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M.S. Hussein and E. Farrelly-Pessoa
Instituto de Física, Universidade de São Paulo

and

H.R. Schelin
Divisão de Física Teórica, Instituto de Estudos Avançados, Centro Técnico Aeroespacial, C.P. 6044
12231 São José dos Campos, SP, Brazil

and

R.A. Douglas
IFGW, Universidade Estadual de Campinas,
13100 Campinas, SP, Brazil

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M.S. Hussein and E. Farrelly-Pessoa
Departamento de Física Nuclear
Instituto de Física, Universidade de São Paulo,
C.P. 20516, 01498 São Paulo, S.P., Brazil

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H.R. Schelin
Divisão de Física Teórica, Instituto de Estudos Avançados, Centro Técnico Aeroespacial, C.P. 6044, 12231 São José dos Campos, Brazil

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ABSTRACT

The elastic enhancement factor in charge exchange reactions proceeding via the compound nucleus, predicted to attain the value of 2 in the weak isospin mixing regime by Harney, Weidenmüller and Richter five years ago, is tested here in the system $^{11}B(p,n)^{11}C$ at $\langle E_p \rangle = 14.3$ MeV. Both the DWBA and Hauser-Feshbach calculations employed in the analysis are used in a way which physically simulates a two coupled-channels model. Our results show an enhancement factor larger than 1 indicating that isospin is mainly conserved in this reaction.

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I. INTRODUCTION

The question of isospin dependence in compound nuclear reactions has received a great amount of attention during the last 15 years[1-4]. A consistent theory of these reactions, which contains isospin as a label of the transmission coefficients, would enable the eventual extraction of the isospin mixing parameters which measure the degree of purity of isospin in the compound nucleus. One important consequence of the inclusion of isospin in the statistical cross section (Hauser-Feshbach), discussed by Harney et al.[5], is the presence of a width fluctuation correction which depends on the mixing parameter and which attains in isospin conserved cases the value 2 in the ground to ground charge exchange transitions. This WFC, or charge exchange enhancement factor is absent in other inelastic (p,n) compound transitions.

We should mention that the enhancement factor in the genuine compound elastic scattering, which is predicted to be also about 2 in the strong absorption limit, has already been confirmed experimentally by Kretschmer and Wangler[6] for the system $^{30}Si(p,p)^{30}Si$ at $E_p = 9.8$ MeV. It is clear, therefore, that an experimental verification of the charge exchange WFC is of great importance, as it supplies one more test of the statistical theory of nuclear reactions.

Our aim in this paper is to supply a detailed

analysis of the $^{11}B(p,n)^{11}C$ reaction at $\langle E_p \rangle = 14.3$ MeV, with the objective of testing the compound charge exchange WFC factor discussed above. Notwithstanding the difficulty encountered in performing an analysis of a reaction composed of both direct and compound components, we do manage, however, with a reaction model built for the purpose, to get a reasonable estimate of the elastic enhancement factor.

The plan of the paper is as follows. In Section II we describe briefly the experimental details. In Section III, the reaction model used in the analysis, together with a detailed discussion of the isospin dependent Hauser-Feshbach theory, are fully described. In Section IV, the analysis of the data, and a description of the optical potentials used for the purpose are presented. In Section V the result of our analysis and the discussion of the WFC are given, followed finally by Section VI where conclusions are drawn.

II. EXPERIMENTAL DETAILS

The apparatus and techniques used in the present experiment have been described in detail elsewhere (Refs. 7, 8 and 9), so only the essential features will be described in this paper.

The spectra of neutrons from the reaction $^{11}B(p,n)^{11}C$

have been obtained employing conventional time-of-flight (TOF) techniques. The University of São Paulo Tandem Pelletron provided the pulsed proton beams between 13.7 and 14.7 MeV. The time-averaged on-target beam intensity was about 90 nA. The time resolution of the system, obtained from the FWHM of the target gamma-ray peak, was 1.5 ns. The neutrons were detected in a (12.7 × 2.54 cm)NE213 liquid scintillator optically coupled to a RTC58AVP photomultiplier. Pulse-shape discrimination, used to differentiate the gamma from the neutron events, allowed ~90% of the gamma events to be eliminated from the spectra without incurring any neutron loss. The neutron detection efficiency was calculated using a Monte Carlo computer code. The neutron detection threshold was selected for 2.2 MeV. In equivalent electron energy this corresponds to the Compton edge of the 661 keV gamma from ^{137}Cs.

The boron targets were made by centrifuging a colloidal suspension of the enriched isotope onto a Mylar film[10]. The thicknesses were about 2.5 ± 10% mg/cm^2.

The data for the four low lying states of the reaction $^{11}B(p,n)^{11}C$ were taken from ref. 9 and consisted of three angular distributions at E_p = 14.0, 14.3 and 14.6 MeV along with an excitation function at θ_{LAB} = 20 deg from E_p = 13.7 to 14.7 MeV in intervals of 100 keV. The overall uncertainty associated with the differential cross section was about 12 to 17%. The data for the elastic scattering, angular

distributions at E_p = 12.0, 12.8 and 14.0 MeV, were taken from reference 11. Energy averaging of the experimental angular distributions was performed before comparison with the theoretical results.

