Delta excitations in heavy nuclei induced by (^{3}He,t) and (p,n) reactions

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Delta excitations in heavy nuclei, induced by charge exchange reactions, are studied using the surface response model. The residual pion-exchange interaction and the self-energy of the delta in a nuclear medium is included in the random-phase-approximation response. The peak position observed in (^{3}He,t) reactions can be explained by the self-energy of the delta extracted from pion-nucleus scattering, and the magnitude of the cross section is consistent with Glauber theory. The comparison to (p,n) data is reasonable; contributions from neutron decay of the delta, which are left out in the calculations, constitute a substantial experimental background.

I. INTRODUCTION

Charge exchange reactions at intermediate energies are a promising tool for probing the isovector spin response of heavy nuclei. Excitations of the delta resonance have been studied experimentally both in (p,n) reactions[1] and more recently in (^{3}He,t) reactions.[2] A striking feature is a strong peak with a position that is insensitive to the mass of the target nucleus. In (^{3}He,t) reactions on heavy nuclei the peak position is about 250 MeV at forward angles and it deviates significantly from predictions based on quasi-free delta production. In (p,n) reactions[1] the peak position seems to be shifted towards larger excitation energies (about 310 MeV) and a substantial cross section is observed at even higher excitations, in contrast to (^{3}He,t) reactions.

In the present paper we study charge exchange reactions in the delta region using the surface response model of Refs. 3—5, which is based on Glauber theory and the surface response of semi-infinite nuclear matter. This model will immediately give the observed feature that the peak position is insensitive to the mass of the target nucleus. The target dependence enters mainly via the effective number of nucleons that contribute to the reaction. These nucleons are located near the surface of the target nucleus due to a strong absorption in the interior of the nucleus.

To account for the delta excitation we need to specify the elementary delta production mechanism in nucleon-nucleon collisions. We use the meson-exchange Hamiltonian theory of Ref. 6, which gives a good description of nucleon-nucleon scattering up to 1 GeV. The phenomenological parameters are different from the values commonly used, in particular with respect to the rho meson exchange, which is strongly suppressed in the delta excitation. We shall, therefore, ignore contributions from rho mesons. We note that our approach is different from the Feynman-diagram approach[7] in defining delta excitations.

The medium effects on the delta excitation and propagation are treated in the surface response model. We consider the effects of the residual pion exchange interaction and the self-energy of the delta. The residual pion exchange interaction is treated in the random phase approximation (RPA). The delta self-energy has been consistently investigated[8] within the πNN Hamiltonian theory of Ref. 6, and a microscopic understanding was obtained for the absorptive part of the self-energy extracted from the delta-hole model of pion-nucleus scattering. We shall follow the method of Ref. 8 for the delta self-energy as closely as possible.

In Sec. II we use the formulation of Ref. 6 to write the cross section for delta production in nucleon-nucleon collisions. The validity of the model is tested by comparison with measured exchange reactions on protons.[9,10] In Sec. III the formalism is extended to define delta excitations in p(^{3}He,t) reactions taking into account the composite structure of the projectile. It is then quite simple, as discussed in Sec. IV A, to incorporate this model into the surface response model and generate differential cross sections for reactions on heavy nuclei. We present our results in Sec. IV B, and Sec. V contains the conclusions of our study.

II. DELTA EXCITATIONS IN NUCLEON-NUCLEON COLLISIONS

The inclusive cross section for nucleon-nucleon collisions in the delta region can be derived from the meson-exchange theory of delta excitation.[6] The basic mechanism for the reaction is shown in Fig. 1. We shall only consider the contribution from spectatorlike particles (denoted by p'_1 in Fig. 1) and ignore the contribution from the delta decay (p'_2 in Fig. 1). The derivation is tedious mainly due to the kinematics of the three-body πNN final state. We shall not give a detailed presentation here but only state the result and write it in a form that makes it easy to generalize to (^{3}He,t) reactions. Thus we write the dependence on the projectile and the detected particle explicitly in order to distinguish them from the target nucleon.

