(p,n) and (^{3}He,t) reactions in coincidence with $p\pi^+$ in ^{12}C

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Recent measurements on the energy spectra of ejectiles in the (p,n) and (^{3}He,t) reactions in coincidence with the $p\pi^+$ charged particles and integrated over their energies and angles are analyzed theoretically in the DWIA framework. It is assumed that the $p\pi^+$ events are generated by the direct decay of Δ^{++}. Due to the peripheral nature of the reaction the Δ^{++} itself is assumed to be produced through the quasifree $pp \to n\Delta^{++}$ process. The interaction for this process is described by the pseudovector one-pion-exchange relativistic Lagrangian. The parameters of this Lagrangian are taken such that it reproduces the measured spin averaged cross sections on the $pp \to n\Delta^{++}$ reaction very well, over a wide energy range. Our calculated cross sections for the ejectile spectra on ^{12}C agree very well with the corresponding measured cross sections.

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I. INTRODUCTION

Historically, the first charge exchange reaction which distinctly excited the spin-isospin mode in nuclei was the (p,n) reaction. It was performed at beam energy beyond 100 MeV [1] at the Indiana University Cyclotron Facility. Since the similar excitations were not seen below 100 MeV, this observation surprised every one and generated a great deal of interest in their studies. Consequently, a large number of such experiments have been done since then using (p,n), (^{3}He,t), and heavy ions, with beam energies varying from 100 MeV to around 1 GeV per nucleon [2–4]. At lower excitations (10–20 MeV), all these experiments show the Gamow-Teller (GT) excitations. But, as the beam energy increases, they start exhibiting an additional bump around 300 MeV nuclear excitation. Since this excitation energy is in the vicinity of the delta excitation of a nucleon, this bump is understandably interpreted as the intrinsic spin-isospin excitation of a nucleon in the nucleus to the delta isobar. Thus, in the same experiment, as the beam energy increases, one sees the spin isospin response of the nucleus on the nuclear level as well as on the nucleonic level. This obviously is very exciting and promises a rich field to harvest the spin isospin degrees of freedom in nuclei. Stimulated by this a large amount of theoretical studies has been done in this field [5,6]. The GT part of the spectrum has been understood to a great extent now. It is understood to proceed essentially in one step. The piece of the nucleon-nucleon interaction which initiates the excitation and its dependence on the beam energy is understood in terms of the one-pion plus rho-exchange potential. The cause for the missing strength in the GT transition, of course, is still far from settled.

The understanding of the delta part of the ejectile spectrum, on the other hand, is far from being clear. One of the most intriguing features in the inclusive neutron spectra has been the large (about 35 MeV) energy shift in the position of the "delta peak" in all nuclei relative to that in the hydrogen target. Various theoretical calculations, in terms of the one-pion or one-pion plus rho-exchange potential generalized to the delta transition, and including the distortion of the continuum particles in one form or other have failed to reproduce this shift. Therefore, in some quarters, it is seen as the signature of the medium effect on the delta mass. In a recent calculation due to Udagawa *et al.* [7], an attempt has been made to reproduce this shift by including the correlations in the delta-hole state through an energy dependent π-exchange interaction.

In the hope to resolve the above issue and to disentangle the contribution from different channels to the peak in the inclusive spectra, recently, somewhat exclusive measurements have been done on (p,n) reactions at KEK [3] and (^{3}He,t) reactions at Saturne [4]. In these experiments the ejectile spectra have been measured where the ejectile is detected in coincidence with the charge particles, like, $p\pi^+$, pp, p, and π^+. The measurements in these experiments have been done on ^{12}C and hydrogen targets. The beam energy in the KEK experiment has been 831 MeV (1.5 GeV/c momentum) and the coincidence particles are detected in a large acceptance (12° to 141°, covering a solid angle of 88% of 4π) spectrometer called FANCY. The beam energy in the Saturne experiment has been 2 GeV and the coincidence particles are detected in the "4π" detector, DIOGENE. The total experimental set-up at Saturne allows particle identification between 20° and 132° and the detection energy thresholds of 15 and 35 MeV for pions and protons, respectively. In a subsequent experiment [8], the pions in the (^{3}He,$t\pi^+$) reaction are also momentum analyzed and the angular correlation between the direction of the momentum transfer and the angle of emission of the pions has been established.

