Broad structure in $t$ spectra from ($^3$He,$t$) reactions at $E_{^3He}=130$ MeV: Its angle and target-mass dependence

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Triton spectra from $^3$He-induced reactions on $^{27}$Al, $^{60}$Co, $^{98}$Nb, and $^{187}$Au targets at $E_{^3He}=130$ MeV have been measured in the $7.5^\circ \leq \theta_t \leq 24^\circ$ angular range in 1.5$^\circ$ steps. The spectra exhibit a broad structure; the centroid energy $E_c$ and the full width at half maximum $\Gamma$ of this "bump" are found to be independent of the target mass number $A$. Their average values are $E_c=87$ MeV and $\Gamma=48$ MeV with estimated errors of about $\pm 2$ MeV in both cases. Within the error bars the bump cross section is found to be consistent with $A^{1/3}$ proportionality and tends to decrease exponentially with angle; however, $A^{1/2}$ dependence cannot be excluded. In addition, the angular distributions possibly show indications for a weak oscillation pattern.

NUCLEAR REACTIONS $X^3$(He,$t$), $X=^{27}$Al, $^{60}$Co, $^{98}$Nb, $^{187}$Au; $E=130$ MeV; measured $d^2\sigma/\rho$, $\theta/d\rho$; deduced $d\sigma/d\Omega\Gamma$ (FWHM) and centroid energy $E_c$ of the broad structure.

I. INTRODUCTION

Observation of a broad structure ("bump") in $t$ spectra from the ($^3$He,$t$) reaction at incident energies of 68 and 90 MeV, and 130 MeV (Ref. 2) has been reported from our laboratory. Several experimental features of the $t$ bump were presented and discussed qualitatively. In particular, the $t$ bump was found to be located at $E_x \approx 1/3 E_{^3He}$, with the full width at half maximum (FWHM) $\Gamma \approx 1/3 E_{^3He}$. The bump cross sections measured at $E_{^3He}=90$ MeV for $\theta_t=12^\circ$ and $22^\circ$ were found to be roughly proportional to $A^{1/5}$. Qualitative arguments were presented in favor of a ($^3$He,$d$) ($d,t$) breakup-pickup process as a possible reaction mechanism.

This paper reports the results of further experimental work at $E_{^3He}=130$ MeV performed with the following objectives: (i) to study the $A$ dependence of the $t$ bump properties; for this purpose $^{27}$Al, $^{98}$Co, $^{99}$Nb, and $^{187}$Au were used as targets, and (ii) to extract angular distributions of the bump cross section; triton spectra have been measured from $7.5^\circ$ to $24^\circ$ (lab) in 1.5$^\circ$ steps.

II. EXPERIMENT

The experiment was performed at the Jülich isochronous cyclotron JULIC. The extracted $^3$He beam ($\Delta E/E \approx 0.3\%$) hit the target without prior momentum analysis. Beam intensities ranging from a few nA at most forward angles up to $\sim 200$ nA at larger angles were used. The targets were self-supporting foils of 5–9 mg/cm$^2$. The charged reaction products were detected by two $\Delta E-E$ telescopes mounted $3^\circ$ apart from each other inside a 1 m diameter scattering chamber. Side-entry 31 mm thick Ge(Li) detectors were used as $E$ counters. A choice of 1 mm $\Delta E$ counters was made as a compromise between the particle detection cutoff at low energies and the good particle separation. Each telescope was coupled through standard electronics to two particle identifier units to achieve optimal separation for the $p-d-t$ and for the $^3$He-$\alpha$ particle groups. A tantalum collimating system (with an angular opening $\Delta \theta \approx 0.4^\circ$), thick enough to stop the high energy protons, was placed in front of each telescope. A Ge(Li) monitor detector was situated at a fixed angle of $\theta_z=30^\circ$. The beam was carefully focused onto a viewer prior to data taking. An experimental run using a "hole" target was performed to achieve negligible background. Energy calibration was accomplished using a CH$_3$CD$_2$-Au target.

III. RESULTS AND DISCUSSION

Figure 1 shows some of the measured triton spectra for $^{27}$Al, $^{60}$Co, $^{99}$Nb, and $^{187}$Au targets. The spectra at very forward angles ($\theta_t=9^\circ, 10.5^\circ$) exhibit a pronounced and asymmetric broad structure (bump), similar to the previous observation at $E_{^3He}=68$ and 90 MeV. It can be seen that the $t$-bump cross section $d\sigma/d\Omega$ falls off rapidly with angle, faster than that of the underlying background. The bump practically disappears at $\theta_t=24^\circ$, except perhaps for $^{27}$Al. It is interesting to note, that
for the $^{27}$Al case, Fig. 1 (see arrow) shows an additional small bump located at an excitation energy $E_x \approx 18$ MeV in the residual $^{31}$Si nucleus. This bump which is probably due to the excitation of the giant dipole resonance components and/or other isovector resonances (e.g., Gamow-Teller) seems to be worth further investigation.

Quantitative evaluation of the t bump necessitates knowledge of the underlying background. In the present work, background subtraction has been done by assuming two shapes for the background spectrum, namely

(i) Linear: at $E_x = 40$ MeV the t spectrum is assumed to consist only of background which drops linearly to zero at $E_x = 120$ MeV. This procedure gives an upper limit to $d\sigma/d\Omega$ and $\Gamma$ (FWHM), and a lower limit to $E_x$ (centroid energy) of the bump.

(ii) Curved: the shape of the background spectrum is assumed to be that of the t spectrum at $\Theta_x = 24^\circ$, since the t bump practically disappears in most cases at this angle (see Fig. 1). Prior to subtraction, the background spectrum is matched to the t spectrum at $E_x = 40$ MeV. This procedure gives a lower limit to $d\sigma/d\Omega$ and to $\Gamma$, and an upper limit to $E_x$.

