Contribution of unbound deuteron disintegration to the reaction $^{12}C(^{16}O,pn)^{26}Al$

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The contribution of proton-neutron pairs in the singlet state to the cross section of the $^{12}C(^{16}O,pn)^{26}Al$ at 30 MeV bombarding energy, which was measured by *pn*-coincidence techniques, was found negligible.

[NUCLEAR REACTIONS $^{12}C(^{16}O,pn)^{26}Al$, $E = 30$ MeV; measured *pn* coincidences, E_p; deduced % of unbound deuteron emission; Ge(Li) detectors, NE 213 scintillation detectors, Si surface barrier detectors.]

A proton-neutron pair can be emitted in a nuclear reaction via two distinctly different processes; either via successive evaporation of nucleons or from the disintegration of singlet deuterons as soon as the latter are found outside the potential of the residual nucleus.

In a previous experimental study[1] of the reaction $^{12}C(^{16}O,pn)$ at 30 and 36 MeV it was concluded that a significant fraction of its cross section was due to the emission and the subsequent decay of unbound deuterons. According to evaporation model estimates,[2] however, only a small fraction, between 3 and 10%, relative to the stable deuteron emission is expected to proceed via singlet deuteron emission. It is the intention of the present investigation, therefore, to clarify whether or to what extent unbound deuteron emission contributes to the cross section of the $^{12}C(^{16}O,pn)$ reaction. Such a conclusion is pertinent to the proper comparison between theoretical and experimental cross sections for *pn* and *d* exit channels in heavy-ion reactions. Furthermore, it will help the interpretation of the competition between *pn* and *d* emission recently measured[3] in the $^{12}C(^{16}O,pn/d)^{26}Al$ reaction.

In the present study proton-neutron coincidence techniques were utilized in order to observe the fraction of *pn* originating from singlet deuteron disintegration. Thin, 50 $\mu g/cm^2$, targets of ^{12}C were bombarded with 30 MeV ^{16}O beams supplied by the NRC Demokritos Tandem Accelerator. For proton detection a $\Delta E - E$ counter telescope of silicon detectors of 50 and 2000 μm thickness was used. The neutrons were detected with a NE 213 organic scintillator. Standard pulse-shape discrimination technique was utilized in order to reject the γ-ray pulses from the scintillators's output.

Particle identification with pile-up rejection, and fast-coincidence circuitry for *p-n* coincidence were employed. The raw data were stored event by event on magnetic tape by an on-line PDP-11/15 computer. Random coincidences were measured and subtracted although these never exceeded 10% of the total coincidence rate.

The different angular dependence of a proton and a neutron emitted either successively or via the disintegration of a single deuteron was exploited in order to characterize the process by which the proton-neutron pairs were produced. Although *pn*-coincidence data were obtained at several angles, special attention was given to symmetric detection geometries, that is $\theta_p = \theta_n$ and $\theta_p = -\theta_n$ about the beam axis.

The maximum angle θ_{max} between protons and neutrons produced by the disintegration of a singlet deuteron d^* is a function of the energy E_{BU} released in the unbound deuteron breakup