III. THEORY

At the incident proton energies involved in this work, both a direct reaction process and a compound nucleus formation process contribute to the reaction mechanism. A precise account of these competing processes would require an exact coupled channels calculation for the direct interaction and a more sophisticated than usual Hauser-Feshbach type calculation for the compound nucleus process. Owing to the enormous complexity of such calculations we have assumed a reaction model and analysis techniques which enables the standard distorted wave Born approximation (DWBA) and Hauser-Feshbach (HF) computer codes to be employed. We proceed with a description of this reaction model.

III.1. THE REACTION MODEL FOR THE DIRECT INTERACTION

The coupled channels equations for describing a nuclear scattering are

$$(E_1 - H_1^\circ)\,\psi_1 = \sum_{j \neq 1} V_{1j}\,\psi_j \qquad (1)$$

$$(E_j - H_j^\circ)\,\psi_j = \sum_{k \neq j} V_{jk}\,\psi_k \qquad (2)$$

where the symbol 1 refers to the entrance channel and the matrix element V_{jk} is defined by $\langle \phi_j | V_1 | \phi_k \rangle$ where ϕ depends on the internal coordinates of the members of the partition j or k. V_1 is the total interaction potential in the entrance channel and ψ_j, (ψ_k) is the part of the wave function that depends on the relative coordinates of the members of the partition j, (k). The Hamiltonians are

$$H_1^\circ = T_1 + U_1 \qquad (3)$$

and

$$H_j^\circ = T_j + U_j \qquad (4)$$

where T is the kinetic energy operator and U are the usual elastic scattering optical potentials defined by

$$U_1 = \langle \phi_1 | V_1 | \phi_1 \rangle \quad \text{and} \quad U_j = \langle \phi_j | V_j | \phi_j \rangle$$

For the two channel coupling model which we have chosen to describe our neutron differential cross sections to the first four states in ^{11}C, equations (1) and (2) may be written

$$(E_1 - H_1^\circ)\,\psi_1 = V_{12}\psi_2 + V_{13}\psi_3 + V_{14}\psi_4 + V_{15}\psi_5 \qquad (5)$$

$$(E_2 - H_2^\circ)\,\psi_2 = V_{21}\psi_1 + V_{23}\psi_3 + V_{24}\psi_4 + V_{25}\psi_5 \qquad (6)$$

$$\vdots$$

$$(E_5 - H_5^\circ)\psi_5 = V_{51}\psi_1 + V_{52}\psi_2 + V_{53}\psi_3 + V_{54}\psi_4$$

where the subscripts 1 through 5 refer to the p_0, n_0, n_1, n_2, n_3 channels respectively. The Hamiltonians H_j^o are now non-Hermetian since they must account for flux absorption in any direct channels which have been omitted in our description and to any compound nucleus formation which may occur in the reaction process.

Concentrating on equations (5) and (6) we assume for a given pair

$$(E_1 - H_1^\circ)\,\psi_1 = V_{12}\psi_2 \qquad (7)$$

$$(E_2 - H_2^\circ)\psi_2 = V_{21}\psi_1 \quad , \qquad (8)$$

where it should be noted that the terms on the RHS of equation (5) which are omitted in equation (7) will actually be taken into account since the U_1 for the proton entrance channel is obtained from the shape elastic data and so these terms, plus those for any other channels not explicitly shown in equation (5) which are coupled to the elastic channel, are included in

a phenomenological way. The omission of the terms on the RHS in equation (6) is a restriction on our model whose severity may be estimated by the goodness of fit to the data.

We may also write

$$(E_1 - H_1')\,\psi_1 = 0 \qquad \text{where } H_1' = H_1^\circ + V_{12}G_2^\circ V_{21} \qquad (9)$$

$$(E_2 - H_2')\psi_2 = 0 \qquad \text{where } H_2' = H_2^\circ + V_{21}G_1^\circ V_{12} \qquad (10)$$

where the G are the usual Green's functions defined by

$$G_2^\circ = (E_2 - H_2^\circ + i\varepsilon)^{-1} \qquad \text{and} \qquad G_1^\circ = (E_1 - H_1^\circ + i\varepsilon)^{-1}$$

The general solutions to equations (7) and (8) are

$$\psi_1 = \chi_1 + G_1^\circ V_{12}\psi_2 \qquad \text{where } (E_1 - H_1^\circ)\chi_1 = 0 \qquad (11)$$

and

$$\psi_2 = G_2 V_{21}\psi_1 \qquad \text{where } (E_2 - H_2^\circ)\chi_2 = 0 \qquad (12)$$

For the DWBA approximation V_{12} of equation (7) is set equal to zero and V_{21} in equation (8) is retained. The transition amplitude becomes

$$T_{21} = \langle \chi_2^{(-)}\phi_2 | V_1 | \phi_1 \chi_1^{(+)} \rangle$$

or

$$T_{21} = \langle \chi_2^{(-)} | V_{21} | \chi_1^{(+)} \rangle \qquad (13)$$

wherein, for the χ defined through equations (11) and (12), the V_{21} represents the residual interaction. The (-) and (+) indicate that the usual boundary conditions have been applied to the incident and emergent waves.

