$^{12}C(p,n)^{12}N$ reaction at 120, 160, and 200 MeV

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Angular distributions for the ground-state ($\Delta J^{\pi} = 1^+$) and 0.96-MeV ($\Delta J^{\pi} = 2^+$) transitions in the $^{12}C(p,n)^{12}N$ reaction have been measured at incident energies of 120, 160, and 200 MeV. The measured values of the differential cross section align themselves into smooth curves independent of incident energy when converted into plane-wave cross section values and plotted versus momentum transfer. This information supports the hypothesis that the spin-isospin term of the effective interaction is almost energy independent in this energy region. Microscopic distorted-wave impulse approximation calculations are presented.

[NUCLEAR REACTIONS $^{12}C(p,n)^{12}N$, $E = 120$, 160, 200 MeV; measured neutron spectra at several angles between $\theta = 0°$ and $\theta = 30°$; extracted $\sigma(E,\theta)$ to g.s. and 0.96-MeV states of ^{12}N. Compared angular distributions with microscopic calculations. Deduced plane-wave cross sections versus momentum transfer.]

I. INTRODUCTION

Experimental studies of the (p,n) reaction at intermediate energies, currently being carried out using the Indiana University Cyclotron Facility (IUCF), are providing new information on isovector modes of excitation in nuclei.[1-4] In particular the 0° (p,n) cross sections have been found to be proportional to the squares of the corresponding Fermi and Gamow-Teller (GT) matrix elements extracted from β-decay measurements.[2]

Recently Petrovich, Love, and McCarthy[5] have discussed the separation of current and spin contributions to the isovector excitation of $M1$ transitions to states in the target by (e,e') reactions, and to their isobaric analogs via the (p,n) reaction. They point out that the orbital and spin contributions can be obtained by combining information from inelastic electron scattering at small momentum transfers with (p,n) cross sections at forward angles. In Ref. 6 Petrovich develops, using the Born approximation, expressions for the cross sections for $0 \to J$ normal parity and abnormal parity transitions. He notes that the products $v(E,q)\ \rho(q)$ are the essential parts of the scattering potential $U(q)$ in momentum space. Here $v(E,q)$ are Bessel transforms of the nucleon-nucleus effective interaction components and $\rho(q)$ are Bessel transforms of orbital current and spin transition densities. In particular, it is shown in Ref. 5 that for $0^+ \to 1^+$ transitions (using the fact that the tensor interaction, the spin-orbit interactions, and the $L = 2$ transition densities are small near $q = 0$), the cross section for the $L = 0$ (p,n) transition can be written

$$\frac{d\sigma}{d\Omega} \approx 8\pi\left(\frac{\mu}{2\pi\hbar^2}\right)^2 \frac{k_f}{k_i} 3\left|v^c(E,q)\rho^s(q)\right|^2 , \qquad (1)$$

where μ denotes the relativistic reduced energy divided by c^2, and k is the wave number. Of the different $v(E,q)\ \rho(q)$ terms in the amplitude of the differential cross section,[5,6] the product of the spin-dependent central component of the effective interaction $v^c(E,q)$ and the spin transition density $\rho^s(q)$ dominates the $0^+ \to 1^+$ transition at low q. The current transition density $\rho^l(q)$ for $0^+ \to 1^+$ transitions excited in the (p,n) reaction couples to the projectile only through the spin-orbit interaction which is essentially zero at $q = 0$.

In the above approximate equation (1) neither distortion nor knockout exchange amplitudes are included explicitly, but both distortion and knockout exchange are treated exactly in the calculations to be presented below. It is shown in Refs.

2 and 6 that, for low q, distortion effects can be approximated by simply introducing a scale factor N^D. Then we can write

$$\sigma(0^\circ)_{\exp} \propto \left| N^D v^c(E,q) \rho^s(q) \right|^2 ,$$

where $\sigma(0^\circ)_{\exp}$ is the experimental differential 0° (p,n) cross section and the constant of proportionality is just a product of kinematic factors.