The expression that we obtain for the double differential laboratory cross section for detecting the spectatorlike nucleon in nucleon-nucleon collisions is

$$\frac{d^2\sigma}{d\Omega\, d\omega}=\frac{1}{(2\pi)^2}\frac{p'_1}{p_1}E_1(p_1)E'_1(p'_1)\,|\,V_{\mathrm{N}\Delta,\mathrm{NN}}(q_c)\,|^2 \times C f_{\mathrm{DW}} S(q,\omega)\ . \tag{1}$$

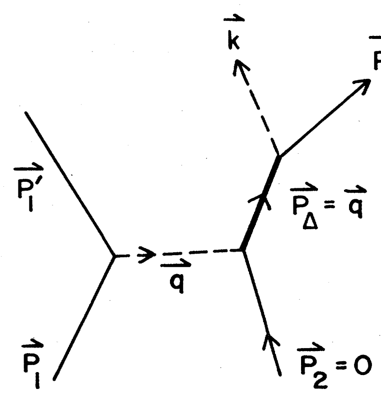

FIG. 1. Diagram for the basic delta production mechanism in nucleon-nucleon collisions.

In the following we explain the different factors in this expression. The momentum variables p_1, p'_1, and q are shown in Fig. 1. The energies E_1 and E'_1 refer to the total energies of the projectile and the detected particle. The energy loss ω and momentum transfer q are also given in the laboratory system.

The meson-exchange interaction $V_{N\Delta,NN}$ is taken from Ref. 6. In the Hamiltonian formulation of the problem[11] it is defined in terms of the momentum transfer q_c in the nucleon-nucleon center of mass frame,

$$V_{N\Delta,NN}(q_c) = -\frac{f_{\pi NN} f^*_{\pi N\Delta}}{m_\pi^2} \left[\frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 + q_c^2} \right]^2 \times \frac{\sigma_1 \cdot \mathbf{q}_c \mathbf{S}_2 \cdot \mathbf{q}_c}{q_c^2 + m_\pi^2} \tau_1 \cdot \mathbf{T}_2 . \quad (2)$$

The momentum transfer $\mathbf{q}_c$ can be expressed by the laboratory momenta $\mathbf{p}_1$ and $\mathbf{q}$ as follows

$$\mathbf{q}_c = \mathbf{q} - \frac{1}{2} \left[\frac{m_\Delta - m}{m_\Delta + m} \right] \frac{\mathbf{p}_1}{A_1} , \quad (3)$$

where A_1 is the mass number of the projectile ($A_1 = 1$ for nucleon-nucleon collisions).

The factor C is determined by the kinematics of the delta decay and the transformation of the NN-NΔ amplitude from the center of mass to the laboratory frame,

$$C = (\omega + m) \frac{E_N(K) + E_\pi(K)}{E_N(K) E_\pi(K)} \frac{E'_1(Q') E_\Delta(Q') E_1(Q) E_N(Q)}{E'_1(p'_1) E_\Delta(q) E_1(p_1) m} . \quad (4)$$

The total energy is denoted by E_N for the target nucleon, E_π for pions, and E_Δ for the delta. The momentum K is associated with the delta decay. It is determined by the invariant mass m^* of the delta-excited nucleon as follows

$$E_N(K) + E_\pi(K) = m^* = \sqrt{(m+\omega)^2 - q^2} . \quad (5)$$

The momentum Q in Eq. (4) is evaluated in the center of mass frame of the projectile and the target nucleon, and it is determined by

$$E_1(Q) + E_N(Q) = \sqrt{[E_1(p_1) + m]^2 - p_1^2} . \quad (6)$$

The momentum Q' is similarly associated with the detected particle and the delta-excited target nucleon,

$$E'_1(Q') + E_\Delta(Q') = \sqrt{[E'_1(p'_1) + E_\Delta(q)]^2 - p_1'^2} . \quad (7)$$

The factor f_{DW} is a distortion factor that originates from the NN-NΔ transition operator, $T_{N\Delta,NN} = \Omega_{NN} V_{N\Delta,NN}$, where Ω_{NN} describes the nucleon-nucleon scattering before the delta decay takes place in the final state. We neglect the off-shell effect of Ω_{NN} and treat $f_{DW} = |\Omega_{NN}|^2$ as an adjustable parameter in order to reproduce the magnitude of measured cross sections for the basic p(p,n) reaction.