The analyses [9] of the above exclusive data suggest that there are two class of channels which contribute to the peak in the inclusive data. One class of events originates from the single pion "coherent" production and another class from the initial single step delta production, p(or ^{3}He)$N \to n$(or t)Δ. The $p\pi^+$ events are probably the direct decay products of the dominant Δ^{++} charge state, while other channels, having p, $2p$, etc., are produced by the final state interaction of the delta in the recoiling nucleus. As regards the energy shift in the inclusive spectra, the exclusive data suggest that it primarily occurs due to coherent pion production channel and the final state interaction produced $2p$ channel. The $p\pi^+$ channel shows insignificant shift.

In order to understand the delta production reactions fully, it is now necessary that we understand the two class of channels appearing in these reactions thoroughly. A beginning in this direction has been made in the literature. The attention has mostly focused on the coherent pion production part, because it is novel and provides new physics in the field of pion propagation in nuclear medium. The typical papers related to these efforts are given in Ref. [10]. Similar efforts on coherent pion production has also been made in the photoinduced reactions [11].

In the present paper we, however, focus attention on another class of events which originates from the single step delta production. We consider that the beam particle interacts with one nucleon in the nucleus. This nucleon gets excited to the delta isobar. Calculating the three body final state kinematics, we find that, for the ejectile measurements done at KEK and Saturne, the delta so produced mostly lie in the continuum. The $p\pi^+$ events are produced by the subsequent decay of Δ^{++}, i.e.,

$$p + A(B+p) \rightarrow n + B + \Delta^{++}, \quad (1)$$

$$\Delta^{++} \rightarrow p + \pi^+. \quad (2)$$

The understanding of this channel is important because (i) it forms a large portion of the cross section in the inclusive data, and, (ii) having a simple reaction mechanism, it provides means to check the validity of the $pp \rightarrow n\Delta^{++}$ interaction, obtained from the analysis of this reaction in free state, in the nuclear medium.

Specifically, we calculate the cross section in DWBA for the $(a, b\Delta^{++})$ reaction. The interaction in the initial and final states in this model is incorporated through the use of distorted waves for the projectile, ejectile, and the Δ^{++}. Furthermore, since, due to strong absorption of the projectile and ejectile, the Δ is produced in the low density surface region of the target nucleus, we consider the elementary delta production process, $pp \rightarrow n\Delta^{++}$, in the nucleus in a quasifree process. Consequently, the transition interaction for this process in the nucleus is taken from the study of the same process in the free state. We have used the one-pion-exchange potential for it. This potential, as shown by Dmitriev *et al.* [12] and Jain *et al.* [13], reproduces very well the spin averaged cross sections for the elementary process, $pp \rightarrow n\Delta^{++}$, over a wide energy range. We, of course, use the relativistic covariant form for it. The nonrelativistic static version of this potential is not quite adequate because of the large energy transfer involved in the delta production process [6].

In Sec. II we give the formalism for the $A(a, b\Delta^{++})B$ reaction and relate the calculated cross sections to the measured coincident $p\pi^+$ events in the (p, n) and $(^3\mathrm{He}, t)$ reactions. In Sec. III we compare these calculated cross sections with the experimental data.