For allowed β decay Gamow-Teller transitions, the GT matrix element, $\mathfrak{M}_{GT}$, gives a direct measure of $\rho^s(q=0)$. The essential relation is[5,7]

$$\mathfrak{M}_{GT}{}^2 = 6\pi \left| \rho^s(q=0) \right|^2 .$$

The GT matrix element can be obtained[7] from known log*ft* values. The strength of the effective interaction $v^c(E, q \simeq 0)$, therefore, can be empirically obtained. It is normally expressed as the magnitude of the volume integrals of $q=0$ components of the spin-dependent isovector central term of the effective interaction $J_{\sigma\tau}$. It is well known[8-10] that at intermediate energies for isospin flip transitions the effective nucleon-nucleus interaction may be replaced by the free nucleon-nucleon (N-N) t matrix. Values of $J_{\sigma\tau}$ at $q=0$, calculated from the N-N t matrix have been reported[9] at several energies. In particular, in the energy range 100–200 MeV it is shown to be almost energy independent.[9]

The $^{12}C(p,n)\,^{12}N$ (g.s.) transition provides an excellent test ground for the above calculations. The $^{12}N(1^+) \to {}^{12}C(0^+)$ β^+ decay rate[11] implies that for the $(0^+ \to 1^+)$ $T=1$, $M1$ transition in ^{12}C, $\rho^s(q=0) = 0.223$, an empirical value which agrees, quite well[5] with the value 0.221 obtained from the Cohen and Kurath wave functions.

We have used these wave functions to calculate the differential (p,n) cross sections including knockout exchange with and without distortion. The latter represents the plane-wave (PW) cross section calculations. The experimental cross sections are then divided by the ratio of the two calculations, $N(E,q) = \sigma_{DW}(E,q)/\sigma_{PW}(E,q)$, to yield the PW cross section values. The PW cross sections for the (p,n) transitions to the ground state (1^+) and to the 0.96-MeV (2^+) state have been obtained for values of momentum transfer q, up to $q \simeq 1.2$ fm^{-1}. The data seem to indicate the possibility of extending the factorization of the cross section indicated in Eq. (1) to higher values of q.

II. EXPERIMENTAL METHODS

The present experiment was performed using the beam swinger time-of-flight facility[12] at the Indiana University Cyclotron. Flight paths of 60–100 m and time compensated large volume (15 cm × 15 cm × 100 cm long) neutron detectors[13] were used. Subnanosecond time resolution was achieved by tilting the detectors at the appropriate angle.[13] Angular distributions were measured between $\theta_L = 0^\circ$ and $\theta_L = 25^\circ$ in steps of approximately 5°. The ^{12}C targets were 30–40 mg/cm^2 thick graphite.

Proton beams with time structure suitable for time-of-flight measurements were obtained by selecting one out of four pulses from the cyclotron. This permits the interval between proton pulses to be increased from 35 to 140 ns. A time-compensated rf signal was used as a stop signal. The compensation was derived by monitoring pulses from elastically scattered protons detected in a small fast plastic scintillator near the target.

Time-of-flight and pulse-height information were stored in a series of histograms in the IUCF data-acquisition computer. At the completion of a data run the histograms, live time, and scaler information were transferred onto a magnetic tape.

Absolute (p,n) cross sections were obtained by measuring the absolute efficiency of the neutron detector for the given experimental conditions. This efficiency was determined using the method described in Ref. 14.

III. RESULTS AND ANALYSIS

A sample time-of-flight spectrum for the $^{12}C(p,n)\,^{12}N$ reaction at $\theta_L = 0^\circ$ and $E_p = 160$ MeV is shown in Fig. 1, where the relative yield is

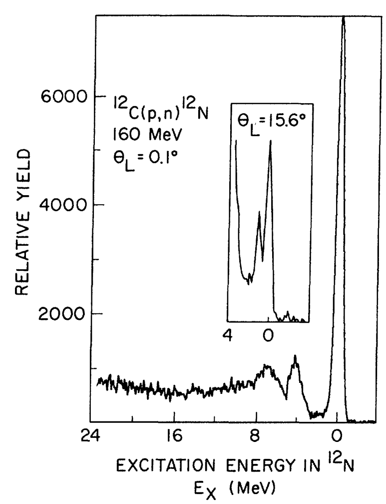

FIG. 1. Neutron time-of-flight spectrum obtained at $\theta_L = 0^\circ$ for the $^{12}C(p,n)^{12}N$ reaction at 160 MeV. The abscissa represents excitation energy (MeV) in ^{12}N. The inset represents the spectrum at $\theta_L = 15.6^\circ$ showing the yields for the ground-state and 0.96-MeV transitions. A flight path of 92 m was used.