Finally, the response function $S(q,\omega)$ is determined by the position and the width of the delta resonance

$$S(q,\omega) = \frac{\Gamma(K)}{2\pi} \left\{ \left[m + \omega - m_\Delta - \frac{q^2}{2(m+\omega)} \right]^2 + [\Gamma(K)/2]^2 \right\}^{-1} . \quad (8)$$

This nonrelativistic approximation is quite accurate in the cases we study, and it is easy to handle and include in the surface response model (see below). We parametrize the width of the delta as in Ref. 12,

$$\Gamma(K) = \Gamma_0 \left[\frac{K}{K_0} \right]^3 \left[\frac{K_0^2 + \Lambda_\Gamma^2}{K^2 + \Lambda_\Gamma^2} \right]^2 . \quad (9)$$

Here K is the πN momenta determined by Eq. (5), and K_0 is the value one obtains for $m^* = m_\Delta$.

The parameters of our model are taken from Refs. 6, 8, and 12,

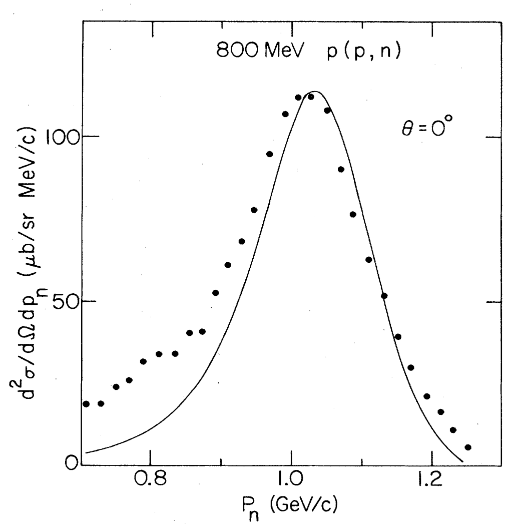

FIG. 2. Differential cross sections for 800 MeV (p,n) reactions on protons at $\theta = 0°$, as functions of the momentum of the detected neutron. The experimental results (dots) are from Ref. 9. The calculated curve for spectatorlike neutrons was obtained from Eq. (1).

TABLE I. Spin-isospin factors in the cross section Eq. (1) due to the operator $\sigma_1 \cdot \hat{\mathbf{q}} \mathbf{S}_2 \cdot \hat{\mathbf{q}} \tau_1 \cdot \mathbf{T}_2$ in the pion-exchange interaction. The factors are given for (p,p′) and (p,n) reactions on different targets, both when the detected particle is a spectator and when it comes from the delta decay.

	Reaction	on p	on n	on ^{40}Ca
Spectator	(p,p′)	$\frac{4}{9}$	$\frac{4}{9}$	$\frac{4}{9}$
	(p,n)	$\frac{4}{3}$	$\frac{4}{9}$	$\frac{8}{9}$
Decay	(p,p′)	$\frac{44}{27}$	$\frac{4}{9}$	$\frac{28}{27}$
	(p,n)	$\frac{4}{27}$	$\frac{4}{9}$	$\frac{8}{27}$

$$m_\Delta - m = 296 \text{ MeV}, \quad \Gamma_0 = 120 \text{ MeV} ,$$
$$\Lambda_\pi = 650 \text{ MeV}, \quad \Lambda_\Gamma = 300 \text{ MeV} , \tag{10}$$
$$f^*_{\pi N\Delta} = 2 f_{\pi NN} = 2 ,$$

and we use the convention:

$$\langle \tfrac{1}{2} || \sigma_1 || \tfrac{1}{2} \rangle = \sqrt{6}; \quad \langle \tfrac{3}{2} || \mathbf{S}_2 || \tfrac{1}{2} \rangle = 2 .$$

The value of Λ_π has been extracted to fit basic nucleon-nucleon scattering data,[6] and it is consistent with a vanishing small effect of ρ meson exchange.

