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Resonant diproton spectrum measured using the reaction $^2H(d,{}^2p)2n$ at 15.7 MeV

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(Received 18 March 1991)

According to the kinematic analysis two sets of laboratory angle pairs, coplanar and noncoplanar, were selected and the coincidence spectra of two protons outgoing from $^2H(d,{}^2p)2n$ reaction induced by 15.7 MeV deuteron were measured. The resonant spectrum of the diproton has been obtained. The peak, mean, and width of the spectrum are 0.43 ± 0.09 MeV, 0.45 ± 0.05 MeV, and 0.14 ± 0.13 MeV, respectively. The lifetime of the state is estimated to be $(4.8\pm4.3)\times10^{-21}$ s.

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

I. INTRODUCTION

The study of nucleon-nucleon interactions is of fundamental importance to nuclear physics. It provides us with the essential knowledge of the forces in nuclear systems. At low energy the spin and isospin of nucleon-nucleon systems have four possible combinations: $(S,T)=(1,0)$, $(0,1)$, $(1,1)$, and $(0,0)$, among which $(1,0)$ is the bound state of deuteron and $(0,1)$ corresponds to the singlet states of the dinucleon systems, including singlet deuteron, diproton, and dineutron. To date, experiments have described only evidence on the existence and range of the internal energies of the singlet states of dinucleons, and these states are not yet well known.

In recent decades there have been numerous investigations of the low-energy proton-proton interaction. These studies include measurements of the *p-p* scattering length and effective range [1–4], the deuteron disintegration induced by proton [5–10] and $^3He(\gamma,2p)n$ reactions [11], and one- or two-nucleon transfer reactions induced by ^3He [12–16].

The *p-p* interaction for low-energy scattering has been successfully treated by evaluation of the scattering length and effective range. The scattering result predicts that the lowest singlet state of the two protons is unstable. The data of the *p-p* final-state interaction show that in the spectra there is a broad peak for low relative *p-p* energy. The maximum occurs for $E_{pp}\sim0.4$ MeV [6]. Furthermore, extensive researches on the ^2He resonant state have been carried out via $(\alpha,{}^2He)$ reactions on $1p$- and $2s1d$-shell nuclei and $(d,{}^2He)$ reactions on ^6Li, ^{10}B, and ^{12}C by Jahn *et al.* [17], Fister *et al.* [18], and Stahel *et al.* [19], and a review of ^2He sequential decay experiments has been given recently by de Meijer and Kamerans [20]. ^2He energy spectra have been obtained from these reactions by a kinematically complete coincidence measurement of two protons with small relative energies. Projected proton energy spectra show an enhancement of the cross section over phase space as a result of the final-state interaction between two protons in a relative $^1S_0$ state.

Experimental systems capable of detecting nuclear reaction products in the resonant final state can open up a wide range of unexplored nuclear reactions. Robson [21] has pointed out that particle decay of a resonant system always produces a certain amount of kinematic focusing for the emitted pair in the laboratory reference frame. In general, the breakup energy of such a resonant system is expected to be relatively low compared with its kinetic energy, and therefore, the position of the breakup products will be confined to a fairly small cone. So it is possible to detect the resonant system by detecting the two products in coincidence. As mentioned above, several authors [17–21] have measured $(\alpha,{}^2He)$ and $(d,{}^2He)$ reactions by this method. However, because of the fixed positions and large acceptance angles of the two detectors, their experiments could only confirm resonant states, but failed to obtain the resonant spectrum.

This work is designed to measure the resonant diproton spectrum by using the $^2H(d,{}^2p)2n$ reaction at different geometries and to obtain some information on the properties of the diproton. The kinetic energies of two protons at different angles are measured at coplanar and noncoplanar geometries by using an improved detection method. Here we report our measured results of the breakup energy, the level width, and the lifetime of the diproton.