II. FORMALISM

The differential cross section for the $A(a, b\Delta)B$ reaction is given by

$$d\sigma = [\mathrm{PS}]\langle |T_{fi}|^2 \rangle, \quad (3)$$

where [PS] is the factor associated with the phase space and the beam current. It is given by

$$[\mathrm{PS}] = \frac{1}{j(2\pi)^5} \frac{M_B m_a m_b \mu}{E_B E_a E_b E_\mu} \times \rho(\mu^2) d\mu^2 \delta^4(P_f - P_i) d\mathbf{k}_b d\mathbf{k}_\Delta d\mathbf{K}_B. \quad (4)$$

Here j is the beam current and P_x denotes the four-momentum. The fact that the delta does not have a fixed mass is incorporated through the distribution function, ρ, which is given by

$$\rho(\mu^2) = \frac{1}{\pi} \frac{m^* \Gamma(\mu)}{(\mu^2 - m^{*2})^2 + m^{*2}\Gamma^2(\mu)}, \quad (5)$$

with m^*=1232 MeV. The form of Γ is provided by the analysis of the $\pi^+ p \rightarrow \pi^+ p$ data [14], giving

$$\Gamma(\mu) = \Gamma_0 \frac{k^3(\mu^2, m_\pi^2)[k^2(m^{*2}, m_\pi^2) + \gamma^2]}{k^3(m^{*2}, m_\pi^2)[k^2(\mu^2, m_\pi^2) + \gamma^2]}. \quad (6)$$

Here k is the momentum in the $\pi^+ p$ center of mass system and the values of Γ_0 and γ are 120 and 200 MeV, respectively.

The angular brackets around $|T_{fi}|^2$ in Eq. (3) represent the appropriate sum and average over the spins in the final and initial states. Assuming that the delta production is a one step process, the t matrix, T_{fi}, is given by

$$T_{fi} = \langle \chi_b^-, \chi_\Delta^- \langle b, \Delta, B | \sum_i H_{\mathrm{int}}(i) | A, a \rangle, \chi_a^+ \rangle, \quad (7)$$

where i represents the "active" nucleons in the nucleus, which can be excited to delta. χ's are the distorted waves. They represent the attenuation and dispersion of the beam, ejectile, and the delta currents by the nucleus.

As the energies of the continuum particles in the present paper are in the range of "intermediate energies" we use the eikonal approximation for χ's. We write

$$\chi_{\mathbf{k}}^+(\mathbf{r}) \approx e^{i\mathbf{k}\cdot\mathbf{r}} D_{\mathbf{k}}^+(\mathbf{r}), \quad (8)$$

where $D_{\mathbf{k}}$, the modulating function, is given by

$$D_{\mathbf{k}}^+(\mathbf{r}) = \exp\left(-\frac{i}{\hbar v} \int_{-\infty}^{z} V(\mathbf{b} + \hat{k}z')dz' \right). \quad (9)$$

Here V is the distorting potential and v is the speed of the particle.

Since the delta is a spin-isospin excitation of a nucleon, the interaction Hamiltonian, H_{int}, is a spin-isospin interaction. The possible candidates for it, in the boson exchange models, are the one pion and one rho exchange. Out of them, as the work of Jain *et al.* [13] and Dmitriev *et al.* [12] have shown, the spin averaged cross sections on the elementary reaction, $pp \to n\Delta^{++}$, can be well described, over a wide energy range, by the one-pion-exchange interaction only. The rho-exchange potential has not been found consistent with the data [15]. We accordingly take one pion exchange for $H_{\rm int}$ and write

$$H_{\rm int} = \mathcal{L}_{\pi N\Delta} G_\pi \mathcal{L}_{\pi ab}, \tag{10}$$

where G_π is the pion propagator. The pion-nucleon Lagrangian, $\mathcal{L}$, in the pseudovector coupling, is given by

$$\mathcal{L} = \frac{fF}{m_\pi}\bar{\psi}_N \gamma^\nu \gamma^5 \tau \psi_N \cdot \partial_\nu \phi_\pi + \frac{f^* F^*}{m_\pi}\bar{\psi}^\nu_\Delta \mathbf{T} \psi_N \cdot \partial_\nu \phi_\pi, \tag{11}$$

where f (f^*) and F (F^*) are, respectively, the coupling constant and the form factor at the πNN ($\pi N\Delta$) vertex. The values of f and f^* are taken as 1.008 and 2.156, respectively. For the form factors we have taken a monopole form,

$$F(t) = \frac{(\Lambda^2 - m_\pi^2)}{(\Lambda^2 - t)}, \tag{12}$$

where the length parameter Λ, which fit the $pp \to n\Delta^{++}$ data, is around 700 MeV/c and is taken same for F and F^*. t $(= \omega^2 - \mathbf{q}^2)$ is the four-momentum transfer.

