PHYSICAL REVIEW C VOLUME 47, NUMBER 2 FEBRUARY 1993

# Breakup energy spectrum of singlet deuterons measured using $d+d \rightarrow d^*+d^*$ four-body reaction at 15.7 MeV

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(Received 21 May 1992)

A kinematically complete measurement of the four-body breakup reaction $d+d \rightarrow d^*+d^* \rightarrow p+n+p+n$ has been performed at 15.7 MeV bombarding energy. A ring-detector system consisting of a charged-particle detector and a neutron detector is used to define a singlet deuteron, i.e., $d^*$; a charged-particle detector is used to measure spectra of products produced by another $d^*$ at five angles. A velocity-distribution diagram has first been obtained, and by performing a fit the most probable breakup energy of the singlet deuteron in the laboratory system is obtained, 0.054±0.012 MeV. A final state interaction calculation using known $p$-$n$ singlet phase shifts predicts the expected proton spectra.

PACS number(s): 25.10.+s, 21.10.Dr, 25.45.−z

## I. INTRODUCTION

Historically the deuteron has played an important part both in nuclear force and nuclear reaction studies. A deuteron is a proton-neutron system in its lowest $T=0$, $S=1$ state, and it is well known that this system has a closely related $T=1$, $S=0$ state which is commonly referred to as the "singlet deuteron" denoted by $d^*$. It is, therefore, interesting to investigate the properties of the singlet deuteron and the role of it in nuclear reactions.

After it was originally suggested by Temmer [1] that one could exploit the isospin property of the singlet deuteron for nuclear spectroscopic purposes, several authors have discussed the use of such a "particle" as a spectroscopic tool [2–4]. The $d^*$ was first observed in neutron pick-up reactions $(p,d^*)$ by Cohen *et al.* [5]. The measured $n$-$p$ coincidence spectra show significant enhancement at low $np$ relative energy $E_{np}$, mainly due to the final-state interaction. The $(p,d^*)$ reactions induced by 12–17 MeV protons on $^7$Li, $^9$Be, $^{13}$C, $^{25}$Mg, and $^{117}$Sn have been investigated by Cohen [6] and Otte [7].

He-induced one-nucleon transfer reactions with an unbound ejectile have been studied for quite some time. The $^{10}$B($^3$He,$d^*$)$^{11}$C reaction has been studied at 8, 10, and 11 MeV [8], and the $^{13}$C($^3$He,$d^*$)$^{14}$N reaction at 13 MeV [9]. The normalization factor for the ($^3$He,$d^*$) reactions has been calculated by Janetzki [9] and Limm [10]. A review of the reaction mechanism of the sequential breakup process of the ($^3$He,$d^*$) reactions has been given recently by de Meijer [11]. Three-body breakup spectra from a kinematically complete measurement of the $^2$H($p$,2$p$)$n$ [12], $^2$H($p$,$pn$)$p$ [13], and $^2$H($d$,$dp$)$n$ [14] reactions have been analyzed to estimate the cross section for the production of $d^*$. Various authors [15–17] have reported the evidence of $d^*$ production in the kinematically complete measurement of the $^2$H($\alpha$,$p\alpha$)$n$ reaction in which the shape of the energy-sharing distribution is peaked in the kinematic region where the $n$-$p$ relative kinetic energy in the final state is zero ($E_{np}=0$).

The main emphasis of the above-mentioned studies was on the reaction mechanism. To our knowledge, the breakup energy spectrum of the singlet deuteron has not yet been measured directly, even though some authors stated that it was well known. Nomoto [18] has suggested that the sharp peak in the $^{13}$C($p$,$p'n$)$^{12}$C reaction's angular distribution for $E_p \simeq E_n$ was due to the formation of a singlet deuteron in a decaying intermediate state at about 0.06 MeV, but Hare and Papini [19] pointed out that the breakup energy was about 0.092 MeV. In our preliminary works [20,21] on the $^2$H($d$,$d^*$)$d^*$ reaction, the most probable breakup energy of the singlet deuteron in the laboratory system was measured to be between 0.041 and 0.082 MeV.

In this work, the proton energy spectra of the singlet deuteron are obtained by kinematically complete measurements of the four-body reaction $^2$H($d$,$d^*$)$d^*$. According to measured kinetic energies and laboratory angles of one of the outgoing particles, the radius of the sphere formed by velocities of the particles in the center-of-mass system of the $d^*$ is determined, from which the most probable breakup energy of the singlet deuteron is obtained. Here we report the measured results.