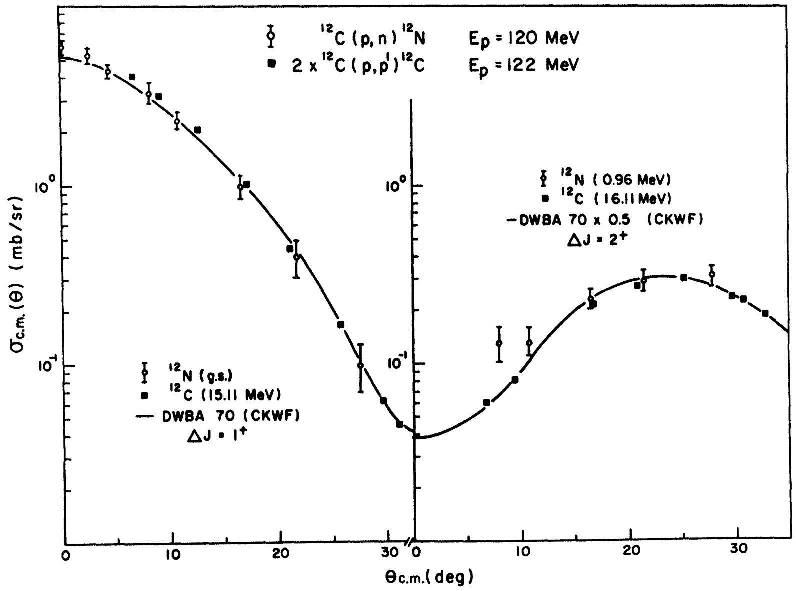

FIG. 2. Angular distribution for the ground-state and 0.96-MeV transitions in the $^{12}C(p,n)^{12}N$ reaction at $E_p = 120$ MeV; the present data are compared to the $^{12}C(p,p')^{12}C$ results at $E_p = 122$ MeV from Ref. 15. The latter values have been multiplied by 2 (see text). The solid lines are microscopic DWBA70 calculations.

presented versus excitation energy in ^{12}N. With the subnanosecond time resolution of the neutron detector and a flight path of 92 m, the neutron groups to the ground state ($L = 0$) and to the first excited state ($E_x = 0.96$ MeV, $L = 2$) are clearly separated. This is shown as an inset in Fig. 1, for the spectrum at $\theta_L = 15.6°$. Except for the ground-state transition, no other transition characterized by $L = 0$ was observed below 30 MeV excitation energy.

The angular distributions for the ground-state and 0.96-MeV transitions obtained at 120 MeV are shown in Fig. 2. We also present the data obtained at $E_p = 122$ MeV (Ref. 15) for the $^{12}C(p,p')^{12}C$ reaction leading to the $J^\pi = 1^+$, $T = 1$, $E_x = 15.11$-MeV state, and to the $J^\pi = 2^+$, $T = 1$, $E_x = 16.11$-MeV state, isobaric analogs of the ^{12}N (g.s.) and ^{12}N (0.96 MeV) states, respectively. If isospin is conserved, the $^{12}C(p,p')^{12}C$ (15.11) and the $^{12}C(p,n)$ ^{12}N (g.s.) reactions should be related[16] by the equation,

$$\frac{d\sigma}{d\Omega}(p,p') = \frac{1}{2}\frac{d\sigma}{d\Omega}(p,n),$$

and the same relation is expected between the cross section for the transitions to the 16.11-MeV state in ^{12}C and the first excited state in ^{12}C and the first excited state in ^{12}N at $E_x = 0.96$ MeV. Twice the value of the measured (p,p') cross section has been presented in Fig. 2. A comparison of these cross sections at $E_p = 62$ MeV has been reported in Ref. 14. The differential cross section for the $^{12}C(p,n)$ ^{12}N (g.s.) transition at $E_p = 160$ MeV is presented in Fig. 3; also in the same figure we present the measured cross section at 200 MeV for the sum of the transitions to the ground state and to the 0.96-MeV state. The 0.96 MeV state was not resolved at 200 MeV.