To evaluate T_{fi}, we note, as shown in the earlier work from our group [16], that the main effect of distortion due to χ's in T_{fi} is the reduction in its magnitude. The dispersive effects are small. Also, it is known that the momentum dependence of the $H_{\rm int}$ in the range of the momentum transfer relevant for the $pp \to n\Delta^{++}$ process is weak [17]. In view of these, for evaluating $\langle H_{\rm int}\rangle$, we use asymptotic momenta of the continuum particles a, b, and Δ. For the πab vertex this gives

$$\langle|\Gamma_{\pi ab}(t)|^2\rangle \equiv \frac{1}{2}\sum_{\sigma_a\sigma_b} |\langle b, k_b|\mathcal{L}_{\pi ab}|k_a, a\rangle|^2 = 2\left|\frac{fF(t)}{m_\pi}\rho_{ba}\right|^2 t, \tag{13}$$

where ρ_{ba} is the transition density for the intrinsic structure in $a \to b$. For the (p,n) reaction, it is obviously unity.

The evaluation of the $\pi N\Delta$ vertex inside a nucleus, in general, is difficult. For a spin zero target nucleus, however, it is easy to work out. We obtain

$$\sum_{M_B\sigma_\Delta}\left|\langle\chi_b^-, \langle\chi_\Delta^-, \{\Delta, B\}|\sum_i \mathcal{L}_{\pi N\Delta}(i)|A\rangle, \chi_a^+\rangle\right|^2 = \langle|\Gamma_{\pi N\Delta}(t)|^2\rangle |F_{BA}(\mathbf{Q})|^2, \tag{14}$$

where

$$\langle|\Gamma_{\pi N\Delta}(t)|^2\rangle = \frac{1}{2}\sum_{\sigma_\Delta\sigma_N} |\langle\pi^+ N \to \Delta\rangle|^2 \approx \frac{2}{3}\left|\frac{f^*F^*}{m_\pi}\right|^2 [t - (\mu^2 - m_N^2 + t)^2/4\mu^2]. \tag{15}$$

N in the above equation can be a proton or a neutron in the nucleus.

The nuclear structure part $F_{BA}(\mathbf{Q})$ is given by

$$|F_{BA}(\mathbf{Q})|^2 = \sum_{N=n,p} C_N^\Delta \sum_{l,m} \frac{N(l)}{(2l+1)}|G_{lm}(\mathbf{Q})|^2, \tag{16}$$

where $N(l)$ is the number of "active" nucleons (neutrons or protons) in a shell of orbital angular momentum l. C_N^Δ is the isospin factor arising from the $N \to \Delta$ transition. Its value is 1 for $p \to \Delta^{++}$ transition and 1/3 for $n \to \Delta^+$ transition. $G_{lm}(\mathbf{Q})$ is the "distorted" momentum distribution of the nucleon, N, in the shell "lm" in the target nucleus. It is given by

$$G_{lm}(\mathbf{Q}) = (2\pi)^{-3/2}\langle\chi_b\chi_\Delta|\phi_{lm}(\mathbf{r})\chi_a\rangle. \tag{17}$$

$\mathbf{Q}$ $(= \mathbf{P}_a - \mathbf{P}_b - \mathbf{P}_\Delta)$ is the momentum of the recoiling nucleus in the laboratory.

The phase space factor [PS] in Eq. (3), for the energy-momentum distribution of the ejectile in laboratory works out as

$$\begin{aligned}[\mathrm{PS}] &= K\rho(\mu^2)d\mu^2 d\Omega_\Delta dE_b d\Omega_b \\ &= K\rho(\mu^2)(P_b/E_b)d\mu^2 d\Omega_\Delta dP_b d\Omega_b,\end{aligned} \tag{18}$$

where

$$K = \frac{m_a m_b \mu M_B}{2\pi^2}\frac{P_b {P_\Delta}^3}{2P_a[{P_\Delta}^2(E_i - E_b) - E_\Delta(\mathbf{P}_a - \mathbf{P}_b)\cdot\mathbf{P}_\Delta]}. \tag{19}$$

Here E_i is the total laboratory energy in the incident channel.