The cross section for an 800 MeV p(p,n) reaction at zero degrees is shown in Fig. 2. The adjusted value of f_{DW} is 0.15, and the position of the measured[9] peak is quite well reproduced. Some discrepancy is seen at smaller neutron momenta, probably due to contributions from neutron decay of the delta. The decay channel contributes 10% to the total p(p,n) cross section in the delta region. This can be seen from Table I, where we list for different reactions the numerical factor in the cross section that originates from the spin-isospin operators in Eq. (2).

III. (^{3}He,t) REACTIONS ON FREE NUCLEONS

At first glance a (^{3}He, t) reaction looks like a (p,n) reaction, where one of the protons in the ^{3}He nucleus is replaced by a neutron. We shall therefore base our calculation of (^{3}He,t) cross sections on the expressions given in Sec. II. There the dependence on the projectile and the detected particle is explicitly displayed. For p_1 and E_1 we shall now use the momentum and total energy of the ^{3}He nucleus, and for p_1' and E_1' we use the same quantities for the detected triton. The mass number A_1 in Eq. (3) is now three. Let us call the exchange cross section we obtain in this way, $(d^2\sigma/d\Omega\, d\omega)_0$. To account for the spatial extension of the charge distribution of ^{3}He we include the square of the charge form factor $F_c(q_\mu^2)$ and use the following expression

$$\frac{d^2\sigma}{d\Omega\, d\omega} = \left[\frac{d^2\sigma}{d\Omega\, d\omega} \right]_0 | F_c[q^2 - (\omega/c)^2] |^2 \tag{11}$$

for (^{3}He,t) reactions on free nucleons.

The elementary delta production amplitude already contains the nucleon form factor, and we shall therefore use the ^{3}He point-particle form factor obtained from a three-body Faddeev calculation[13] in our calculations. The form factor is normalized to one at zero momentum transfer, so we have tacitly assumed that only one of the protons can contribute to the exchange reaction. This is consistent with the fact that one of the final neutron states in the triton is already occupied. Anyway, we adjust the distortion factor f_{DW} in Eq. (1) to fit absolute cross sections at zero degrees. The validity of the model is then tested in its prediction for larger angles.

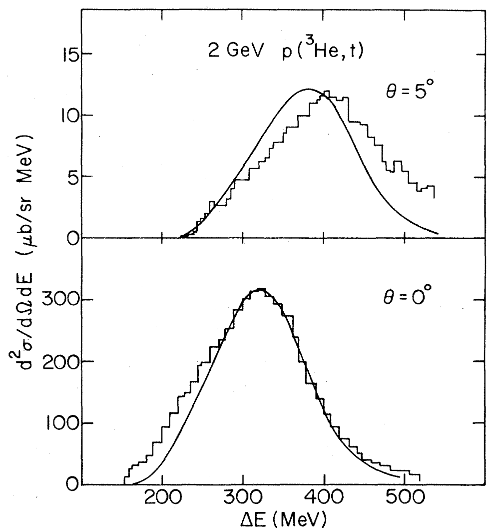

FIG. 3. Differential cross sections for 2 GeV (^{3}He,t) reactions on protons at $\theta = 0°$ and 5°, as functions of the energy loss of the detected triton. The experimental results (histograms) are from Ref. 10. The calculated curve is based on Eq. (11), using the point-charge form factor of ^{3}He from Ref. 13.