At intermediate energies the distorted-wave impulse approximation (DWIA) is frequently used for interpreting nucleon-nucleus scattering. The effective interaction V^{eff} is generally assumed to be the t matrix for free nucleon-nucleon scattering. We have used the t matrix as parametrized by Love and Franey[17] at several energies based on N-N scattering phase shift results at these energies. Exchange contributions are calculated exactly with a modified version of the code DWBA70.[18] Relativistic effects were also included in the calculations. The optical potentials were obtained from Refs. 15 and 19 and are given in Table I. We have used the same potentials for protons and neutrons. A calculation done with neutron potentials interpolated to an energy adjusted to the ground-state Q value ($Q = -18.126$ MeV) resulted in values approximately 2% higher than those obtained with same optical potentials for neutrons and protons. It is well known that one of the best shell-model descriptions for low-lying states in nuclei with $A = 12$ are provided by the calculations of Cohen and Kurath.[20] Transition densities based on these wave functions for ^{12}N were used in the DWBA70 calculations, assuming single particle wave functions for the bound parti-

TABLE I. Optical potential parameters used in the calculations. (Values interpolated from those of Ref. 19.) The potentials are defined by $U(r) = V_C(r) + Vf_R(r) + iWf_I(r) + V_{so}g_{so}(r)$, where V_C is the Coulomb potential for a uniformly charged sphere; $f(r) = 1/(1+e^x)$, where $x = (r-R)/a$ with $R = rA^{1/3}$; $g_{so}(r)$ has the usual Thomas form. Energies have units in MeV while geometrical parameters are in fm. The potentials are for use with relativistic kinematics (Ref. 19).

E	V	r_0	a	W	r'	a'	V_{so}	r_{so}	a_{so}	r_C
120	−18.3	1.20	0.65	−10.6	1.30	0.64	−4.57	0.9	0.5	1.2
160	−13.5	1.20	0.67	−12.2	1.24	0.62	−4.25	0.9	0.5	1.2
200	−11.0	1.20	0.69	−14.0	1.17	0.59	−3.9	0.9	0.5	1.2

cle to be of harmonic-oscillator form with an oscillator parameter $\mu = 0.552$ fm^{-1}. Wave functions are not too sensitive to the choice of the value of the oscillator parameter. Different values of μ have been used for the (p,p') transitions in ^{12}C excited by 122 MeV protons and reported in Ref. 15. A difference of only a few percent in the calculated cross section values resulted when the μ values of Ref. 15 where used. Wave functions constructed from Woods-Saxon potentials with reasonable parameters gave similar results.

The DWBA70 calculations shown in Fig. 2 for the $L=0$ transition include central, spin-orbit, and tensor contributions all with exchange and fit the data quite well without renormalization. The distorted-wave Born approximation (DWBA) calculation for the $L=2$ transition at 120 MeV also fits the data quite well but needs a normalization of 0.5. A similar value for the normalization was found in the ^{12}C(p,p') analysis and possible reasons are discussed in Ref. 15.

In Fig. 3 a DWBA calculation is presented for the $\Delta J = 1^+$ transition to the ^{12}N g.s. at 160 MeV; it agrees quite well with the experimental values. This case as well as the calculations shown in Fig. 2 were done with the 140-MeV t matrix as parametrized by Love and Franey.[17] Two calculations are presented at 200 MeV: one for the $\Delta J = 1^+$ ground-state transition (broken line) and a second one (solid line) which represents the sum of the calculated cross section for the $\Delta J = 1^+$ transition and half (see above) the calculated cross section for the $\Delta J = 2^+$ transition to the 0.96 MeV state. These calculations were done with the 210 MeV t matrix as parametrized in Ref. 17. The forward angles ($\theta \lesssim 10°$) are dominated by the $\Delta L = 0$ transfer, with $\Delta L = 2$ contributions becoming important for $\theta \gtrsim 20°$. The agreement with the ex-