If, while measuring the energy spectrum of the ejectile, the emission angle and the mass of the delta are not resolved, the corresponding calculated cross section for the ejectile energy spectrum can be obtained by integrating Eq. (3) over Ω_Δ and μ^2. This gives

$$\frac{d^2\sigma}{dE_b d\Omega_b} = \int_{\mu_{mn}}^{\mu_{mx}} d\mu^2 \rho(\mu^2)\int d\Omega_\Delta K\langle|T_{fi}|^2\rangle, \tag{20}$$

TABLE I. Calculated nucleon optical potentials and maximum delta mass (μ_{mx}) at various nucleon energies. Except the last one, which corresponds to proton, all energies are neutron energies. μ_{mx} is for $1p$ shell nucleons. All quantities are in MeV.

T_N	V_N	W_N	μ_{mx}
300	-15	-32	1430
400	-11.5	-33	1340
450	-10.6	-34	1292
500	-10	-37	1244
600	-7.8	-44	1148
650	-6	-48	1100
830	+8	-80	-

where μ_{mn}=nucleon mass+m_π. The value of the upper limit, μ_{mx}, depends upon the ejectile energy. It increases with the decrease in the ejectile energy (see Table I).

For a proton target, the expression corresponding to Eq. (20) for the ejectile spectrum does not involve any integration over μ^2 or Ω_Δ. This happens due to absence of the recoiling nucleus. Because of this, in the (p,n) reaction, while for a proton target, the measured neutron energy spectrum has a direct correlation with the mass distribution $\rho(\mu^2)$ of the delta, for a nuclear target this correlation gets somewhat fuzzy. The energy spectrum, though still may show a peak, its position, compared to H target, can get shifted and the distribution broadened. The measured neutron energy spectrum (in coincidence with p and π^+) on the ^{12}C target [3], in fact, exhibits this feature. In comparison to the hydrogen target, this spectrum is significantly broadened and shifted somewhat toward lower momenta.

For the (^{3}He,t) reaction, even for the H target, the triton energy distribution gets modified from $\rho(\mu^2)$ due to the ^{3}He$\to t$ transition density factor.

Since, in our model, the p and π^+ in the exit channel are produced by the decay of Δ^{++}, the ejectile spectrum in coincidence with a p and π^+, if integrated over the four momenta of p and π^+, can also be given by Eq. (20).

III. RESULTS AND DISCUSSION

Measurements in charge-exchange reactions with $p\pi^+$ in coincidence with the ejectile have been done in (p,n) and (^{3}He,t) reactions at 831 MeV and 2 GeV beam energies, respectively. Here, we analyze both these data on ^{12}C target nucleus. The common inputs, which both these reactions require, are the bound-state wave functions and the prescription for the distortion of the outgoing delta.

The ground state of ^{12}C is assumed to have the filled $1s_{1/2}$ and $1p_{3/2}$ shell configuration. The cross section is calculated for the conversion of a nucleon in any of these shells. For the nucleon radial wave functions in these shells we have used the Woods-Saxon as well as the oscillator forms. However, the difference found with these two forms in the final cross section is insignificant. Hence, in the following, we present the results with the oscillator form only. The oscillator length parameter b is

TABLE II. Some typical values of calculated delta optical potentials. All quantities are in MeV.

T_Δ	V_Δ	W_Δ	μ
$\leq$ 100	-33	-45	-
150	-28	-41	1170
200	-18	-30	1100

taken equal to 1.66 fm [18]. This value of b is consistent with the electron scattering data on ^{12}C.