$$\sin\tfrac{1}{2}\theta_{max} = \frac{E_{BU}}{E_{d^*}} , \qquad (1)$$

where E_{d^*} is the energy of the singlet deuteron. Indicatively, for the reaction $^{12}C(^{16}O,d^*)$ assuming to populate the ground and 417-keV excited state of ^{26}Al at 30 MeV bombarding energy and 30° angle of emission with respect to the beam one obtains $\theta_{max} = 9.3°$ and 9.5°, respectively, with the assumption that $E_{BU} = 60$ keV. In the present experiments the detectors subtended an angle of 10°. The employed experimental arrangement, therefore, was appropriate for the efficient detection of proton-neutron pairs contributed from singlet deuteron disintegration with low break-up energy. In fact, for $E_{BU} \leq 60$ keV both particles will reach their respective detectors at the $\theta_p = \theta_n$ geometry. It should be mentioned that the density of states function of the p-n singlet system[4] favors breakup with small E_{BU}. Furthermore, when E_{BU} is very small the energies of the protons and neutrons are nearly equal, and equal to $\frac{1}{2}E_0$, where $E_0 = E_{d*} + E_{BU}$. Thus, the distribution of E_p is strongly peaked at $E_p = \frac{1}{2}E_0$,[5] and is symmetrical about that value since the neutrons and protons are practically equivalent. In measuring the experimental distribution of E_p at $\theta_p = \theta_n$ one detects ordinary (^{16}O,*pn*) as well as (^{16}O,*d**) reactions. At $\theta_p = -\theta_n$ geometry one expects that the *pn*-coincidence contribution from successive evaporation will be nearly the same with the $\theta_p = \theta_n$ data due to the symmetry about the beam axis. In fact, a slight divergence from symmetry, less than 1.7%, is estimated from the ratio of Jacobians $(J^+ - J^-)/J^-$. $J^+ = J(\theta_p = \theta_n)$ and $J^- = J(\theta_p = -\theta_n)$ are the Jacobians of the transformation

$$J\left[\frac{\Theta,\Phi}{\theta,\phi}\right] = \frac{d\Omega_{\rm c.m.}(\Theta,\Phi)}{d\Omega_{\rm lab}(\theta,\phi)}\ , \qquad (2)$$

where (Θ,Φ) and (θ,ϕ) are the polar and azimuthal angles at the c.m. and the laboratory systems, respectively, and $d\Omega_{\rm c.m.}$ and $d\Omega_{\rm lab}$ are the corresponding detector solid angles. Furthermore, the opposite side data can be considered to give only the successive evaporation background since previous experimental investigations[4,6] have shown that these contain negligible contribution from singlet deuteron disintegrations.

Energy spectra of protons in coincidence when all neutrons emitted the reaction ^{12}C(^{16}O,*pn*)^{26}Al were measured at 30 MeV bombarding energy at several proton and neutron detection angles about the beam axis. From these data, shown in Table I normalized with respect to the beam current, it was obtained that no enhancement of coincidence events occurred at the same side geometry. Furthermore, the energy distribution of the protons was smooth without any peaking at one-half the maximum available energy.

TABLE I. Normalized proton-neutron coincidence events at the indicated angles with respect to the beam.

θ_p deg	θ_n deg	Number of *pn* coincidences
15	15	2420±50
15	−15	2447±50
30	30	774±35
30	−30	791±35
−30	−30	791±35
−30	30	780±35

Both observations suggest that the proton-neutron pairs emitted in the reaction are almost exclusively due to successive evaporation of nucleons from the compound nucleus. An upper limit of about 3.5% relative to the total *pn* emission, equal to the statistical uncertainty of the measurements, may be assigned to proton-neutron pairs in the singlet state. Taking into account that for the reaction ^{12}C(^{16}O,*pn*/*d*)^{26}Al it has been measured[3] that $\sigma_{pn}/\sigma_d = 3.1$, one obtains that an upper limit of about 11% of the stable deuteron cross section may be associated with singlet deuteron emission.

The present results, suggesting negligible singlet deuteron contribution to the ^{12}C(^{16}O,*pn*) reaction, are in agreement with evaporation-model expectations. The experimental technique and the method of analysis employed here was different than the one previously employed.[1] The apparently overestimated *d** contribution derived in this previous study should be associated with the limited resolution of the missing mass spectrum employed there, which did not permit unequivocal conclusions. Since, as it has been shown here, the *pn* production in the bombardment of ^{12}C with ^{16}O is almost exclusively due to successive evaporation, it is appropriate to compare experimental σ_{pn}/σ_d ratios with Hauser-Feshbach predictions. In fact a very good agreement has been previously observed[3] between experimental and theoretical cross section ratios for the reaction ^{12}C(^{16}O,*pn*/*d*)^{26}Al.

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