For our two channel coupling case it is possible to get a more realistic estimate of the transition amplitude using, in a DWBA calculation, the expression

$$T_{21} = \langle \chi_2^{(-)} | V_{21} | \psi_1^{(+)} \rangle \qquad (14)$$

for which the V_{12} of equation (7) is not set equal to zero but rather has its effect included by generating $\psi_1^{(+)}$ from an optical potential extracted from fits to the shape elastic data.

The $\chi_2^{(-)}$ appearing in equation (14) are generated by the neutron optical potentials which predict the correct neutron transmission coefficients in the statistical analysis of the compound nuclear process. These wave functions are the solutions of equation (12). More details of this calculation are presented in the Section below (Optical Potential).

For calculating the transition amplitude of equation (14) we used the computer code DWBA70[12]. The nuclear matrix element V_{21} was evaluated from the Bertsch et al.[13].

G-matrix interaction which provided central terms (combinations of spin-isospin scalar and vector interactions) plus the non-central spin orbit and tensor terms whose strengths and ranges were chosen in accordance with reference 14). The description of the p-shell nuclear states involved neutron-proton Z^J coefficients (particle-hole spectroscopic factors) derived from the Lee-Kurath[15] values and provided for us in the proper representation by F. Petrovich and A. Carpenter[16]. Normalization factors (table 1) for the $^{11}B(p,n)^{11}C$ cross sections resulting from inadequacies found by Grimes et al.[17] in both the nuclear wave functions and the Bersch isovector components at $E_p = 26$ MeV were applied to all our calculated neutron cross sections. In the table the total normalization factors are presented along with their decomposition into a part, N_{pn}, attributed to the wave function and independent of energy plus a part attributed to the interaction component N_τ or $N_{\sigma\tau}$ which may possess an energy dependence.

From the work of Petrovich et al.[14] on the system $^{6,7}Li+p$ at 45 MeV and 26 MeV we extrapolated the energy dependence of these interaction components to 14 MeV and concluded that the variation at this energy with respect to the 26 MeV results is about 3%.

III.2. THE COMPOUND NUCLEAR CHARGE EXCHANGE REACTIONS AND THE CORRESPONDING WIDTH FLUCTUATION CORRECTION

In the conventional analysis of compound nucleus reactions, the total angular momentum plays a crucial role as the conserved quantum number that labels the compound resonances and the transmission coefficients. The extension of the Hauser-Feshbach theory to include isospin as an additional channel spin is straightforward and has been fully developed by Grimes et al.[1] and especially in great detail by Weidenmüller et al.[3,4]. Such an extension is required for the study of isospin mixing in reactions such as (p,n) proceeding via the compound nucleus.

One particular finding of Harney et al.[5], which deserves special attention, is the existence of a width fluctuation correction (WFC), popularly referred to as the elastic enhancement factor (EEF) in the compound charge exchange (p,n) reaction populating the ground state of the residual nucleus, which is predicted in the case of weak isospin mixing to contribute a factor of about 2 to the cross sections calculated with conventional Hauser-Feshbach codes which do not contain isospin as a labeling quantum number. This factor is not present in any other inelastic channel. Of course, the WFC is always present in compound elastic cross sections calculated with the usual Hauser-Feshbach formula. A very nice experimental verification of the WFC in the $p+^{32}S$ elastic scattering was

reported in by Kretschmer and Wangler[5].

Since one of the major aims of the present work is to test the charge exchange WFC factor in the system $^{11}B(p,n_0)^{11}C$ at $E_p = 14.3$ MeV, we present below a reasonably complete account of the isospin dependent Hauser-Feshbach theory as developed by Weidenmüller et al.[3,4].

In complete accordance with the development of pre-compound reactions given by Agassi et al.[18], Harney et al.[3,4] present the isospin dependent fluctuation cross section as a result of a diffusion process involving the population of two classes of compound nucleus states distinguished through their total isospin: the isobaric analog resonances, specified by isospin $t^>$ and the compound nucleus background states with isospin $t^< = t^> - 1$. If the incident particle has isospin $t = \frac{1}{2}$ and the target nucleus t_A, then $t^> = t_A + \frac{1}{2}$ and $t^< = t_A - \frac{1}{2}$. The isospins $t^>$ and $t^<$ are then used to label two sets of transmission coefficients, in the same way that the number of excitons is used as a label of the different transmission coefficients in pre-compound processes. Denoting the above mentioned transmission coefficients by $T^>_{\alpha,t_Z}$ and $T^<_{\alpha,t_Z}$ where α refers to the channel and t_Z the isospin projection of the incident particle.