The results for 2 GeV (^{3}He,t) reactions on free protons are shown in Fig. 3 with $f_{\mathrm{DW}} = 0.124$. The peak position as well as the overall shape of the measured cross section[10] is very well reproduced at zero degrees. The prediction at five degrees is not unreasonable considering the fact that the cross section has dropped by a factor of 30. In the calculation this is achieved mainly by the strong dependence of the form factor on the momentum transfer. In fact, the peak positions in Fig. 3 are also sensitive to the form factor. Our approach is clearly different from the approach of Ref. 10, where an attempt was made to extract a three-nucleon form factor from fitting the data at all angles.

In contrast to the p(p,n) cross section shown in Fig. 2, the agreement in Fig. 3 at higher excitations is very good, which indicates that a contribution from the delta decay is unimportant for (^{3}He,t) reactions. The neutron decay of a delta, bound to a neutron and a proton, will probably have a very small branch to a final triton nucleus.

IV. EXCHANGE REACTIONS ON HEAVY NUCLEI

In the surface response model[3–5] the inelastic cross section for nucleon-nucleus collisions is calculated as a product of the elastic nucleon-nucleon cross section, the surface response of semi-infinite nuclear matter, and a normalization constant. The latter two quantities are determined consistently from Glauber theory for single scattering on heavy nuclei.

In the following we modify this model slightly in order to describe exchange reactions on heavy nuclei. The basic cross sections for (p,n) and (^{3}He,t) reactions, Eqs. (1) and (11), already contain a response function due to the width of the delta resonance. We shall therefore base our calculations directly on these formulas and only modify the response function $S(q,\omega)$ to account for the Fermi motion and the interactions in a heavy nucleus. We assume for simplicity that the neutron and proton densities are identical and use the average spin-isospin factor of $\frac{8}{9}$ to calculate the exchange cross section, cf. Table I.

A. Response functions and interactions

We use the local Fermi gas approximation to calculate the surface response of semi-infinite nuclear matter. This approximation is discussed in Ref. 5 and it is justified for large momentum transfers. For exchange reactions in the delta region the momentum transfer is also quite large, even at forward angles due to the large excitation energy.

The free polarization operator for delta-hole excitations in infinite nuclear matter is

$$\Pi^0_{\Delta h}[\rho(z),q,\omega] = \frac{4}{(2\pi)^3} \int_F d\mathbf{k}\{[\epsilon_{\Delta h} - \omega - i\Gamma(K)/2]^{-1} + [\epsilon_{\Delta h} + \omega + i\Gamma(K)/2]^{-1}\} . \tag{12}$$

The integration is over all momenta k inside the Fermi sphere, and the Fermi momentum is determined by the local density $\rho(z)$, where z is the coordinate perpendicular to the slab surface. We have here included the finite width $\Gamma(K)$ of the delta resonance. This width is still given by Eq. (9) but the argument K determined in Eq. (5) by the invariant mass of the delta-excited target nucleon is affected by the Fermi motion. The delta-hole excitation energy is [cf. Eq. (8)]

$$\epsilon_{\Delta h} = m_\Delta + \frac{(\mathbf{k}+\mathbf{q})^2}{2\left[m+\omega+\dfrac{k^2}{2m}\right]} - m - \frac{k^2}{2m} . \tag{13}$$

To be consistent with the model of $V_{\mathrm{N}\Delta,\mathrm{NN}}$, Eq. (2), the pion-exchange interaction between delta-hole states is taken to be

$$V_{\mathrm{N}\Delta,\mathrm{N}\Delta} = -\left[\frac{f^*_{\pi\mathrm{N}\Delta}}{m_\pi}\right]^2 \left[\frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 + q_c^2}\right]^2 \frac{\mathbf{S}_1^+\cdot\mathbf{q}_c\,\mathbf{S}_2\cdot\mathbf{q}_c}{q_c^2+m_\pi^2} \times T_1^+\cdot\mathbf{T}_2 , \tag{14}$$

where q_c is the momentum transfer, Eq. (3), in the nucleon-nucleon center of mass system.

