CONTRIBUTIONS OF ELASTIC, INELASTIC AND ABSORPTIVE BREAKUP TO THE INCLUSIVE DEUTERON SPECTRUM OF THE REACTION $^{28}\text{Si}(^3\text{He},d)$ AT $E_{^3\text{He}} = 52$ MeV

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Deuteron–proton coincidence data from the reaction $^{28}\text{Si} + ^3\text{He}$ at $E_{^3\text{He}} = 52$ MeV show contributions from elastic, inelastic and absorptive breakup. The latter process accounts for about 75% of the inclusive continuum deuteron yield at $\theta_d = 10^\circ$. Systematics of these mechanisms are presented.

Recently it has been shown by Matsuoka et al. [1] that in ($^3\text{He}$, d) reactions projectile breakup is the dominant process contributing to the inclusive deuteron spectrum. Elastic breakup accounts only for about 40% of this cross section [2]. Here we present an investigation on the nature and magnitude of the processes that contribute to the inclusive deuteron spectrum. Beside elastic breakup these processes are inelastic and absorptive breakup. The latter is the dominant process contributing to the inclusive yield.

The reaction $^{28}\text{Si} + ^3\text{He}$ has the advantage that in $^{29}\text{P}$ the proton threshold (2.75 MeV) is significantly lower than the other particle thresholds (10.46 MeV for alphas and 17.87 MeV for neutrons). Therefore at $E_{^3\text{He}} = 52$ MeV the only particles that can be coincident with deuterons in the inclusive spectrum with $E_d > 30$ MeV are protons. Thus the inclusive deuteron yield is almost fully accounted for by the p–d coincidence yield.

With the deuteron detector fixed at $\theta_d = -10^\circ$ a 30 step in-plane angular correlation has been measured in which the proton detector covered the angular range $10^\circ < \theta_p < 155^\circ$ and $-155^\circ < \theta_p < -27^\circ$. The experiments were performed with a 52 MeV momentum analyzed $^3\text{He}$-beam from the AVF cyclotron of the KVI. A self-supporting natSi target (92% $^{28}\text{Si}$) with a thickness of 2.36 mg/cm$^2$ was used. The deuterons were detected in a telescope consisting of a 0.1 mm $\Delta E$ and a 5 mm $E$ silicon detector. In some of the experiments the $E$ detector was tilted 45° to obtain an effective depth of 7 mm, sufficient for stopping all deuterons with the exception of those from the reaction $^{28}\text{Si}(^3\text{He},d)^{29}\text{P}$(g.s.). The forward proton-angle data ($|\theta_p| < 90^\circ$) were obtained with a telescope similar to the one used for deuteron detection. Also the data at $\theta_p = 153^\circ$ have been obtained with a $\Delta E - E$ telescope. It was observed that protons were the only charged particles with a significant yield in coincidence with deuterons. Yet at forward angles, $|\theta_p| < 90^\circ$, a telescope was used because particle identification reduces strongly the rate of random coincidences. At backward angles the protons are by far the most abundant charged particles, and particle identification is not necessary. Therefore a single $E$ detector of 5 mm thickness was used for protons at $90^\circ < |\theta_p| < 155^\circ$, enabling detection of protons to a much lower energy.

Fig. 1 shows a two-dimensional $E_p$ versus $E_d$ spectrum at $\theta_d = -10^\circ$ and $\theta_p = -145^\circ$. In the spectrum one observes four loci corresponding to the reaction $^{28}\text{Si}(^3\text{He},pd)^{28}\text{Si}$. At relatively low proton energies there is an intense concentration of "uncorrelated" events. In fig. 2 the corresponding total kinetic energy (TKE = $E_d + E_p$) spectrum is shown. One observes the transitions to the ground state ($0^+$) and the levels at 1.78(2$^+$), 4.62(4$^+$) and 6.88 MeV(3$^-$). These are precisely the states that are strongly excited in inelastic scattering [3]. The TKE-spectra at forward proton...
angles (not presented here) are dominated by the ground-state transition (see also ref. [2]). The background, due to the "uncorrelated" events, shown in fig. 1, becomes apparent at backward proton angles.