Harney et al. then write for the average fluctuation cross section for the transition $\alpha \to \beta$, the following:

$$\sigma_{\alpha\beta} = \langle \hat{T}'_{\alpha} \,|\, M^{-1} \,|\, \hat{T}'_{\beta} \rangle \qquad (15)$$

where the vector $|\hat{T}'_{\beta}\rangle$ is just $\begin{pmatrix} T'^{>}_{\beta} \\ T'^{<}_{\beta} \end{pmatrix}$, with $T'^{\gtrless} = \sqrt{\frac{1}{\rho_{\gtrless}}}\, T^{\gtrless}_{i}$, with $\rho_{>}(\rho_{<})$ being the density of states of the $t^{>}$ ($t^{<}$)-states in the compound nucleus and $T^{\gtrless}_{i}$ the transmission coefficients referred to earlier. The matrix M is given by[3)]

$$M = 2\pi \begin{pmatrix} \Gamma^{>} & -\sqrt{\Gamma^{\downarrow}_{<}\,\Gamma^{\downarrow}_{>}} \\ -\sqrt{\Gamma^{\downarrow}_{<}\,\Gamma^{\downarrow}_{>}} & \Gamma^{<} \end{pmatrix} \qquad (16)$$

where the "total" widths are defined by

$$\begin{aligned} \Gamma_{<} &= \Gamma^{\downarrow}_{<} + \sum_{\alpha} \Gamma_{<,\alpha} \quad , \quad \Gamma_{<,\alpha} = \frac{T^{<}_{\alpha}}{2\pi \rho_{<}} \\ \Gamma_{>} &= \Gamma^{\downarrow}_{>} + \sum_{\alpha} T_{>,\alpha} \quad , \quad \Gamma_{>,\alpha} = \frac{T^{>}_{\alpha}}{2\pi \rho_{>}} \\ \Gamma^{\downarrow}_{i} &= \mu\, \Gamma_{i} \end{aligned} \qquad (17)$$

The transmission coefficients $T^{<}$ and $T^{>}$ are related to the conventional isospin independent coefficients through simple isospin coupling coefficients.

One has, in fact

$$T^{>}_{\alpha,t_z} = \left(t_A, t_A^{(z)}; t_\alpha t_\alpha^{(z)} \,|\, t^{>}, t_A^{(z)} + t_\alpha^{(z)}\right)^2 T_{\alpha,t_z} \qquad (18)$$

If we consider now a (p,n) reaction, then the transmission coefficients for protons $T^{>}_{\alpha,-\frac{1}{2}}$ and $T^{<}_{\alpha,-\frac{1}{2}}$ and neutrons $T^{>}_{\beta,+\frac{1}{2}}$, $T^{<}_{\beta,+\frac{1}{2}}$ attain the following values in terms of the isospin independent transmission coefficients,

$$\begin{aligned} T^{>}_{\alpha,-\frac{1}{2}} &= \left(\tfrac{1}{2}, t_A, -\tfrac{1}{2}, t_A \,|\, t_A+\tfrac{1}{2}, t_A-\tfrac{1}{2}\right)^2 T_{\alpha,-\frac{1}{2}} \\ &= (2t_A+1)^{-1}\, T_{\alpha,-\frac{1}{2}} \\ T^{<}_{\alpha,-\frac{1}{2}} &= \left(\tfrac{1}{2}, t_A, -\tfrac{1}{2}, t_A \,|\, t_A-\tfrac{1}{2}, t_A-\tfrac{1}{2}\right)^2 T_{\alpha,-\frac{1}{2}} \\ &= 2t_A\,(2t_A+1)^{-1}\, T_{\alpha,-\frac{1}{2}} \quad , \\ T^{>}_{\beta,+\frac{1}{2}} &= \left(\tfrac{1}{2}, t'_A, \tfrac{1}{2}, t_A-1 \,|\, t_A+\tfrac{1}{2}, t_A-\tfrac{1}{2}\right)^2 T_{\beta,\frac{1}{2}} \\ &= 2t_A\,(2t_A+1)^{-1}\, T_{\beta,+\frac{1}{2}} \quad , \\ T^{<}_{\beta,+\frac{1}{2}} &= \left(\tfrac{1}{2}, t'_A, \tfrac{1}{2}, t_A-1 \,|\, t_A-\tfrac{1}{2}, t_A-\tfrac{1}{2}\right)^2 T_{\beta,+\frac{1}{2}} \\ &= (2t_A+1)^{-1}\, T_{\beta,+\frac{1}{2}} \end{aligned} \qquad (19)$$

where t'_A is the isospin of the residual nucleus.