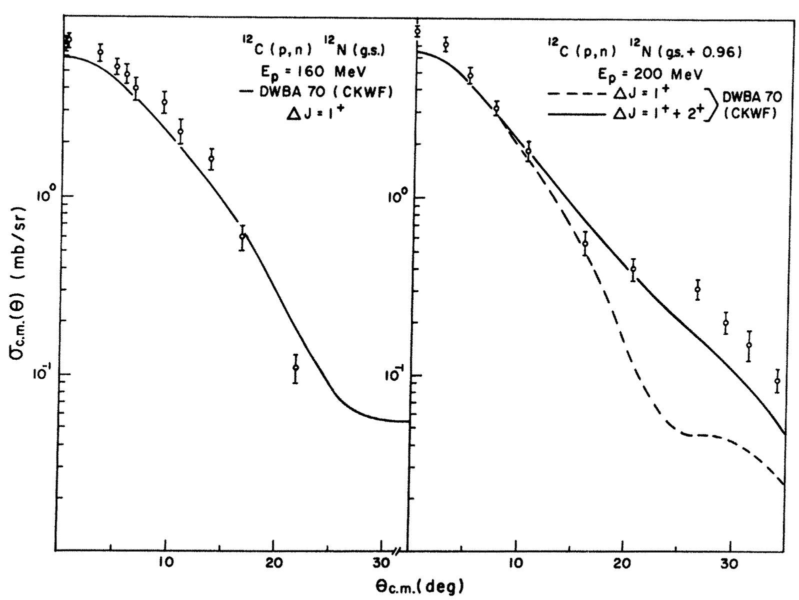

FIG. 3. Angular distributions for the ground-state transition in the ^{12}C$(p,n)^{12}$N reaction at 160 MeV and for the ground-state + 0.96-MeV transitions at 200 MeV. The solid lines are microscopic DWBA70 calculations.

perimental data may be considered good.

Calculations were also done as above but with optical potential strengths equal to zero ($V = W = V_{so} = 0$). We denote these calculations as PW calculations. The ratio $N(E,q)$ between the DW and PW results may be considered as a measure of distortion effects and is both momentum transfer, q, and energy dependent. Values for $N(E,q)$ were calculated at 120, 160, and 200 MeV. The measured (p,n) cross section values $\sigma(E,q)$, were divided by $N(E,q)$ to obtain values for $\sigma_{PW}(E,q)$ which are plotted versus the momentum transfer q in Fig. 4.

The data points at 120, 160, and 200 MeV for the ground-state transition cluster along a smooth curve. Note that only $\sigma_{PW}(E,q)$ values corresponding to $\theta \leq 10°$ for 200 MeV are shown, as in this region the ground-state transition dominates. In a similar fashion the data points at 120 and 160 MeV for the 0.96 MeV ($\Delta J = 2^+$) transition also may be represented by a smooth curve.

The ($0^+ \to 1^+$) ground-state transition is an abnormal parity isovector transition and depends on the spin-dependent isospin term of the effective interaction; the fact that the PW data points at 120, 160, and 200 MeV cluster along a single smooth curve indicates that this effective interaction in the region up to $q \sim 1$ fm^{-1} and between 120 and 200 MeV is almost energy independent.

The ($0^+ \to 2^+$) transition to the 0.96-MeV state is a normal parity isovector transition with contributions from the central, spin orbit, and tensor terms of the effective interaction. Both the spin-dependent and spin-independent isospin terms may contribute to the excitation of this state. However, at intermediate energies it is known[2,6,8] that the spin-dependent part of the effective interaction is more important that the spin-independent part, so that the $\Delta S = 1$ contributions are larger than those for $\Delta S = 0$. The PW data points at 120 and 160 MeV cluster along a single smooth curve, indicating that the effective interaction describing the transition is almost energy independent. This agrees with the results for the ground-state transition, a pure spin-dependent interaction. This seems to indicate that at intermediate energies the $\Delta S = 1$ contribution dominates the (p,n) transition to the 0.96-MeV state in ^{12}N. This is also corroborated by DWBA70 calculations. A calculation done with a transition density[20] characterized by a pure $\Delta S = 0$, $\Delta L = 2$, is reduced by almost an order of magnitude, while a calculation with a pure $\Delta S = 1$, $\Delta L = 2$ is only 10% lower than the calculation with the total ($\Delta S = 0 + 1$, $\Delta L = 2$) transition densities.

