(^{3}He,t) Reaction at Intermediate Energies

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Data are presented for the (^{3}He,t) reaction at energies of 600 MeV, 1.2 GeV, and 2 GeV on targets ^{nat}C, ^{54}Fe, and ^{89}Y. The low-excitation-energy regions of the spectra are dominated by isospin-spin excitations. Cross-section calculations in distorted-wave impulse approximation with parameters from *NN* data account reasonably well for the data. At 2-GeV bombarding energy a strong excitation of the Δ resonance is observed for all targets.

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In this Letter we present data for the (^{3}He, t) reaction at intermediate energies. The reaction has been studied at Laboratoire National Saturne at bombarding energies 600 MeV, 1.2 GeV, and 2 GeV on targets ^{nat}C, ^{54}Fe, and ^{89}Y. The reaction shows the same spectacular selectivity for $\sigma\tau$ excitations as does the (p,n) reaction at similar energies.[1-3] This is illustrated in Fig. 1, where 0° spectra for the (p,n) and (^{3}He, t) reaction at 200 MeV per nucleon are compared. The spectra are dominated by excitation of states carrying Gamow-Teller strength, whereas the isobaric-analog states which carry the Fermi strength are weakly excited. The (^{3}He,t) reaction could thus become an important tool for the study of $\sigma\tau$ excitations at intermediate energies, in particular in the higher part of this energy region where it is difficult to obtain comparable energy resolution for (p,n). If we think of the Δ isobar as a $\sigma\tau$ excitation of the nucleon it seems

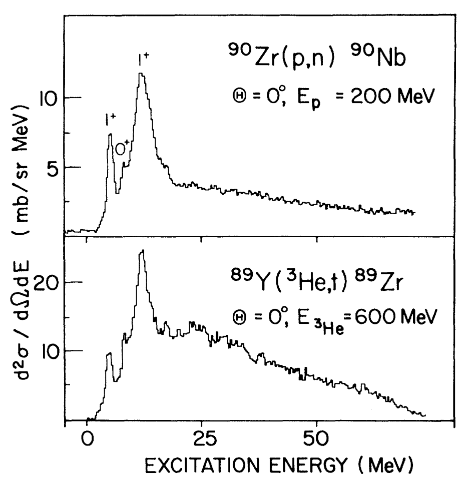

FIG. 1. Energy spectra from (p,n) and (^{3}He,t) reactions at 200 MeV per nucleon bombarding energies. The 0° (p,n) spectra for ^{90}Zr (Ref. 3) and ^{89}Y (Ref. 4) are very similar, but a detailed analysis is only available for the ^{90}Zr spectra.

that the (^{3}He, t) reaction could also be useful for the study of the role of Δ's in nuclei. In the discussion on the missing Gamow-Teller (GT) strength the importance of the Δ has been emphasized.[5] The (^{3}He, t) reaction could even turn out to be simpler than the (p,n) reaction since the projectile excitation into Δ with subsequent decay into the triton ground state is very much suppressed.

The data are obtained with the spectrometer SPES IV,[6] which allows analysis of tritons up to 2 GeV. The spectrometer is a D5Q6 instrument with 35 m between target and focal plane. The angle is changed by changing the direction of the beam impinging on the target. A time-of-flight measurement between scintillators 16 m apart determines the mass of the analyzed particle. In the present experiment the momentum range $\Delta p/p$ was 7% and the resolution $\delta p/p \sim 10^{-3}$. The solid angle was 0.1 msr and the beam currents were 1–20 nA. The targets were foils of C (48 mg/cm^2), ^{54}Fe (85 mg/cm^2, 94% enriched), and ^{89}Y (45 mg/cm^2). With these numbers it typically took 10 min to obtain a spectrum. Angular distributions were obtained for the low-excitation-energy region in steps of 2° from $\theta = 0°$ to 10° for 600 MeV and out to 6° for 1.2 and 2 GeV. For the energy region $E_x = 100$ to 500 MeV we have only forward-angle data, because of background problems when the beam at larger angles enters the aperture into the spectrometer. The background in the spectra is in general very low. This can be exemplified by noting that the low-lying states in ^{13}N can be studied from the 1% ^{13}C in the natural carbon target (Fig. 2). The absolute cross sections are obtained at 600 MeV, from a known activation cross section[7] for ^{12}C into ^{11}C, to determine a ratio between a monitor detector and the beam current. At 1.2 and 2 GeV the cross sections are obtained from elastic-scattering yields from the H in a CH target combined with data[8] from $p + {}^3$He at the same momentum transfer and similar c.m. energies. The absolute cross sections for the (^{3}He, t) data so obtained are believed to be accurate to 25%. The energy resolution was 1.1 MeV at 600 MeV, 1.8 MeV at 1.2 GeV, and 3.2 MeV at 2 GeV.