## II. EXPERIMENTAL ARRANGEMENT

The reaction

$$d+d \rightarrow d^*+d^* \rightarrow p+n+p+n \quad (1)$$

is a cascade process. At the first stage of the reaction, which can be considered as a two-body process, two $d^*$ are formed. Then the $d^*$'s emerge in opposite directions in the c.m. system and break up. The breakup products $p$ and $n$ of the singlet deuteron move with equal and opposite velocities in the $d^*$ c.m. system, while their velocity vectors form a spherical surface with its center at the terminal of $V^c_{d^*}$ and its radius equals the c.m. velocity of $p$ (or $n$), $V^c_p$ (or $V^c_n$) (Fig. 1). In Fig. 1 $V_c$ is the center-of-mass velocity of the system and $V^c_{d^*}$ is the velocity of $d^*$ in the c.m. system. If the straight line, which denotes the direction of the laboratory velocity of the outgoing pro-

 

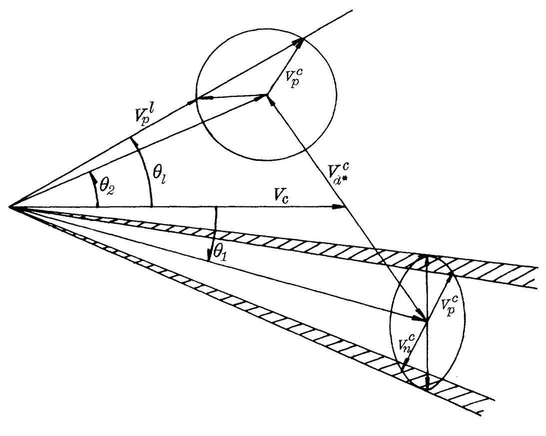

FIG. 1. Kinematic diagram of the $d+d \rightarrow d^*+d^*$ reaction. The shaded areas represent the sensitive ranges of the ring-detector system.

ton, intersects the spherical surface, the corresponding laboratory velocity is double-valued, denoted by $V_p^l$. In this case, the corresponding spectra have two peaks. Experimentally, if the spectra of the outgoing protons (or neutrons) are measured at more than two intersection angles, we can solve for $V_p^c$ from the equations of a circle in the polar coordinate system,

$$(V_p^c)^2=(V_{d^*}^l)^2+(V_p^l)^2-2V_{d^*}^1 V_p^1\cos(\theta_l-\theta_2), \quad (2)$$

then

$$E_{\rm BU}=2E_I=m_p(V_p^c)^2 , \quad (3)$$

where $V_{d^*}^l$ and $\theta_l$ are the laboratory velocity of the $d^*$ and the corresponding laboratory angle, respectively; $V_p^l$ and $\theta_2$ are the laboratory velocities of the outgoing protons and the corresponding laboratory angles respectively; $E_{\rm BU}$ is the most probable breakup energy of the singlet deuteron in the laboratory system and $m_p$ is the proton mass; $E_I$ is the kinetic energy of the proton relative to the center of mass of $d^*$; and $V_p^l$ can be obtained from the peak energies of the measured proton spectra.

The most probable breakup energy is expected to be relatively small compared with the $d^*$ kinetic energy and therefore the position of the outgoing particles will be confined to a fairly small cone. Placing a neutron detector immediately behind a solid-state charged-particle detector and adopting a coincidence between the two detectors, one can get signals sensitive to the breakup event of one of the singlet deuterons produced by the reaction. On the other hand, if a charged-particle detector is placed at 180° relative to the first $d^*$ in the c.m. system and a coincidence among the three detectors is adopted, the four-body breakup event passing through the singlet deuteron intermediate state will be clearly defined.

In this experiment, a ring Si(Au) detector (denoted as detector 1) was placed at 30° and a liquid-scintillation neutron detector with the same solid angle as that of the solid-state detector was placed 10 cm behind it to detect the breakup event of one singlet deuteron by coincidence measurement. The subtended angle of the ring-detector system was from 8.6° to 15.6°, which is large enough to involve breakup events corresponding to the breakup-energy range between 0.03 and 0.08 MeV. A small Si(Au) detector (denoted as detector 2) with solid angle of $9.5\times10^{-4}$ sr was located at angles of 34°, 36°, 38°, 40°, and 41° on the opposite side of the beam line to detect the protons emitted by the other $d^*$, which belongs to the same reaction events defined by the *p*-*n* detection system, using triple coincidence. Figure 2 displays the experimental arrangement.