The calculated PW cross sections $\sigma_{PW}(q)$ have been plotted in Fig. 4. The description of the ground-state transition is rather good, while the calculated values for the $\Delta J = 2^+$ transition have to be multiplied by 0.5 to fit the data.[15]

In the 120–200 MeV energy range a value $\sigma_{PW}(q=0) = 15.6$ mb/sr is calculated using $\rho^s(q=0)$

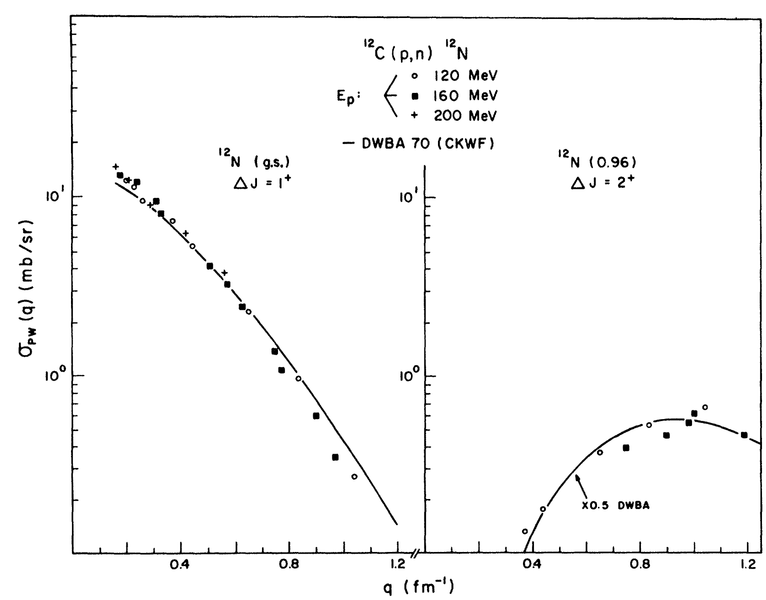

FIG. 4. Plane-wave cross sections for the $^{12}C(p,n)^{12}N$ (g.s.) and $^{12}C(p,n)^{12}N$ (0.96-MeV) transitions calculated from the measured cross sections at 120, 160 and, 200 MeV. The solid lines represent DWBA70 plane-wave calculations. The $\Delta J = 2$ PW calculation has been multiplied by 0.5 (see text).

$= 0.223$ obtained from the allowed $^{12}N(1^+) \rightarrow {}^{12}C(0^+)$ β^+ decay and $v^c(E,q=0) = 174$ MeV fm^3 from Ref. 17. This represents the value at 140 MeV for the extrapolated PW $^{12}C(p,n)$ $^{12}C(p,n)$ ^{12}N (g.s.) cross section at zero momentum transfer. A slight decrease (a few percent) is expected in this value with increasing energy up to 210 MeV, representing the energy dependence of $v^c(E,q=0)$.

The relation between plane-wave cross sections and $v^c(E,q)$ $\rho^s(q)$ given in Eq. (1) is approximately valid[5] for small values of the momentum transfer q. The data shown in Fig. 4 indicate that a similar relation could be obtained for larger values of q, and the (p,n) PW cross section values could be used to obtain empirical quantities related to functions of $v^c(E,q)$ and $\rho^s(q)$. As indicated in Ref. 5, studies of inelastic electron scattering yield values of the orbital current and spin transition densities. These results, for small values of q, can be used with (p,n) data to separate the orbital current and spin contributions to isovector $M1$ transitions. The present study indicates that a similar analysis could also be extended to larger values of q.