Equations (12) and (14) are used to evaluate the RPA polarization operator

$$\Pi_{\Delta h} = (1 - \Pi^0_{\Delta h} V_{\mathrm{N}\Delta,\mathrm{N}\Delta})^{-1}\Pi^0_{\Delta h} . \tag{15}$$

Another important interaction is the absorption (annihilation) of the delta in a nuclear medium. It is induced by $\mathrm{N}\Delta\rightarrow\mathrm{NN}$ transitions during the delta propagation in the nuclear medium. Its effect is therefore beyond the RPA treatment of the delta-hole propagation. The associated dynamics can conveniently be described by a complex potential in the delta propagator. In the local density approximation the imaginary part of this potential can be deduced[8] from the delta-hole model of pion-nucleus scattering. Its value is about 40 MeV in light nuclei. A theoretical attempt[8] to derive this empirical value from the meson exchange Hamiltonian of Ref. 6 shows that only 60% is due to the two-body $\mathrm{N}\Delta\rightarrow\mathrm{NN}$ interaction. This implies that multinucleon processes must play an important role. The real part of the delta-nucleus potential is not well defined in the phenomenological delta-hole model. We use the theoretical value[8] of ~ -30 MeV.

In our calculations based on Eq. (15), the above information about the delta-nucleus interaction is equivalent to changing the delta mass and width parameter to

$$m_\Delta - m = 266 \text{ MeV and } \Gamma_0 = 200 \text{ MeV} . \tag{16}$$

Pion-nucleus scattering takes place mainly in the surface region, so we feel that it is reasonable to apply empirical values in the calculation of the surface response. However, the values given above have been deduced from pion scattering on light nuclei ($A<16$), and they should therefore be considered as qualitative for the reactions we study.

In the phenomenological approach based on Eq. (16) any interaction other than Δ or π multiple scattering induced by $V_{\mathrm{N}\Delta,\mathrm{N}\Delta}$ has been included in the added delta-nucleus complex potential. We therefore ignore Landau-Migdal short-range correlations when calculating the RPA response.

The field $F(z)$ that generates the surface response is determined consistently from Glauber theory and has been discussed in detail in Ref. 5 Sec. II B. The associated response function is obtained from the RPA polarization operator as follows

$$S(q,\omega) = -\frac{1}{\pi}\mathrm{Im}\int dz\,|F(z)|^2\Pi_{\Delta h}[\rho(z),q,\omega] \times \frac{N_{\mathrm{eff}}}{\sigma^{(1)}} . \tag{17}$$

Here $\sigma^{(1)}$ is the total single-scattering cross section from Glauber theory and N_{eff} is the effective number of target nucleons that contribute; $N_{\mathrm{eff}} = \sigma^{(1)}/\sigma_{\mathrm{N}}$, where σ_{N} is the total nucleon-nucleon cross section (cf. Ref. 3). The normalization has been chosen such that this response function can be used directly in Eq. (1) to obtain the cross section for (p,n) or (p,p′) reactions on heavy nuclei. For (^{3}He,t) reactions we further perform the modifications discussed in Sec. III and include the ^{3}He point charge form factor according to Eq. (11).

B. Results

We have already tested our model of charge exchange reactions in the delta region by studying the basic p(p,n) and p(^{3}He,t) reactions. Hereby the only free parameters of the model, viz., the distortion factors $f_{\rm DW}$ in Eq. (1), were fixed for each reaction. In order to calculate the same exchange reactions on heavy nuclei we have to specify the absorption cross section that goes into the Glauber calculation. The nuclear density of the target nucleus is taken from Ref. 14.

The calculated cross sections for an 800 MeV (p,n) reaction on ^{208}Pb at zero degrees are shown in Fig. 4 together with the experimental result of Ref. 1. A total nucleon-nucleon cross section of $\sigma_{\rm N}=40$ mb was used, which yields $N_{\rm eff}=8.4$ in the Glauber calculation.

The pion-exchange interaction in the nucleus is seen to increase the cross section (dashed-dotted curve) compared to the free response calculation (dashed curve). There is also a minor shift of the peak position towards lower excitations, from 325 MeV to about 300 MeV.