Since we calculate the cross sections for the ejectile energy spectrum integrated over the delta angle, the delta energy in our calculations varies over a wide range. To describe the delta distortion, we, therefore, require the delta optical potential over this range of energy. For $T_\Delta \leq 100$ MeV we refer to the delta-hole model of Hirata *et al.* [19] for a pi-nucleus interaction in the range of the (3,3) resonance and take $W_\Delta = -45$ MeV and $V_\Delta = -33$ MeV. For $T_\Delta > 100$ MeV we use the high energy ansatz and write

$$V(r) = (i+\alpha)W\rho(r)/\rho(0), \tag{21}$$

where the imaginary part

$$W_\Delta = -\frac{\hbar k_{\Delta N}}{2E_{\Delta N}}\sigma_T^{\Delta N}\rho_0. \tag{22}$$

$\sigma_T^{\Delta N}$ is the delta-nucleon total cross section. It is the sum of the elastic and the reactive part, $\sigma_T^{\Delta N} = \sigma_{\rm el}^{\Delta N} + \sigma_r^{\Delta N}$. Assuming that the delta and proton elastic dynamics are not very different we write $\sigma_{\rm el}^{\Delta N} \approx \sigma_{\rm el}^{NN}$ and $\alpha_{\Delta N} \approx \alpha_{NN}$. For the reactive part, since up to about T_Δ=1.5 GeV the main reactive channel in ΔN scattering is $\Delta N \to NN$ [20], using the reciprocity theorem we write

$$\begin{aligned}\sigma_r^{\Delta N} &\approx \sigma^{\Delta N\to NN}\\ &= \frac{1}{2}\frac{k_{NN}^2}{2k_{\Delta N}^2}\sigma(pp\to n\Delta^{++}),\end{aligned} \tag{23}$$

where k_{NN} is the momentum in the NN center of mass, with the same energy as available in the ΔN center of mass. An extra factor 1/2 is introduced to account for the identity of particles in the final state. The resultant optical potentials are listed in Table II.

A. (p,n) reaction

For neutron and proton, the distorting potentials are obtained using the high energy ansatz as given by Eqs. (21) and (22). σ_T^{NN} and α_{NN} in it are taken from the experimental data on nucleon-nucleon scattering. The value of ρ_0 is taken equal to 0.17 fm^{-3}. With these input the nucleon optical potentials at different energies are listed in Table I.

The radial shapes of the different potentials are approximated by the charge density distribution of ^{12}C, i.e.,

$$\rho(r)/\rho(0) = [1+\alpha r^2/\beta^2]e^{-r^2/\beta^2}, \tag{24}$$

where the parameters α and β, as determined by the elastic electron scattering data [21], are $\alpha = 1.247$ and $\beta = 1.649$ fm. The calculated neutron energy spectrum, after integrating over the delta mass and its emission angle, at 1.5 GeV/c beam momentum and at zero degree neutron angle is shown in Fig. 1. If it is assumed that all the $p\pi^+$ events arise from the decay of Δ^{++}, the experiments with which these results should be compared are the neutron energy spectrum measured in coincidence with $p\pi^+$ and integrated over their 4π angle and energies. The KEK measurements of Chiba *et al.* [3] on the neutron spectrum in coincidence with the $p\pi^+$ are of this kind, except that the detector geometry in this experiment is such that all the $p\pi^+$ events are not recorded. Chiba *et al.* estimate that in the hydrogen target, where all the $p\pi^+$ events necessarily arise from the decay of Δ^{++}, the recorded events account for about 65% of the total events. We assume the same factor for the ^{12}C target. The experimental data on ^{12}C are shown in Fig. 1. To correspond to these data, the calculated cross sections are also reduced to 65% of their calculated values. It is remarkable to see that the calculated spectrum agrees very well with the measured one, in magnitude as well as in shape.