The values of the C-G coefficients, given in closed form in the second line below the equations for $T^{\gtrless}_{\beta,j+\frac{1}{2}}$ correspond to the case $t'_A = t_A$. In terms of the isospin dependent transmission coefficients the cross section for a compound (p,n) reaction (α=p+A) (β=n+(A+p-n)), is obtained directly from Eqs. (15) and (16), and for a given partial wave J is

$$\sigma_{\alpha\beta}(J) = \frac{\pi}{k_\alpha^2}(2J+1)\Big\{ N^{<} T^{>}_{\alpha,-\frac{1}{2}} T^{>}_{\beta,\frac{1}{2}} + N^{>} T^{<}_{\alpha,-\frac{1}{2}} T^{<}_{\beta,\frac{1}{2}} + z\Big[T^{>}_{\alpha,-\frac{1}{2}} + T^{<}_{\alpha,-\frac{1}{2}}\Big]\Big[T^{<}_{\beta,\frac{1}{2}} + T^{>}_{\beta,\frac{1}{2}}\Big]\Big\} \times \Big((N^{>}+z)(N^{<}+z) - z^2\Big)^{-1} \quad (20)$$

where, following the notation of Harney et al.[3],

$$N^{\gtrless} = \sum_\alpha T^{\gtrless}_{\alpha,-\frac{1}{2}} + \sum_\beta T^{\gtrless}_{\beta,\frac{1}{2}}$$

represents the summed contributions of all p and n channels coupled to the isobaric ($t^>$) or background ($t^<$) states and

$$z \equiv \Gamma^{\downarrow}_{>} \rho_{<} = \Gamma^{\downarrow}_{<} \rho_{>}$$

Using the relations between $T^{\gtrless}_{\alpha t_Z}$ and $T^{\gtrless}_{\beta t_Z}$ and the isospin independent transmission coefficients given in Eq. (19), we obtain immediately

$$\sigma_{\alpha\beta}(J) = \frac{\pi}{k_\alpha^2}(2J+1)\left[\frac{(N^{<}+N^{>})\frac{2t_A}{(2t_A+1)^2} + z}{(N^{<}+z)(N^{>}+z) - z^2}\right] T_{\alpha,-\frac{1}{2}} T_{\beta,\frac{1}{2}} \quad (21)$$

where, of course, $T_{\alpha t_Z}$ and $T_{\beta t_Z}$ are calculated from isospin independent optical potentials. In order to obtain a form for $\sigma_{\alpha\beta}(J)$ which permits the extraction of the enhancement factor, we rewrite Eq. (21) in the equivalent form

$$\sigma_{\alpha\beta}(J) = \frac{\pi}{k_\alpha^2}(2J+1)\left[\frac{\frac{2t_A}{(2t_A+1)^2} + \frac{z}{N^{>}+N^{<}}}{\frac{N^{<}N^{>}}{N^{<}+N^{>}} + z}\right] T_{\alpha,-\frac{1}{2}} T_{\beta,\frac{1}{2}} \quad (22)$$

For a charge exchange reaction, where both target and residual nuclei are in their ground states, Weidenmüller et al. show that the first term inside the parenthesis in Eq. (22) acquires an additional factor of 2. When comparing Eq. (22) (with the factor of 2 included), with the usual isospin-independent Hauser-Feshbach expression $T_{\alpha,-\frac{1}{2}} T_{\beta,\frac{1}{2}} / \sum_\gamma T_{\gamma,t_Z} \equiv \sigma^{HF}_{\alpha\beta}$, Harney et al. identify the charge exchange WFC, $W_{c.e.}$ as

$$\sigma_{\alpha\beta}(J) = W_{c.e.}\, \sigma^{H.F.}_{\alpha\beta}(J) \quad (23)$$

$$W_{c.e.} = \frac{(1+\delta_{n n_0})\frac{2t_A}{(2t_A+1)^2} + \frac{z}{N^{>}+N^{<}}}{\frac{2t_A}{(2t_A+1)^2} + \frac{z}{N^{>}+N^{<}}},$$

$N^{>}+N^{<} \equiv \sum_\gamma T_{\gamma, t_z}$

which shows that in the weak isospin case, $z \ll 1$, W is ~ 2 for the (p,n_0) transition (namely the ground state transition)

and 1 for all other inelastic (p,n) transitions. We should mention that the genuine compound elastic scattering cross section does contain the elastic enhancement factor of 2 independent of the strength of the isospin mixing.

In the analysis of the $^{11}B(p,n)^{11}C$ reaction performed here, we have to employ a nuclear reaction model composed of the compound nucleus Hauser-Feshbach part, assumed to have the form of Eq. (23) plus the direct (p,n) contribution, calculated within the simplified version of coupled channels theory described in Subsection III.1.

IV. THE ANALYSIS

The choice of the "channel" wave functions appearing in Eq. (14) was effected through a parametrization of the proton and neutron optical potentials. For the form of these potentials we adopted the real and imaginary volume terms of the microscopic potential calculated by Yamaguchi[19] at $E_p = 15$ MeV ($^{40}Ca+p$ system) for which the values of the geometrical parameters were extrapolated to the system $^{11}B+p$ by comparison of the nuclear density distribution derived from electron scattering data in the two target nuclei[20]. Furthermore, the optical model fits to the $^{11}B+p$ elastic data required the inclusion of a spin orbit term which was subsequently maintained. Thus parametrization of

potentials of the general form

$$V(r) = V_o f(r) + iW_o g(r) + V_{so} h(r)\, \vec{\sigma}.\vec{l} \qquad (24)$$

where the form factors are the usual Wood-Saxon type

$$\left(1 + \exp x_i\right)^{-1} \qquad (25)$$

with $x_i = (r - R_i)/a_i$, $R_i = r_{oi} A_i^{1/3}$

was performed by simulating the Yamaguchi microscopic potential by a Woods-Saxon function and allowing,in the interest of best fits, small adjustments in the initial values.