A more dramatic shift of the peak position to about 260 MeV of excitation is observed when we furthermore include the medium effect on the delta self-energy according to the prescription of Eq. (16) (fully drawn curve). The calculated peak position seems to be wrong. There is, however, a kind of shoulder in the data at the calculated peak position. Such a shoulder is present at the same position in most of the (p,n) reactions shown in Fig. 5 of Ref. 1. Our calculation is not inconsistent with the data since we have ignored the contribution from neutron decay of the delta. From Table I we estimate that this channel will exhaust at least 25% of the total (p,n) cross section.

The calculated cross section for a 2 GeV (^{3}He,t) reaction on ^{40}Ca at zero degrees is shown in Fig. 5 together with the data of Ref. 2. We used a ^{3}He-nucleon cross section of 120 mb (i.e., three times the total nucleon-nucleon cross section) in the Glauber calculation, which yields $N_{\rm eff}=1.8$. The dashed curve was obtained from the free response, i.e., without any residual interactions in the nucleus. This energy loss distribution has about the same peak position, 310 MeV, and width, 136 MeV, as in the reaction on protons shown in Fig. 3. This is somewhat surprising, since one would expect that the Fermi motion would increase the width. However, only the tail of the density is probed in the surface response model due to the large ^{3}He-nucleon cross section used in the Glauber calculation.

The dot-dashed curve shows the effect of the pion-exchange interaction in the RPA surface response. The effect is much weaker than for the (p,n) reaction shown in Fig. 4, which is a consequence of the much lower density being probed in the (^{3}He,t) reaction.

The fully drawn curve in Fig. 5 shows the cross section we obtain when we also include the effect on the delta self-energy [Eq. (16)]. The calculated peak position at 250 MeV is in good agreement with the experiment. The peak height is also consistent with the data. Detailed calculations show as expected that the peak position is insensitive to the mass of the target nucleus. An example is shown in Fig. 6 for reactions on ^{208}Pb.

The most striking difference between Figs. 4 and 5 is the large discrepancy between theory and experiment in the (p,n) reaction at higher excitations, whereas the agreement is much better for the (^{3}He,t) reaction. We associate this discrepancy, as already mentioned, with the neutron decay of the delta, which is not included in the calculation and which we expect to be unimportant for (^{3}He,t) reac-

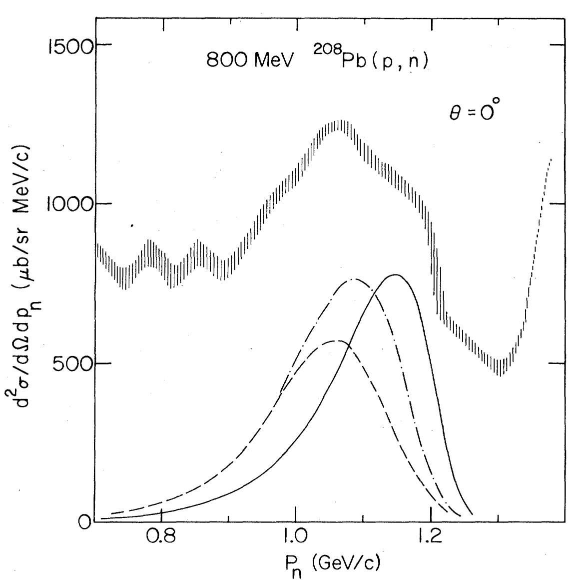

FIG. 4. Differential cross sections for 800 MeV (p,n) reactions on ^{208}Pb at $\theta=0°$, as functions of the momentum of the detected neutron. The experimental results (hatched curve) are from Ref. 1. The calculated curves are based on Eq. (1), using response functions of semi-infinite nuclear matter. The dashed curve was obtained from the free response, the residual pion-exchange interaction is included in the RPA response for the dashed-dotted curve, and the fully drawn curve includes both pion exchange and the phenomenological self-energy of the delta according to Eq. (16).