Figures 2 and 3 show 0° spectra for the carbon target at 600 MeV and 2 GeV. The low-lying part of the forward-angle spectrum is dominated by three peaks, corresponding to the 1^+ ^{12}N ground state (g.s.) and two groups of states ($E_x \sim 4.0$ and 7.1 MeV) characterized by an $l = 1$ transfer. The same three peaks dominate the forward angle

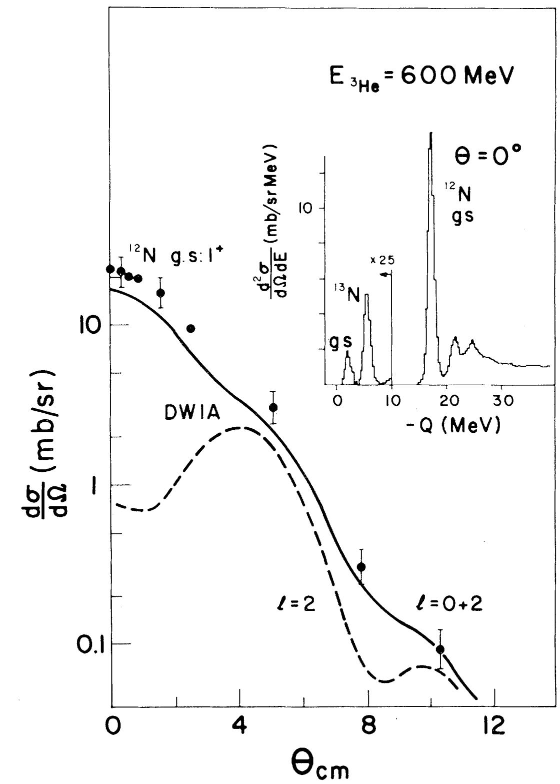

FIG. 2. A 0° triton spectrum from a natural carbon target is shown together with measured and calculated cross sections for the transition to the ^{12}N g.s. The two peaks in the spectrum coming from the 1% ^{13}C isotope are the g.s. and the 3.5-MeV $\frac{3}{2}^-$ state.

(p,n) spectra at 200 MeV.[9] Also shown in Fig. 2 is a calculated angular distribution for the g.s. transition in the impulse approximation. Following the notation of Petrovich[10] we write the transition amplitude as a product of a distortion and a form factor,

$$T = \int D(\vec{r}) F(\vec{r}) d^3r.$$

In a momentum representation the form factor in the impulse approximation factorizes,

$$F(q) = \nu(q)\rho_p(q)\rho_t(q).$$

The interaction $\nu(q)$ is here taken as the NN interaction parametrized by Love and Franey.[11] For the projectile transition density $\rho_p(q)$ we use $e^{-0.42q^2}$, a fair approximation for $q^2 < 10$ fm^{-2} for the data on the magnetic form factor from electron scattering on ^{3}He.[12] For the target transition density ρ_t we have taken the density calculated from the Cohen-Kurath[13] wave functions for the transition to the 1^+ state.

The optical parameters that enter the calculation of the distortion are calculated in the same

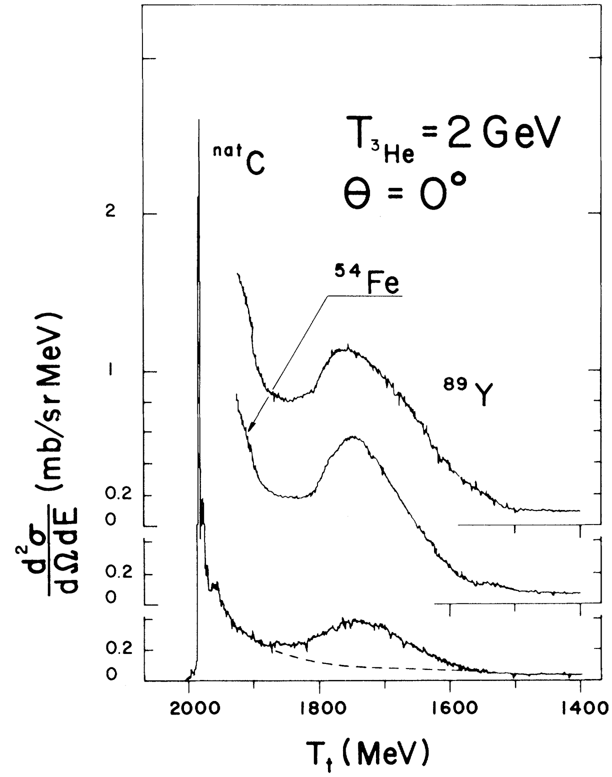

FIG. 3. Energy spectra constructed from position spectra with four different field settings in the spectrometer. The "fine structure" in the spectra is due to efficiency irregularities in the wire chamber. In the carbon spectrum a dotted line shows the assumed background under the broad peak.

approximation with ρ_t now equal to the target g.s. density. The calculations have been performed with the codes ALLWORLD[14] and DWUCK4.[15] In both codes the exchange effect is calculated in a zero-range approximation, but only in the former is the tensor force exchange considered.