The present $^{12}C(p,n)$ ^{12}N results agree extremely well with the $^{12}C(p,p')$ ^{12}C cross sections to analog states reported for incident proton energies of 122 MeV,[15] 155 MeV,[21] and 200 MeV.[21] The ^{12}C (p,n) ^{12}N (g.s.+ 0.96 MeV) cross section at 144 MeV has also been reported by Moake *et al.*[22] as a test of one-pion exchange and the partially conserved axial vector current. We have calculated the distortion factors $N(E,q)$ using optical model potential (OMP) parameters obtained for the $p + {}^{12}C$ elastic scattering analysis at 144 MeV (Ref. 23) and with OMP interpolated from the results in Ref. 19. The obtained values differ by less than 10%, indicating the sensitivity of $N(E,q)$ to OMP parameters. The 144 MeV $\sigma_{PW}(q)$ values are systematically about 25–30% smaller than the present values reported in Fig. 4, for $q \lesssim 0.35$ fm^{-1}. At present we do not understand the reasons for the observed discrepancy.

The inelastic proton scattering at 800 MeV to the ^{12}C 15.11-MeV state has been reported[24] in a search for nuclear critical opalescence. At this energy a distortion scale factor $N^D = 0.63$ has been estimated.[26] The extrapolated (p,p') cross section at a momentum transfer $q=0$ is approximately[24] 2 mb/sr, indicating that the equivalent (p,n) cross sections would be about 4 mb/sr, and thus σ_{PW} $(q=0) \sim 10$ mb/sr. As indicated above, at 140 MeV proton energy we estimate a value $\sigma_{PW}(q=0)$ $= 15.6$ mb/sr for the $^{12}C(p,n)$ ^{12}N(g.s.) cross section. Thus a ratio for $\sigma_{PW}(q=0)$ at 140 MeV and 800 MeV approximately equal to 1.6 is obtained for these two (p,n) cross sections. This value should also be approximately equal to the square of the ratio of the effective interactions $(q=0)$ at these two energies. The latter has been calculated by Love[17] and a ratio 1.56 is obtained, in excellent agreement with the above result.

The $^{12}C(p,n)$ ^{12}N reaction at 99 MeV has recently been reported.[25] Assuming that the 140-MeV t matrix may be used to analyze this data, distortion factors were calculated and PW cross sections were evaluated. When plotted versus q the values are slightly lower than those shown in Fig. 4 but well within the experimental uncertainty. Thus it may be concluded that, within 10–15% uncertainty, values for the spin-dependent isospin term of the effective interaction in the range $0 < q \lesssim 1$ fm^{-1} are energy independent for proton energies between 100 and 200 MeV.

The $\sigma_{PW}(q)$ values shown in Fig. 4 are energy independent between 100 and 200 MeV. This fact has a clear and important practical consequence. Values of the efficiency for neutron detectors in the indicated energy range may be calculated by normalization to the above results.

IV. SUMMARY AND CONCLUSIONS

We have shown that DWIA calculations of the $^{12}C(p,n)$ ^{12}N cross sections reproduce quite well the observed experimental data giving support to the underlying assumptions.

A unique curve for incident energies between 100–200 MeV seems to fit the data points for PW cross sections when plotted versus q for the ground-state transition. This gives empirical evidence in this energy region to an almost energy independent spin-dependent isovector effective interaction. The unique curve seems to indicate that the factorization for the (p,n) cross section as indicated in Eq. (1) seems to be valid for values of q up to $q \sim 1.0$ fm^{-1}.

The $^{12}C(p,n)$ ^{12}N (0.96-MeV) transition seems to be dominated by a pure $\Delta S = 1$, $\Delta L = 2$ transfer. This is corroborated by DWBA70 calculations. The normalization needed to fit the data $(N \sim 0.5)$ similar to that found in inelastic electron scattering[15] indicates the sensitivity of the (p,n) results to nuclear structure calculations.

The effective t matrix taken from phase shifts to N-N scattering data as parametrized by Love and Franey[17] reproduce quite well the energy dependence of $J_{\sigma\tau}(q=0)$ in the 100–200-MeV range and also at 800 MeV.

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[1] D. E. Bainum, J. Rapaport, C. D. Goodman, D. J. Horen, C. C. Foster, M. B. Greenfield, and C. A. Goulding, Phys. Rev. Lett. 44, 1751 (1980).

[2] C. D. Goodman, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, C. C. Foster, W. G. Love, and F. Petrovich, Phys. Rev. Lett. 44, 1755 (1980).