Fig. 3 shows the inclusive deuteron spectrum from the reaction \((^3\text{He}, d)\) at \(\theta_d = -10^\circ\) and deuteron spectra from the reaction \(^{28}\text{Si} (^3\text{He}, pd)\) obtained by gating on the ground and first excited state in \(^{28}\text{Si}\).

The inclusive spectrum (fig. 3a) may be separated into: (i) sharp peaks from the direct proton transfer reaction, (ii) a broad bump centred around \(2/3\) of the \(^3\text{He}\) beam energy and (iii) an evaporation-like tail. The shape of the inclusive spectrum at \(\theta_d = -70^\circ\) is shown as a dashed line in fig. 3a: the broad bump in this spectrum has disappeared and only an evaporation-like spectrum remains. The spectra in figs. 3b–e represent the projections on the \(E_d\)-axis of events along the loci of the \(^{28}\text{Si}\) ground and the first excited state at \(\theta_p = 10^\circ\) (figs. 3b and 3c) and at \(\theta_p = -145^\circ\) (figs. 3d and 3e). At \(\theta_p = 10^\circ\) the spectra show a pronounced bump centred around an energy \(E_d = \frac{2}{3}E_3\text{He} + Q\), where \(Q = -5.945\) MeV for the ground state and \(Q = -7.724\) MeV for the first excited state. The shift in the centroid energy (\(\approx 2\) MeV) is obvious from figs. 3b and 3c. This is consistent with a breakup mechanism in which the proton is a spectator (no nuclear interaction with the target) and the deuteron interacts with the target nucleus in a quasi free scattering process leaving it in the ground or first excited state. The centroid of the bump in these spectra does not coincide with that of the bump in the inclusive spectrum. As observed in refs. [2,4] the position of the centroid changes at larger \(\theta_p\), but since the cross sections fall off rapidly with \(\theta_p\) these changes in position do not show up in the proton-angle integrated spectrum [4]. Therefore the position of the centroid indicates that elastic and inelastic breakup processes are not the most significant contributors to the inclusive spectrum despite the large cross section of these processes at forward angles. The coincident deuteron spectra, figs. 3d and 3e, at \(\theta_p = -145^\circ\) are dominated by sharp peaks due to proton stripping to proton unstable states in \(^{29}\text{P}\). They also show up in the inclusive spectrum. The small continuum components in the figs. 3d and 3e are centred round 34 MeV and indicate that the deuteron rather than the proton is a spectator. It is an important observation that in the \(^{28}\text{Si} (^3\text{He}, pd)\) \(^{28}\text{Si}^*\) reaction, leading to the ground state or the first
excited state, both the proton and deuteron spectator aspects are present and that they can be seen, one enhanced over the other, by choosing the appropriate angle combinations. It is noted that none of the deuteron spectra of figs. 3b–3e contain events contributing to the evaporation-like component in the inclusive spectrum. Fig. 3f shows the projection on the $E_d$-axis of all events (see fig. 1) except those along the loci of the ground state and the first excited state in $^{28}$Si. The events belonging to the loci of the 4.62 MeV($4^+$) and the 6.88 MeV($3^-$) states have been included since no clear separation from the “uncorrelated” events could be made and their cross sections are relatively small. The broad continuum in this spectrum is centred around $E_d = 34$ MeV and coincides with the position of the bump in the inclusive spectrum. In this spectrum the evaporation-like tail is present. In contrast with the angular correlations of the elastic and inelastic breakup which are strongly forward peaked, the angular correlation of these events is more or less isotropic.

Fig. 4 presents several proton spectra obtained by projecting on the $E_p$-axis events that lie within narrow intervals of deuteron energy and a spectrum for a broad interval over the evaporation-like tail in the projected deuteron spectrum $6 < E_d < 20$ MeV. Besides two peaks with shifting energies, resulting from the intersection with the loci of the ground state and first excited state in $^{28}$Si, the spectra peak around 3 MeV and have an exponential slope. This slope is about the same for all spectra except for the spectrum with $6 < E_d < 20$ MeV for which the slope is much steeper. This exponential slope and the fact that the peak position corresponds roughly to the Coulomb barrier suggest an evaporation-like process. The observation of coincident p–d pairs with the deuteron travelling with about the beam velocity and the proton statistically emitted, points to a mechanism in which a part of the projectile (the proton) is absorbed by the target nucleus while the other part of the projectile travels along as a spectator.

