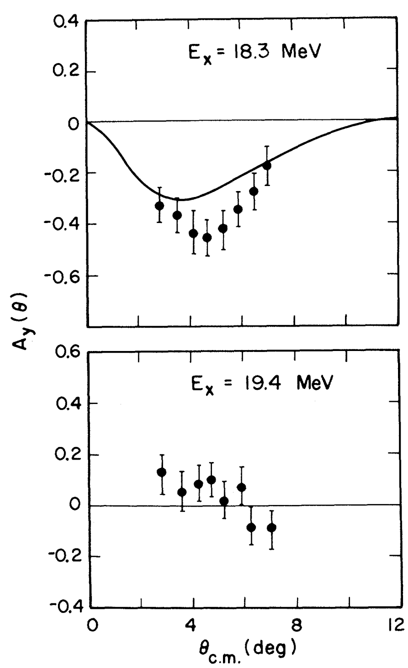

FIG. 3. Analyzing powers for states in ^{12}C whose tentative assignments are 2^-, $T=0$ (18.3 MeV) and 2^-, $T=1$ (19.4 MeV). The solid curve is a distorted-wave calculation described in the text.

tion $(p_{3/2}^{-1}d_{5/2})_{2^-}^{T=0}$ was assumed, but similar results are obtained with other configurations. Calculations for the 19.4-MeV state, however, have not been successful thus far in reproducing the cross section when a spin of 2^- is assumed (recall that any calculation in which $C_1 = 0$ gives $A_y \sim 0$, in agreement with the data).

In summary, we have shown that low-q spin-dependent cross sections at 800 MeV are comparable with such cross sections at 122 MeV. It is thus feasible to extend the measurements to large q to look for differences between proton and electron scattering in the region where critical opalescence may be observed.[19,20] The low-q behavior of the 15.11-MeV 1^+, $T = 1$ state is explained remarkably well over a wide energy region by an IA description based on the cross section for the reaction $p(n,p)n$. Values of A_y which are close to zero for the 15.11-MeV state and negative for the 12.71-MeV state are determined primarily by $\mathrm{Re}(B_{\Delta T}{}^* C_{\Delta T})$. This suggests that A_y for unnatural-parity states is characteristic of the isospin transfer and supports tentative assignments for states observed at 18.3 and 19.4 MeV.

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