Of the multitude of parameters, the absorption parameters W_o for the proton and neutron are especially sensitive in determining the magnitudes of the predicted cross sections. For this reason the choice of the strengths of these terms was reserved for the final adjustment in the magnitudes of the predicted cross sections and the details of the procedure is discussed in detail below.

The final choice of all the other optical parameters was extracted for the proton from optical model calculations for the (p,p_o) cross sections and for the neutron from the DWBA calculations for the (p,n_o) cross sections. At this stage our paramount concern was in reproducing the shape of these cross

sections. Two criteria which insured physical reality were adherred to. First, the variation of the volume integrals of the real potential strength V_o from the Yamaguchi results were held to a minimum and second, the peak to valley ratios in the (p,n_o) cross sections were maximized, since any amount of compound nucleus process which might be added would tend to wash out the structure.

Final values of the parameters obtained (along with W_o values which will be discussed later) are shownin Table 2. It should be mentioned that small variations (*10* % in the geometrical parameters and *8* % in the strength parameters) made little difference in the shape of the cross sections and larger variations violated one or the other of the criteria described above. These values of the optical parameters presented in Table 2 remained fixed throughout the entire analysis.

ABSORPTION POTENTIAL W_o

The remaining part of the analysis concerns the choice of W_o to obtain the "best fit" cross sections in the exit channels for the p_o, n_o, n_1, n_2 and n_3 groups.

The analysis begins by calculating a set of compound nucleus (p,n_o) cross sections whose upper limit is determined by the unitarity principle. A standard computer code, Hauser-5[21], was used for these calculations. Five modes of decay n, p, d, α and ^{3}He were included with a totality of 59 exit channels.

Final state continuum channels were deemed unnecessary[22].

Each of these calculated cross section implies a specific value of W_o^{HF}(neutron) which, in the Hauser 5 code, was considered to be equal to the proton absorption term W_o^{HF}(proton) apart from the Coulomb term. Anyone of these compound nucleus cross sections is referred to generically as $\sigma_i^{HF}(p,n_o)$ with a corresponding $\sigma_i^{HF}(p,p_o)$ and W_i^{HF}(neutron). The (p,n_o) cross sections were chosen as the starting point merely for convenience.

A shape elastic cross section $\sigma_i^{SE}(p,p_o)$ is then obtained by subtracting the elastic compound cross section $\sigma_i^{HF}(p,p_o)$ from the experimental elastic cross section $\sigma^{exp}(p,p_o)$ viz.,

$$\sigma_i^{SE}(p,p_o) = \sigma^{exp}(p,p_o) - \sigma_i^{HF}(p,p_o) \qquad (26)$$

An optical model fit of $\sigma_i^{SE}(p,p_o)$, for which the only free parameter is the absorption term for the protons, yields a value $W_i^{SE}(p,p_o)$. In this way the channel wave functions $\chi_2^{(-)}$ and $\psi_1^{(+)}$ which appear in the direct interaction transition amplitude of equation (14) may be generated through the following choice of W_i(neutron) and W_i(proton) in the optical potentials

$$W_i^{HF}(\text{neutron}) = W_i^{DWBA}(\text{neutron})$$
$$W_i^{SE}(\text{proton}) = W_i^{DWBA}(\text{proton}) \qquad (27)$$

Values of these strengths are also shown in table 2 for the best fit results of figure 2c.

Thus corresponding to each σ_i^{HF} we calculate a corresponding σ_i^{DWBA} using the optical potentials appropriate to the i^{th} compound nucleus and direct interaction case as described above. This is done for all the neutron exit channels of interest (n_0, n_1, n_2 and n_3).

The theoretical cross sections for the n_1, n_2 and n_3 neutron groups are obtained from

$$\sigma_i^{theor.}(n_x) = \sigma_i^{HF}(n_x) + \sigma_i^{DWBA}(n_x) \quad , X=1,2,3 \qquad (28)$$

and for the ground state neutrons

$$\sigma_i^{theor.}(n_0) = W_{c.e.}\,\sigma_i^{HF}(n_0) + \sigma_i^{DWBA}(n_0) \qquad (29)$$