### III. EXPERIMENTAL PROCEDURE

The experiment was performed by using the 1.4 m AVE Cyclotron of the Shanghai Institute of Nuclear Research, Academia Sinica. The energy of the deuteron beam was calibrated to be 15.7 MeV by using a Th $\alpha$ source. A $CD_2$ foil about 500 $\mu g/cm^2$ thick was placed at the center of Ortec-2800 scattering chamber. The electronic instrumentation consisted of standard fast and slow electronic modules. The two charged-particle detectors were followed by charge-sensitive preamplifiers. The cylindrical liquid scintillator was connected to a photomultiplier to detect neutrons. Timing information of charged particles was acquired by using timing filting amplifiers, constant fraction pulse discriminators (CFD's), and a time-to-amplitude converter (TAC). The pulse-height information of charged particles was extracted from the detectors by using shaping amplifiers, delay amplifiers, a pulse stretcher, the gates gated by neutron signals, and analog-to-digital converters (ADC's). The output of the TAC generated a master coincidence pulse which opened the ADC liner gates to initiate event processing. For each event two energy signals were

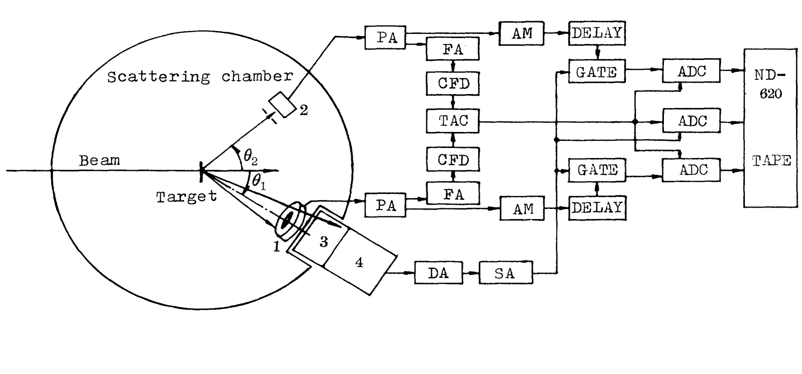


FIG. 2. Scheme of the experimental arrangement 1, ring Si(Au) detector; 2, Si(Au) detector; 3, scintillator; 4, photomultiplier; PA, preamplifier; FA, timing filting amplifier; AM, amplifier; DA, delay amplifier; SA shaping analyzer.

stored by an ND-620 multiparameter acquisition system and displayed as 64×64 channel $E_1$ and $E_2$ arrays. The data, including three signals, the $E_1$ pulse, the $E_2$ pulse, and the time signal, were also recorded event by event on magnetic tape for later off-line analysis.

The time-difference spectra were used to select coincidence events and to discriminate the true events from the backgrounds. The stability of the system was tested by a standard pulse between data runs. No absolute cross section was determined and no normalization was made for counts among runs.

## IV. RESULTS AND ANALYSIS

Data reduction has been carried out on PDP-11 computers. The proton spectra are extracted by projecting the two-dimensional spectra on the $E_2$ axis with a time interval of about 10 ns, which corresponds to the time-difference range between two protons we are interested in. Five two-dimensional spectra corresponding to five $\theta_2$ are obtained. In agreement with the kinematic prediction, there are two obvious enhancements of counts in the regions near 1.7 and 2.6 MeV, respectively, along the $E_2$ axis, and there are continuous spectra nearly between 2 and 3 MeV along the $E_1$ axis since a ring detector has been used for proton 1. For the measurement of the four-body breakup reaction, the most important competing reaction is $^2H(d,dp)n$, and other possible interference may come from the reaction $H(d,pp)n$. At the geometry defined by the three detectors, neither of these two reactions contributes to the selected energy ranges. Figure 3 shows the spectra projected on the $E_2$ axis with the background subtracted. The error bars are statistical only, and the arrows represent the peak positions obtained from corresponding distributions by weighted averages. In Fig. 3, the distance between two peaks obviously varies with angle $\theta_2$.

The experimental data are summarized in Table I. $E_2$ are calculated from Fig. 3 with errors of about 0.07 MeV. The velocities of the protons, $V_p^l$, are calculated from $E_2$ using proton mass $m_p=1$ with errors of about 0.04. The errors of $\theta_2$ are about 0.5°. Using the values of $\theta_2$ and $V_p^l$ in Table I, we are able to make a velocity-distribution diagram of the outgoing protons, which is displayed in Fig. 4. As mentioned above (Sec. II) the velocity vectors of the products of the singlet deuterons will form a spherical surface in the $d^*$ center-of-mass system, and at the reaction plane there will be a circle of velocity vectors. Figure 4 manifests such a kinematic character, where the experimental points cover most of a circle. By least-squares fitting of the data with a circle equation, we obtain the radius of the circle