[3] D. J. Horen, C. D. Goodman, C. C. Foster, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, E. Sugarbaker, T. G. Masterson, F. Petrovich, and W. G. Love, Phys. Lett. 95B, 27 (1980).

[4] D. J. Horen, C. D. Goodman, D. E. Bainum, C. C. Foster, C. Gaarde, C. A. Goulding, M. B. Greenfield, J. Rapaport, T. N. Taddeucci, E. Sugarbaker, T. G. Masterson, S. M. Austin, A. Galonsky, and W. Sterrenburg, Phys. Lett. (to be published).

[5] F. Petrovich, W. G. Love, and R. J. McCarthy, Phys. Rev. C 21, 1718 (1980).

[6] F. Petrovich, in *The (p,n) Reaction and the Nucleon-Nucleon Force*, edited by C. D. Goodman, S. M. Austin, S. D. Bloom, J. Rapaport, and G. R. Satchler (Plenum, New York, 1980), p. 115.

[7] A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. 1, p. 345.

[8] W. G. Love, in *The (p,n) Reaction and the Nucleon-Nucleon Force*, edited by C. D. Goodman, S. M. Austin, S. D. Bloom, J. Rapaport, and G. R. Satchler (Plenum, New York, 1980), p. 23.

[9] W. G. Love, Los Alamos Scientific Laboratory Report No. LA-8303-C, 1980, p. 26 (unpublished).

[10] A. Picklesimer and G. Walker, Phys. Rev. C 17, 237 (1978).

[11] F. Ajzenberg-Selove, Nucl. Phys. A248, 1 (1975).

[12] C. D. Goodman, C. C. Foster, M. B. Greenfield, C. A. Goulding, D. A. Lind, and J. Rapaport, IEEE Trans. Nucl. Sci. NS26, 2248 (1979).

[13] C. D. Goodman, J. Rapaport, D. E. Bainum, and C. E. Brient, Nucl. Instrum. Methods 151, 125 (1978); C. D. Goodman, J. Rapaport, D. E. Bainum, M. B. Greenfield, and C. A. Goulding, IEEE Trans. Nucl. Sci. NS25, 577 (1979).

[14] C. A. Goulding, M. B. Greenfield, C. C. Foster, T. E. Ward, J. Rapaport, D. E. Bainum, and C. D. Goodman, Nucl. Phys. A331, 29 (1979).

[15] J. R. Comfort, S. M. Austin, P. T. Debevec, G. L. Moake, R. W. Finlay, and W. G. Love, Phys. Rev. C 21, 2147 (1980).

[16] R. K. Adair, Phys. Rev. 87, 1041 (1952).

[17] W. G. Love and M. A. Franey, Bull. Amer. Phys. Soc. 25, 730 (1980); Phys. Rev. C (to be published).

[18] R. Schaeffer and J. Raynal (unpublished).

[19] J. R. Comfort and B. C. Karp, Phys. Rev. C 21, 2162 (1980).

[20] S. Cohen and D. Kurath, Nucl. Phys. 73, 1 (1965) and T. S. H. Lee and D. Kurath, Phys. Rev. C 21, 293 (1980).

[21] J. R. Comfort, R. E. Segel, G. L. Moake, D. W. Miller, and W. G. Love, Phys. Rev. C 23, 1858 (1981).

[22] G. L. Moake, L. J. Gutay, R. P. Scharenberg, P. T. Debevec, and P. A. Quin, Phys. Rev. C 21, 2211 (1980); G. L. Moake, Ph.D. dissertation (1979), IUCF Internal Report No. 79-2 (unpublished).

[23] G. L. Moake and P. T. Debevec, Phys. Rev. C 21, 25 (1980).

[24] M. Haji-Saeid, C. Glashausser, G. Igo, W. Cornelius, M. Gazzaly, F. Irom, J. McClelland, J. M. Moss, G. Pauletta, H. A. Thiessen, and C. A. Whitten, Jr., Phys. Rev. Lett. 45, 880 (1980).

[25] J. N. Knudson, B. D. Anderson, D. C. Tandy, J. W. Watson, R. Madey, and C. C. Foster, Phys. Rev. C 22, 1826 (1980).

[26] W. G. Love, private communication.