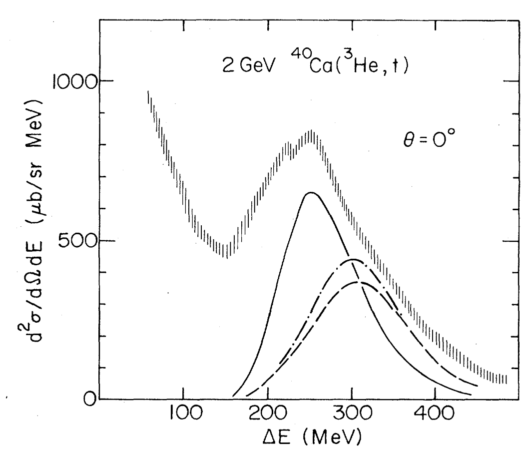

FIG. 5. Differential cross sections for 2 GeV (^{3}He,t) reactions on ^{40}Ca at $\theta=0°$, as functions of the energy loss of the detected triton. The experimental results (hatched curve) are from Ref. 2. The calculated curves are based on Eq. (11), using response functions of semi-infinite nuclear matter. The dashed curve was obtained from the free response, the residual pion-exchange interaction is included in the dashed-dotted curve, and the fully drawn curve includes both pion exchange and delta self-energy in the nuclear medium.

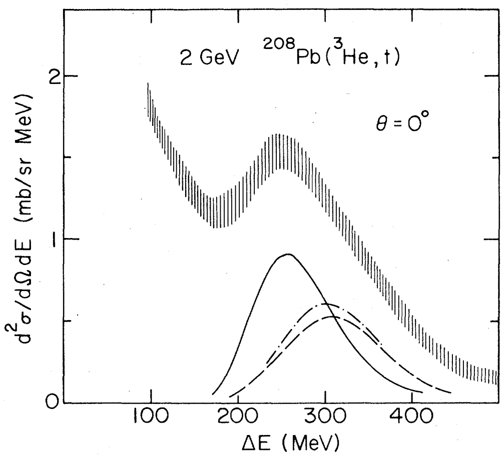

FIG. 6. Similar to Fig. 5 for reactions on ^{208}Pb.

tions. We expect an even larger discrepancy for (p,p′) reactions on heavy nuclei, since the proton decay background is about 70% of the total (p,p′) cross section, cf. Table I.

V. CONCLUSIONS

We have studied (p,n) and (^{3}He,t) charge exchange reactions on heavy nuclei in the delta region. We used the pion-exchange theory for delta excitation to develop a model for the basic reactions on free nucleons. The contribution from the delta decay was ignored and considered as a background in the comparison with experiments. The model was tested against measured cross sections for reactions on protons.

We used the local Fermi gas approximation to generalize this model to describe reactions on heavy nuclei. The response of the nucleus was calculated consistently with Glauber theory for single scattering as in the surface response model. The response function included the effect of Fermi motion, the pion-exchange interaction between delta-hole states, and the phenomenological self-energy of the delta in a nuclear medium. The target dependence enters via Glauber theory and determines the absolute cross section. The peak position is determined by the interactions in the nuclear medium and it is insensitive to the mass of the target nucleus.

The model accounts quite accurately for the main features of the observed delta peak in (^{3}He,t) reactions on heavy nuclei. The peak position is shifted to lower excitation energies than predicted from the free response. The shift is due to the change in the delta self-energy, whereas the residual pion-exchange interaction is weak at the low density probed by these reactions.

The calculations for (p,n) reactions do not reproduce the measured cross sections. They are, however, consistent with a shoulder on the observed delta peak at lower excitations. The (p,n) reactions probe deeper into the nucleus and the residual pion-exchange interaction becomes more significant but the energy shift of the delta peak is still dominated by the change in the delta self-energy. The discrepancy at higher excitations is ascribed to the neutron decay of the delta. This background is not present in (^{3}He,t) reactions, which makes these reactions more attractive for comparison with a simple theory.

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