$$V_p^c=0.232\pm0.038 \ .$$

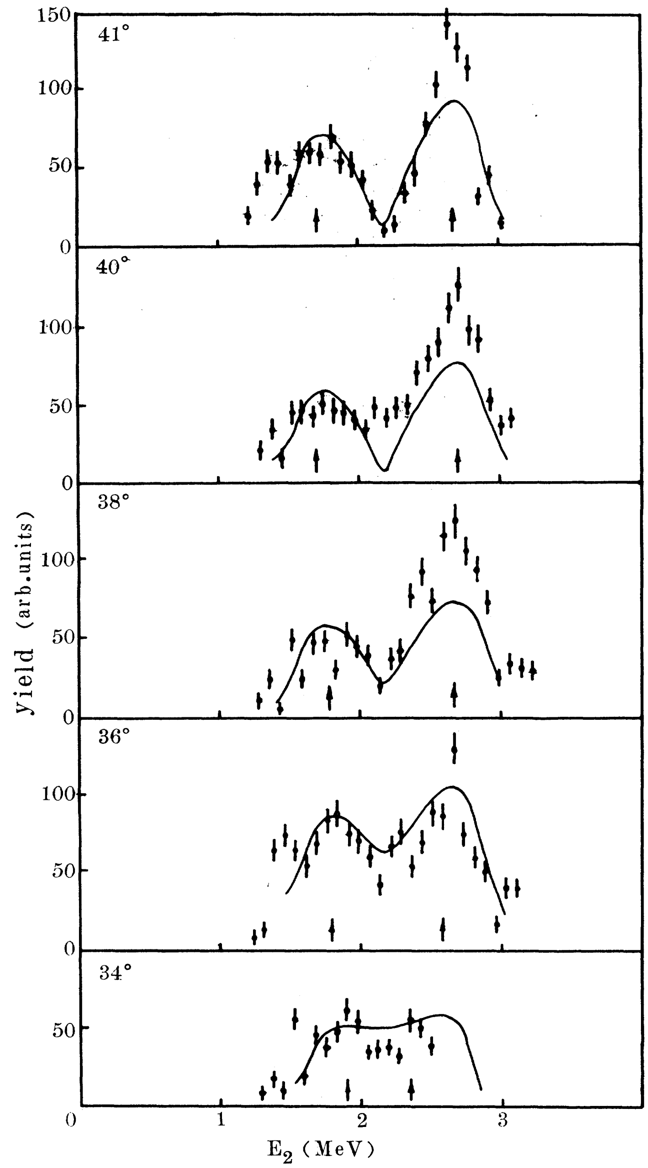


FIG. 3. Projected spectra on the $E_2$ axis. Points are the experimental data; solid lines are the FSI predictions.

According to formula (3) we get the most probable breakup energy of the singlet deuteron

$$E_{BU}=0.054\pm0.012 \text{ MeV} \ .$$

Also it is determined that the laboratory angle of detected $d^*$ is 39.9°.

As can be seen in Fig. 4, detector 2 with a finite subtended angle covers a bigger surface area at the right part

TABLE I. Summary of the experimental data in the measurement of the $d+d\rightarrow d^*+d^*$ reaction.

| $\theta_2$ | 34° | 36° | 38° | 40° | 41° |
|---|---|---|---|---|---|
| $E_2$ (MeV) | 1.89 2.37 | 1.81 2.56 | 1.79 2.69 | 1.69 2.74 | 1.73 2.66 |
| $V_p^l(m_p=1)$ | 1.94 2.18 | 1.90 2.26 | 1.89 2.32 | 1.84 2.34 | 1.86 2.31 |

of the breakup sphere, which corresponds to the higher peak of the spectrum, than at the left part at all selected angles except 34°. In Fig. 3 the total counts in the second peak are more than in the first for all angles but 34°.

The singlet deuteron is known as a virtual state of the $p$-$n$ quasiparticle. Generally such a state may be interpreted in terms of final-state interactions (FSI's). Watson and Migdal [22,23] have shown that, when a final-state $p$-$n$ pair have small enough relative momentum $\hbar k$, their wave function may be written

$$\psi_{np}=\frac{e^{-i\delta}\sin\delta}{k}f(r)\ , \tag{4}$$

where $\delta$ is the elastic scattering phase shift and $r$ is their separation. Thus, the square modulus of the matrix element contains a factor $(\sin^2\delta/k^2)$ for each $p$-$n$ pair in our experimental arrangements. Both the Wigner and the $V_{\sigma\tau}$ components of the nucleon-nucleon force can cause double breakup, and so the four-body final state is assumed to be an incoherent mixture of two ${}^1S_0$ (singlet deuteron) and two ${}^3S_1$ $p$-$n$ pairs. Therefore, the yield $Y(E,\theta)$ is given [24] by