Very often the question is being asked, in the field of delta excitation, about the effect of nuclear distortion on the neutron spectrum. To explore this, in Fig. 2 we present the calculated results without the distortion of any continuum particle along with those including the distortion of all the continuum particles. The comparison of these results show that, in the $(p, n\Delta)$ channel, the main effect of the distortion is the reduction in the magnitude of the cross section. Full distortion reduces the cross sections approximately by a factor of 9. If we include the distortion of delta only, this gives an approximate reduction by a factor of 2. The effect on the position of the peak is small. The distortion shifts it by about 15 MeV/c toward the lower neutron momentum. This is in agreement with the experimental observation where the neutron peak, seen in coincidence with $p\pi^+$ in ^{12}C, is found to be shifted only slightly toward the lower neutron momentum compared to that in the hydrogen target.

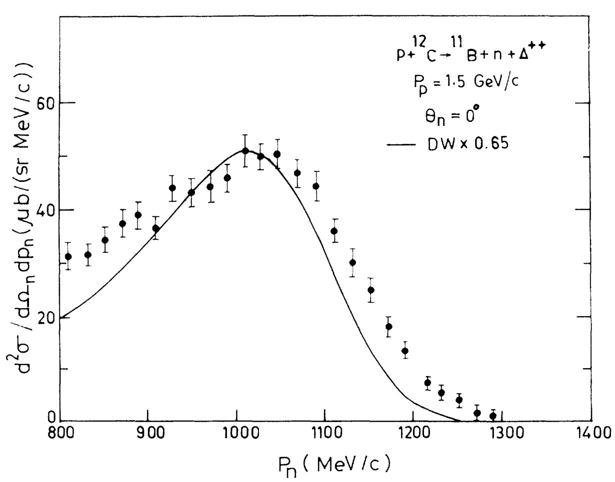

FIG. 1. The calculated neutron momentum spectrum at 0° for the $(p, n\Delta^{++})$ channel integrated over all emission angles and energies of the delta. The experimental points are from Ref. [3]. To correspond to the experimental data, which includes only the 65% of the total events, the calculated results are multiplied by 0.65 (see text).

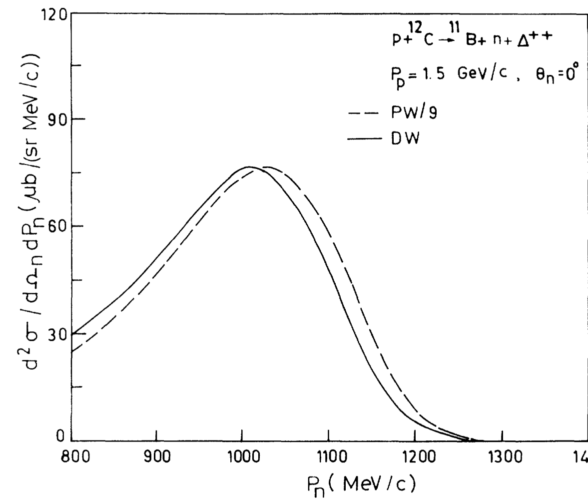

FIG. 2. Effect of distortion in $^{12}C(p, n\Delta^{++})^{11}B$ reaction. The continuous curve includes the distortion of all the continuum particles, while the dashed curve uses plane waves for them.

B. (^{3}He,t) reaction

The spin-isospin $^3\text{He}\to t$ transition density, $\rho_{ba}(q)$, which is required in the high momentum transfer region, is approximated by the following magnetic form factor of ^{3}He:

$$\rho(q) = [\exp(-a^2q^2) - b^2q^2\exp(-c^2q^2)], \tag{25}$$

with $a = 0.645$ fm, $b = 0.456$ fm, and $c = 0.821$ fm. This form factor has been extracted up to q^2=16 fm^{-2} by McCarthy *et al.* [22] from the electron scattering data between 170 and 750 MeV on ^{3}He.

For the distortion of ^{3}He and t, as in the earlier section, we use the eikonal form. However, the distortion factors, D's, now are written in terms of the phase shifts, $\delta(b)$, of these particles, i.e.,

$$D_{^3\text{He}}D_t \approx \exp[2i\delta(b)]. \tag{26}$$

This approximation has been used successfully in the literature in the situation of strong absorption by Johnson and Bethe [23] for pions around the (3,3) resonance and by Jain *et al.* [24] for alphas in the $(\alpha, 2\alpha)$ reaction.