As for the (p,n) reaction[2] we can write, in the limit of momentum transfer $q=0$, the $0°$ cross section for a GT transition as

$$\frac{d\sigma}{d\Omega}(q=0)=\left(\frac{\mu}{\pi\hbar^2}\right)^2 N J_{\sigma\tau}{}^2 B(\mathrm{GT}),$$

where μ is the reduced mass (relativistic), N the distortion factor, $J_{\sigma\tau}$ the volume integral of the interaction in the $\sigma\tau$ channel, and B(GT) the B value for the transition considered. With the same distortion we would therefore have about a factor of 9 larger $0°$ cross section for the $(^3\mathrm{He},t)$ than for the (p,n) reaction at the same energy per nucleon. The measured cross-section ratio for the ^{12}N g.s. transition is about 3 at 200 MeV per nucleon, which means that the distortion in this case is 3 times larger for the $(^3\mathrm{He},t)$ reaction.

The $0°$ cross sections for the ^{12}N g.s. are 23 ± 5, 22 ± 5, and 12 ± 3 mb/sr at 600 MeV, 1.2 GeV, and 2 GeV, respectively. We note that the plane-wave cross sections (corresponding to $N=1$ in the above expression) are 91, 66, and 52 mb/sr for the three bombarding energies, using the Love and Franey[11] parametrization to calculate $J_{\sigma\tau}$.

From the ^{13}C data we can extract the ratio of cross sections for the g.s. and the 3.51-MeV state in ^{13}N.[4] The g.s. transition is a mixed Fermi and Gamow-Teller transition with known B values. The ratio between cross sections determines the ratio between volume integrals of interactions in the $\sigma\tau$- and τ-transfer channels.[16] We find

$$\frac{J_{\sigma\tau}}{J_\tau}=\begin{cases}2.9\mp 0.3 \text{ at 600 MeV (200 MeV/u)}\\ 2.3\mp 0.3 \text{ at 1200 MeV (400 MeV/u)},\end{cases}$$

extracted from $0°$ cross-section ratios 3.0 and 2.6, respectively. At 2 GeV the resolution is not sufficient to get a reliable number for the ratio. The (p,n) experiment at 200 MeV gives $J_{\sigma\tau}/J_\tau = 3.45\mp 0.35$,[16] whereas the parametrization by Love and Franey gives $J_{\sigma\tau}/J_\tau = 2.5$ (210 MeV) and 1.9 (425 MeV). A parametrization based on more recent *NN* data gives 3.0 at 210 MeV and 2.5 at 425 MeV.[17]

The results for the targets ^{54}Fe and ^{89}Y for $E_x < 100$ MeV can be summarized as follows: (i) The spectra are characterized by $\sigma\tau$ excitations. At $0°$ the GT transitions dominate; at the larger angles the $l=1$ and $l=2$ spin multipoles are characteristic features of the spectra.[18] At 600 MeV the $l=1$ transitions for, e.g., ^{54}Fe peak around $\theta=2°$ and at 2 GeV around $\theta=1°$. (ii) The spectra are featureless at larger angles, i.e., at 600 MeV for $\theta>6°$ and at 2 GeV for $\theta>4°$.

In the region of the Δ resonance the forward-angle 2-GeV spectra show for all three targets a rather strong excitation of a broad bump at a Q value of -270 MeV with a width (full width at half maximum) of around 150 MeV. The cross sections at $\theta=0°$ for the broad peaks are 45 mb/sr for carbon, 130 mb/sr for ^{54}Fe, and 165 mb/sr for ^{89}Y (continuum subtracted) with an estimated (relative) uncertainty of ±20%. The cross sections are similar between $0°$ and $1.0°$. At $\theta=4.5°$, which is the next angle where we have data for the broad peaks, the cross sections are less than 2 mb/sr. The $0°$ cross sections are consistent with an $A^{2/3}$ dependence, indicative of a surface effect. The 800-MeV (p,n)

data by Bonner *et al.*[19] also show a strong excitation of a broad peak at $Q = \sim -300$ MeV, with a cross section proportional to $A^{1/2}$.

The difference in resonance energy observed in (p,n) and $(^3\mathrm{He},t)$ reactions could be explained as an effect of the ^{3}He form factor. In the plane-wave limit we can as above write the cross section in a product form. The width of the Δ resonance is therefore in the $(^3\mathrm{He},t)$ reaction folded with the projectile form factor resulting in an (apparent) shift of the observed resonance.

We interpret the broad peaks as excitations of nucleons into Δ's, but a more specific characterization of the resonance awaits more data and a more detailed analysis. The resonance observed could be a result of quasifree Δ production, i.e., the initial nucleon with its Fermi momentum is scattered as a Δ into, e.g., a plane-wave state. Another interesting possibility is an interpretation of the resonance as an envelope of several (coherent) Δ-nucleon-hole states, $\sum_{i=1}^{A}(\Delta N^{-1})_i$ with different spins and parities. We note in this connection that the momentum transfer at $\theta = 0°$ for $Q = -300$ MeV is around $q = 1.5\ \mathrm{fm}^{-1}$, and we would therefore not expect the $l = 0$ GT excitation to be an important component. We see, however, that the present experiment suggests that Δ degrees of freedom could be important for the isospin-spin modes in nuclei.

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