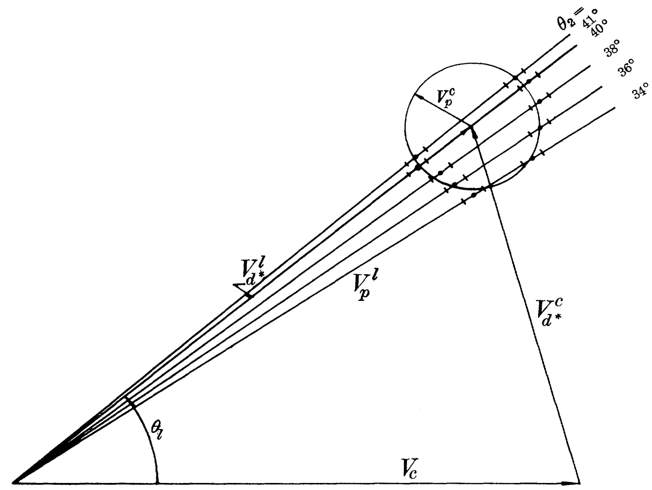


FIG. 4. Velocity-distribution diagram obtained experimentally. Points are the experimental data and the circle is the fitted result with $\theta_l=39.9°$, $V_{d^*}^l=2.09$, and $V_p^c=0.232$.

$$Y(E,\theta)=\int\left[\left[\frac{\sin^2\delta_1}{k_S^2}\right]_S\left[\frac{\sin^2\delta_1}{k_R^2}\right]_R+\eta\left[\frac{\sin^2\delta_3}{k_S^2}\right]_S\left[\frac{\sin^2\delta_3}{k_R^2}\right]_R\right]\rho_F\sin\theta_R\,d\theta_R\,d\phi_R\,dk_R\ , \tag{5}$$

where $\rho_F$ is the density of final states. The subscript $S$ designates the proton detected on the small detector and the neutron emitted nearest to it, and $R$ designates the $p$-$n$ pair detected on the ring assembly. The singlet and triplet $p$-$n$ phase shifts $\delta_1$ and $\delta_3$ were calculated from the effective range parameters of Kühn [25]. Here no integration for neutron emission angles was considered because at our geometry the neutron emission angles are defined. The normalization $A$ and triplet-to-singlet ration $\eta$ were the only parameters adjusted to fit data points. The factors $(\sin^2\delta/k_R^2)_R$ were integrated over the ring-detector geometry under the restriction of overall energy conservation. The FSI predictions are shown in Fig. 3. The peak positions of the spectra, which are of fundamental importance to extracting the most probable breakup energy of the state, were reproduced very well for all the five spectra by the results of the calculation. In general the FSI prediction also fits the experimental shapes fairly well. The calculation was insensitive to the ratio $\eta$. In a wide range of $\eta$ between 0 and 10, no visible change appeared. Thus the singlet deuteron FSI has greater strength than the triplet states. The integration for the $d^*$, detected by the ring-detector system over a range from the value defined by the inside radius of the ring detector (corresponding to the breakup energy of 0.03 MeV) to the value determined by the outside radius (0.08 MeV), made the fitted spectra narrower than what would be obtained if the complete solid angle were used. This results because the overall energy conservation restricts the possible breakup events detected in the small detector. The count losses appear at both low- and high-energy tails of each peak for every spectrum, but the peak positions do not shift with integration limits.

## V. SUMMARY

The $d+d\rightarrow d^*+d^*\rightarrow p+n+p+n$ four-body breakup reaction has been studied by a kinematically complete measurement at 15.7 meV bombarding energy. A ring-detector system consisting of a solid-state detector and a liquid-scintillator neutron detector has been used to define one of the singlet deuterons, and a small solid-state detector has been placed on the opposite side of the beam to detect the protons emitted by the other $d^*$ at five laboratory angles. Five two-dimensional spectra of two proton energies and the corresponding projected spectra have been acquired. The results were compared with predictions based on a FSI calculation by using the known $p$-$n$ singlet phase shift. The calculation predicts the peak positions for all the five spectra very well and fits the shape fairly well for most of the spectra.

The experimental data construct a circle diagram in the velocity space. By fitting the data for the circle equation, the radius of the breakup sphere of the singlet deuteron has been obtained, and the most probable breakup energy of the singlet deuteron in the laboratory system is estimated to be $0.054\pm0.012$ MeV.

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