Fig. 3. Comparison between (a) the singles deuteron spectrum from the reaction $^{28}$Si($^3$He, d) at $\theta_d = -10^\circ$ and projected deuteron spectra of the reaction $^{28}$Si($^3$He, pd) at $\theta_d = -10^\circ$, gated on the ground state $^{28}$Si(0) at $\theta_p = 10^\circ$ (b), $\theta_p = -145^\circ$ (d), gated on the first excited state $^{28}$Si(1) ($E_x = 1.78$ MeV, $J^p = 2^+$) at $\theta_p = 10^\circ$ (c), $\theta_p = -145^\circ$ (e) and antigated on the ground and first excited state; total $^{28}$Si(0 + 1) at $\theta_p = -145^\circ$ (f).
This process is called absorptive breakup and is defined [5] as a reaction in which a subset of projectile nucleons suffers strong interaction with the target nucleus resulting in either evaporation or non-statistical emission of particles from the residual nucleus, leaving the remaining subset of projectile nucleons to continue with essentially their initial momentum prior to the interaction. In heavy-ion physics similar processes are observed and are named incomplete fusion [6,7].

The slope of the proton spectra (fig. 4) corresponds to a temperature $T = 3.4$ MeV. The average initial energy of the absorbed proton is only about 12 MeV. Thus the temperature of 3.4 MeV indicates that the absorbed proton equilibrates only with a few target nucleons before proton emission. The protons corresponding with the low deuteron energy tail ($6 < E_d < 20$ MeV) have a temperature of about 1.2 MeV. This slope is the same as that of the inclusive proton spectrum at backward angles ($-145^\circ$). These events are thus due to a process in which the deuteron dissipates much energy but is not fully equilibrated with the target (the tail of this component extends to rather high energies (see fig. 3a) while the proton is absorbed by the target nucleus. After equilibration a proton is emitted.

In order to compare the singles cross section with the cross sections obtained from the coincidence measurements in the in-plane angular correlations have been integrated over the azimuthal angle $\phi$ under the assumption of a linear $\phi$-dependence [2,3,5-8]. Table 1 gives the comparison of the continuum cross section determined from the inclusive spectrum and those deduced from the coincidence data. The singles yield is within the error bars completely accounted for by the yield of the different coincidence processes. It is found however that only about 50% of the deuterons in the evaporation-like tail region ($6 < E_d < 20$ MeV) are associated with protons. This implies that the intermediate nucleus $^{29}$P has been excited above the neutron threshold ($E_x = 17.87$ MeV).

In conclusion it can be stated above the different processes contributing to the continuum part of the...
$^{28}\text{Si}(^{3}\text{He}, \text{d})$ inclusive spectrum at $\theta_{d} = -10^\circ$ are:

(i) Elastic and inelastic breakup leading to states that are also strongly excited in (free) inelastic scattering. In the case of the reaction $^{28}\text{Si}(^{3}\text{He}, \text{pd})$ these states are the ground state ($0^+$) and the levels at 1.78 MeV($2^+$), 4.62 MeV($4^+$) and 6.88 MeV($3^-$). These reactions both have proton spectator and deuteron spectator contributions.

(ii) ($^{3}\text{He}, \text{pd}$) absorptive breakup in which the proton from the $^{3}\text{He}$ projectile is absorbed by the target nucleus and after a few collisions a proton is emitted. The accompanying deuteron acts like a spectator.

(iii) A process in which the deuteron has an evaporation-like spectrum that extends to quite high energies. The coincidence proton originates from a process in which the proton from the projectile is captured by the target and fully equilibrates. The intermediate $^{29}\text{P}$ is highly excited and decays only partly by proton emission. In the case of the reaction $^{28}\text{Si}(^{3}\text{He}, \text{d})$ the absorptive breakup channel is by far the strongest channel (table 1) and therefore the bump in the inclusive deuteron spectrum is centred around $\frac{2}{3}E_{^{3}\text{He}}$.

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