V. RESULTS AND DISCUSSION

The results of our analysis are summarized in Fig. (1) and (2). In Fig. (1) the points represent the elastic scattering data after subtraction of the compound elastic cross section associated with the Hauser Feshbach predictions for the neutron channels of figure 2c. The full curve in Fig. (1) represents the optical model fit from which the value of W_o^{DWBA} (proton) of table 2 was obtained for calculating

the direct interaction contributions to the data of Fig. 2c. Figures 2a, 2b and 2c represent different HF contributions to the cross sections shown by the full curves well outside the data points. The full curves in these figures passing through the data points are the total theoretical differential cross sections i.e. the illustrated HF with $W_{c.e.}$ = 1 plus the corresponding DWBA. In the best fits, (parameters of table 2, and curves of figure 2c) the dashed curve in the ground state neutron case represents the total theoretical differential cross section for which the value of $W_{c.e.}$ was taken to be 2. Although calculation with $W_{c.e.}$ = 1 seems to account better for the (p,n_o) cross sections at the larger angles involved, we were, however, quite convinced that it is not the best choice since the resulting angle integrated Hauser-Feshbach contribution comes out to be about $\frac{1}{2}$ of the HF contribution to each of the other (p,n) channels, the contribution in each of these other channels being close to 50% of their experimental cross sections. In contrast, with $W_{c.e.}$=2 the angle integrated HF contributions to all (p,n) cross sections including (p,n_o) come out about equal. This conclusion is quite insensitive to the values of W_o (neutrons). The above criterion concerning the equal weight of all angle integrated HF contributions seems to be a reasonable one to use since little difference among

neutron channel transmission coefficients is expected owing to the small values of the excitation energies and spins of the excited states considered. We should stress that several important questions do remain unanswered in so far as the method of analysis is concerned. The two questions which were not touched upon in the paper are the effect of direct channel coupling on the compound nucleus (HF) contribution and the effect of including any direct channel coupling among the different neutron channels in the direct reaction contribution calculated here within a modified DWBA.

VI. CONCLUSIONS

We conclude that an elastic enhancement, $W_{c.e.}$, larger than 1 is appropriate for this reaction, which seems to indicate weak isospin mixing in the compound nucleus ^{12}C at the excitation energy of 29 MeV involved in this work. It would be interesting to further apply our reduced coupled channels model at smaller proton energies, where one expects a larger compound contribution to the cross section, thus increasing the sensitivity with respect to $W_{c.e.}$. An especially interesting region would be the d-shell nuclei where spectroscopic factors have recently become available[23] thus permitting a precise description of the direct process with the consequent assessment, through our procedure, of the degree of isospin mixing in this mass region.

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TABLE CAPTIONS

Table 1 - Normalization coefficients applied to the (p,n) cross sections taken from reference 15.

Table 2 - Optical potential strengths (MeV) and geometric parameters (fm) obtained in the analysis for the $\sigma^{HF(i)}$ contribution of figure 2c.

FIGURE CAPTIONS

Figure 1. Shape elastic differential cross section at $\langle E_p \rangle$ = 13.0 MeV with optical model analysis fit (full curve) using parameters of table 2.

Figure 2. Ground state and first three excited state differential cross sections at $\langle E_p \rangle$ = 14.3 MeV for $^{11}B(p,n)^{11}C$. See text for explanations.

TABLE 1

Transition	J	N_{pn} b)	N_{τ} c)	$N_{\sigma\tau}$ d)	N_{TOT} e)
$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$ (g.s.)	0	-	0.950	-	0.950
	1	0.618	-	0.640	0.396
	2 a)	-	0.950	-	0.475
	3	0.618	-	0.640	0.396
$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	1	0.330	-	0.640	0.211
	2 a)	-	0.950	-	0.475
$\frac{3}{2}^- \rightarrow \frac{5}{2}^-$	1	0.970	-	0.640	0.621
	2 a)	-	0.950	-	0.475
	3	0.970	-	0.640	0.621
$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$ (e.s.)	1	0.470	-	0.640	0.301
	2 a)	-	0.950	-	0.475
	3	0.470	-	0.640	0.301

a) Reduction factor of 2 (account for the isovector quadrupole renormalization), Ref. 10.

b) Nuclear wave functions normalization, Ref. 15.

c) Isovector interaction g_{01} normalization, Ref. 10 and 15.

d) Isovector interaction g_{11} normalization, Ref. 10 and 15.

e) $N_{TOT} = N_{pn} N_{\tau}$ or $(N_{pn} N_{\sigma\tau})$.

TABLE 2

	V_R	r_R	a_R
proton and neutron	50.00	1.35	0.56
	W_0^{DWBA}	r_w	a_w
proton	7.17	1.63	0.23
neutron	2.47	1.63	0.23
	W_0^{HF}	r_w	a_w
proton and neutron	2.47	1.63	0.23
	V_{so}	r_{so}	a_{so}
proton and neutron	5.10	1.19	0.43