In our calculations, for 2 GeV beam energy, we need phase shifts $\delta(b)$ between 1 and 2 GeV. However, in this region, information on the phase shifts exists only for the alpha particle at 1.37 GeV on calcium isotopes [25]. Here, $\exp[2i\delta(b)]$, which gives a good description of the α-elastic scattering data, is found to be purely real and has a one minus Woods-Saxon form. The values of the radius parameter, $r_0(R = r_0A^{1/3})$, and the diffuseness, a, of this functional form are found to be 1.45 fm and 0.68 fm, respectively. For our purpose of describing the distortion of ^{3}He and t, we have taken the same form and same parameters. Because of the relatively loose structure of mass 3 particles, it is likely that the diffuseness parameter a may be larger than 0.68 fm. However, in the absence of any firm information on it we have not incorporated this fact.

In Fig. 3 we show our calculated triton energy spectrum, integrated over all emission angles and energies of the delta, for 2 GeV beam energy and ^{12}C target. For comparison, the measured triton spectrum from Saturne [4] in coincidence with p and π^+ is also shown. However, to compare these data with the calculated cross sections, the latter are multiplied by a reduction factor. This is needed to remove from the calculated cross sections the $p\pi^+$ events which are not detected in the experiment due to angle and energy cuts in the detecting system. A CASCADE calculation due to Gaarde *et al.* [26], on this experiment, suggests that this reduction factor could be around 5. We have taken this value. Comparison of two results in Fig. 3 shows that our calculations reproduce the shape of the experimental distribution well. The magnitude of the cross sections is given with in a factor of about 2.5.

The effect of distortion of continuum particles on the cross section in this reaction is much larger than that in the (p,n) reaction. The distortion of all continuum particles reduces the cross section by about a factor of 37. The position of the peak, however, like the (p,n) reaction, is effected only marginally. It gets shifted toward lower triton energy by about 10 MeV.

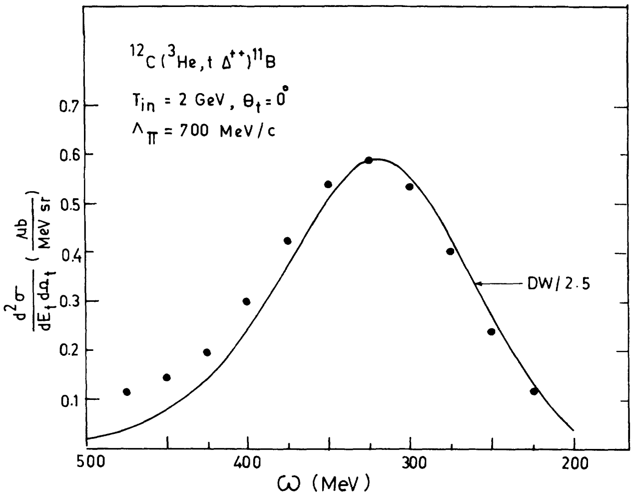

FIG. 3. The calculated energy loss ω $(= E_{^3\mathrm{He}} - E_t)$ spectrum at 0° for the (^{3}He, $t\Delta^{++}$) channel, integrated over all emission angles and energies of the delta. The experimental points are from Ref. [4]. To incorporate in the calculated cross sections the detection cuts in the experiment and consequent loss of events, the calculated results are divided by a factor of 5 (see text). 2.5 is an additional factor.

IV. CONCLUSIONS

Thus, from the analysis presented above, we conclude that in the delta region of the ejectile spectrum in the charge-exchange reactions, like (p,n) and (^{3}He,t), the $p\pi^+$ events seen in coincidence with the ejectile can be accounted mainly by the decay of the Δ^{++} produced in the nucleus. The delta is produced in one step by the interaction of the elastically scattered projectile with a proton in the target nucleus. The interaction responsible for it is the relativistic pseudovector one pion-exchange Lagrangian, with its parameters such that it reproduces the spin averaged cross-section data on the $pp \to n\Delta^{++}$ reaction in the free state.

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