The experimental values of $d\sigma/d\Omega$, $E_x$, and $\Gamma$ and their associated errors are calculated using the following method. At each angle $\Theta_x$ the value of the physical quantity $v_i$ (i.e., $d\sigma/d\Omega$, $E_x$, and $\Gamma$) is given by $v_i = \frac{1}{2}(L^{+} + L^{-})$, where $L^{+}$ and $L^{-}$ are its upper and lower limits (see above), respectively. The error $\pm \Delta v_i$ is estimated to be $|\Delta v_i| = \frac{1}{2}[(L^{+} + \Delta L^{+}) - (L^{-} - \Delta L^{-})]$, $\Delta L^{+}$ and $\Delta L^{-}$ being the respective errors of the limits (due to uncertainties in background subtraction). For each target, the values of $E_x$ and $\Gamma$ are found to be nearly independent of angle. In view of this, the angle-averaged value $\bar{v}$ (of $E_x$ and $\Gamma$, respectively) is determined as

$$\bar{v} = \frac{1}{N} \sum_{i=1}^{N} v_i$$

with error $\pm \Delta \bar{v}$ where

$$(\Delta v)^2 = (\Delta v_1)^2 + (\Delta v_2)^2,$$

$$(\Delta \bar{v})^2 = \frac{1}{N} \sum_{i=1}^{N} (v_i - \bar{v})^2,$$

and

$$(\Delta \bar{v}_x)^2 = \frac{1}{N} \sum_{i=1}^{N} (\Delta v_i)^2,$$

where $N$ is the number of experimental quantities.

Figure 2 shows the extracted values of $E_x$ and $\Gamma$ as a function of $A$. These values are found to be nearly independent of $A$. The target average of these values are $E_x = 87$ MeV and $\Gamma = 48$ MeV, close to $\frac{3}{4} E_{^{27}Al}$ and $\frac{3}{4} E_{^{197}Au}$ respectively. Using the method described above, their associated errors are estimated to be $\pm 2$ MeV in both cases. These
features are similar to those observed previously at lower incident energies. It is worth noting that $\Gamma$ is almost twice as large as Nomura's empirical relation which has the value $[E_{\text{he}}B_{d}(^3\text{He})]^{1/2}$, where $B_{d}(^3\text{He})$ is the deuteron binding energy in the $^3\text{He}$ projectile.

Figure 3 shows the $A$ dependence of the $t$-bump cross section for $\theta_{L} = 9^\circ$, $12^\circ$, $15^\circ$, and $18^\circ$. For $\theta_{L} = 9^\circ$, $12^\circ$, and $15^\circ$ the bump cross section tends to favor an $A^{1/2}$ rather than an $A^{1/3}$ dependence suggested earlier at lower incident energies. However, considering the errors, the $A^{1/3}$ dependence cannot be ruled out. At $\theta_{L} = 18^\circ$, the $A^{1/3}$ dependence is slightly better. Angular distributions of the $t$-bump cross section (in the laboratory system) are shown in Fig. 4. Their overall slopes are found to be roughly independent of $A$; they are characterized mainly by an exponential decrease of the cross section with
angle. In addition, the angular distributions show some indications for a weak oscillation pattern with a common minimum at $\Theta_z \approx 16.5^\circ$ and a maximum at $\Theta_z \approx 18^\circ$.

It is worth noting that a nuclear reaction is considered to be peripheral when the total cross section is proportional to $A^{1/3}$, since the nuclear radius $R = r A^{1/3}$. Such a feature has been experimentally established for the $^3$He $\rightarrow d + p$ breakup process by Matsuoka et al.$^3$ from measurements of $d$ spectra corresponding to $^3$He breakup at $E_{3\alpha} = 70$ and 90 MeV. In addition, assuming $R = 1.4A^{1/3}$, they estimated the total $^3$He-breakup cross section to be $\sigma_\alpha = 2\pi R \Delta R$, with $\Delta R \approx 0.7$ fm (approximately equal to the diffuseness of the nuclear density distribution). This indicates that the contribution from the nuclear interior is practically negligible. As the incident energy of the projectile increases, Baur et al.$^4$ have shown theoretically that the surface localization of the breakup process becomes even more pronounced. Therefore, at $E_{3\alpha} = 130$ MeV used in this work one expects the $^3$He $\rightarrow d + p$ breakup process to be a peripheral one. Consequently, if the present $t$-bump is assumed to be due to a two-step breakup-pickup process, i.e., $^3$He $\rightarrow d + p$ followed by $d + n \rightarrow t$, then since the shape of the measured angular distributions are roughly independent of $A$ (Fig. 4), one might also expect an $A^{1/3}$ dependence of the $t$-bump cross section, in particular at forward angles. The fact that at these angles ($\Theta_z \approx 9^\circ$, $12^\circ$, $15^\circ$; see Fig. 3) the $t$-bump cross section tends to favor an $A^{1/3}$ dependence (Fig. 3) might be interpreted as an indication for additional contributions from other reaction mechanisms. The preference for an $A^{1/3}$ dependence of the $t$-bump cross section at $\Theta_z = 18^\circ$ might then be related at this larger angle to deviations from the above mentioned approximate independence of the shape of the angular distributions for different $A$ values (Fig. 4), possibly due to interference effects. In the breakup-pickup mechanism, an oscillation pattern as discussed above may be expected in the pickup as well as in the breakup steps. It would be interesting if theoretical calculations could be performed and compared with the experimental data.

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