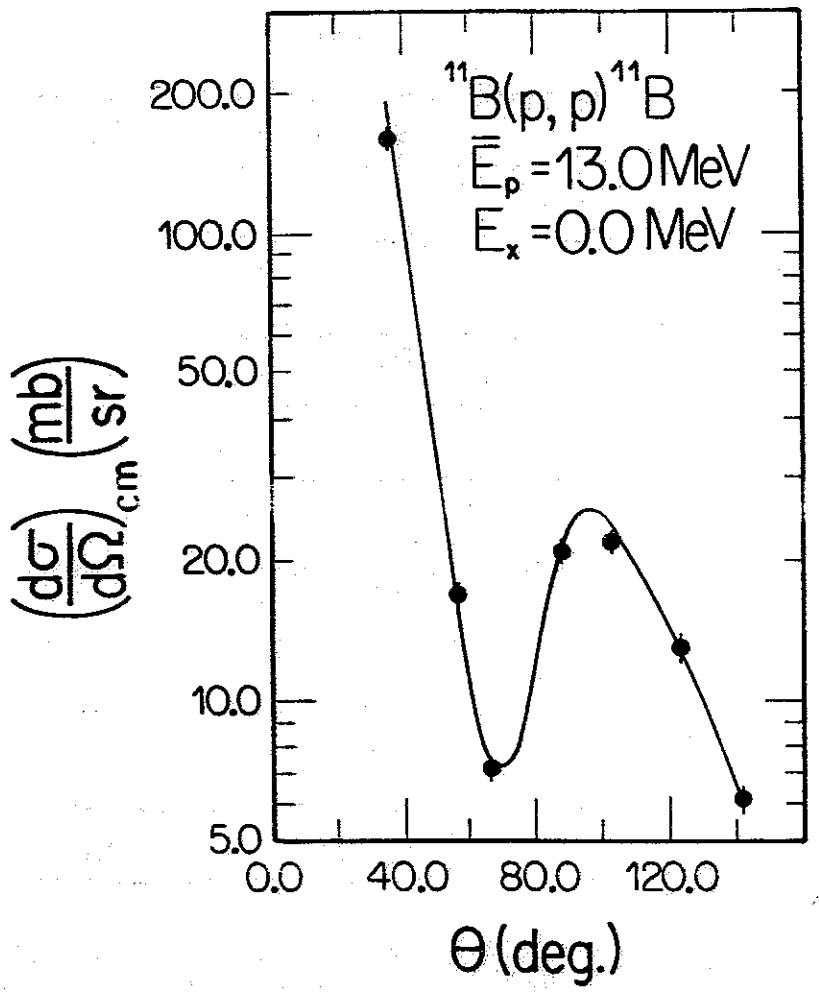

Fig 1.

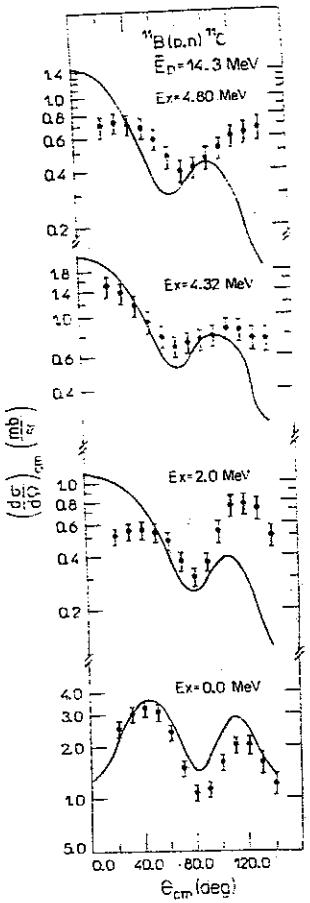

Fig. 2a

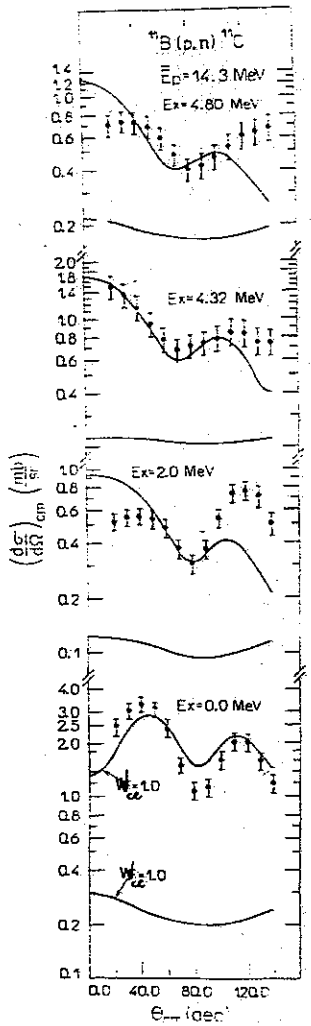

Fig. 2b

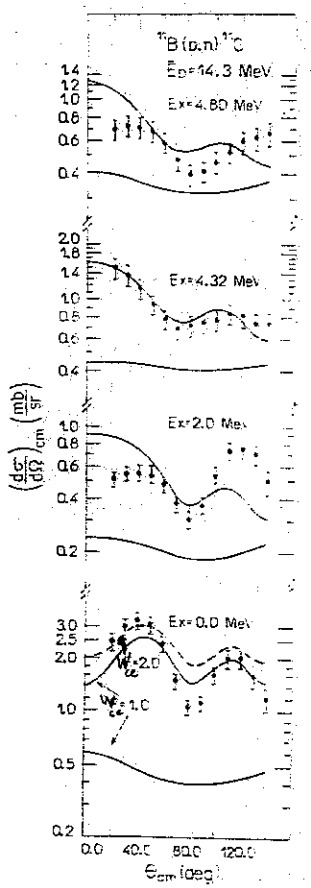

Fig. 2c