II. EXPERIMENTAL ARRANGEMENTS

Suppose that the $d+d$ four-body breakup reaction through the ^2p+2n intermediate state is a cascade process. At the first stage of the reaction, which can be considered as a two-body process, a ^2p system and a $2n$ system are formed. Then ^2p breaks up into two protons confined in a cone in the laboratory system. The size of the cone depends on the c.m. kinetic energy and breakup energy of ^2p. Figure 1 shows the kinematic diagram of the $^2H(d,{}^2p)2n$ reaction, where V_c is the c.m. velocity of the *d-d* system, V_{2p}^c and V_{2p}^l are the c.m. and laboratory velocities of ^2p, respectively, V_p^c are the outgoing proton velocities in the c.m. system of ^2p, V_{pi}^l are the laboratory velocities of protons, θ is the outgoing angle of ^2p in the laboratory system, and $\Delta\theta$ is the angle difference between two protons.

V_p^c depend only on the breakup energy E_{IP} of ^2p,

$$\tfrac{1}{2}m_p(V_p^c)^2=\tfrac{1}{2}E_{IP}\ ,$$

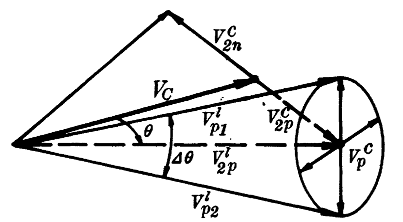

FIG. 1. Kinematics of the $^2H(d,^2p)2n$ reaction.

so that

$$E_{IP}=m_p(V^c_p)^2 \ . \qquad (1)$$

On the other hand,

$$(2V^c_p)^2=(V^l_{p1})^2+(V^l_{p2})^2-2V^l_{p1}V^l_{p2}\cos(\Delta\theta) \ . \qquad (2)$$

If energies E_1 and E_2 of two protons are experimentally measured at a given angle difference $\Delta\theta$, the breakup energy of diproton can be evaluated from formulas (1) and (2). The resulting distribution of breakup energy versus cross sections is called the resonant diproton spectrum. In the experiment measured E_{IP} values are dependent on both the angle difference between two protons and their energies E_1 and E_2, but not on beam energy and outgoing angles of protons.

In the study two kinematic configurations were chosen. In the first one two detectors were placed in the scattering plane around a central angle of 35° with $\Delta\theta=25.6°$, 32.3°, 35.9°, 39.9°, and 43.5°. In the second the detectors were perpendicularly located at two sides of the plane with the same polar angle θ of 34° around which four angle differences 27.5°, 29.3°, 31.3°, and 32.8° were selected.

III. EXPERIMENTAL PROCEDURE

The experiment was performed by using the 1.4 m AVF Cyclotron of Shanghai Institute of Nuclear Research, Academia Sinica. The energy of the deuteron beam was calibrated to be 15.7 MeV using a Th'c α source. A CD_2 foil about 500 $\mu g/cm^2$ thick was placed at the center of ORTEC-2800 scattering chamber. Two Si(Au) detectors of 2 mm sensitive thickness were used to detect the outgoing protons. They were placed on movable arms inside the chamber with a solid angle of about 6.1×10^{-4} sr each. The electronic instrumentation consisted of standard fast and slow electronic modules. All detectors were followed by charge-sensitive preamplifiers. Timing information was derived by using timing filter amplifiers, constant fraction pulse discriminators (CFD's), and a time-to-amplitude converter (TAC). The time resolution obtained with *d-d* elastic scattering at ±45° was 1.4 ns. Pulse-height information was extracted from the detectors using shaping amplifiers, delay amplifiers, pulse stretchers, and analog-to-digital converters (ADC's). The output of the TAC generated a master coincidence pulse which opened the ADC linear gates to initiate event processing. For each event two energy signals were stored by an ND-620 multiparameter acquisition system 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 absolute cross sections of the first configuration were obtained by detecting deuterons of *d-d* elastic scattering from the CD_2 target. The time spectrum was used to select coincidence events and to discriminate *p-p* events from the background with the help of kinematics. The stability of the system was tested by a standard pulse between datum runs. In addition, a monitoring detector was placed at 45° to normalize the data for different angles by detecting *d-d* elastic scattering.

IV. RESULTS AND DISCUSSION

Datum reduction was carried out on PDP-11 computers. The proton spectra were extracted by projecting the two-dimensional spectra on both *x* and *y* axes with a time interval of 0±5 ns. The background subtraction was made in correspondence with the flat part of the time-difference spectra. The breakup energy E_{IP} was deduced from $\Delta\theta$ and the corresponding peak energies E_1 and E_2

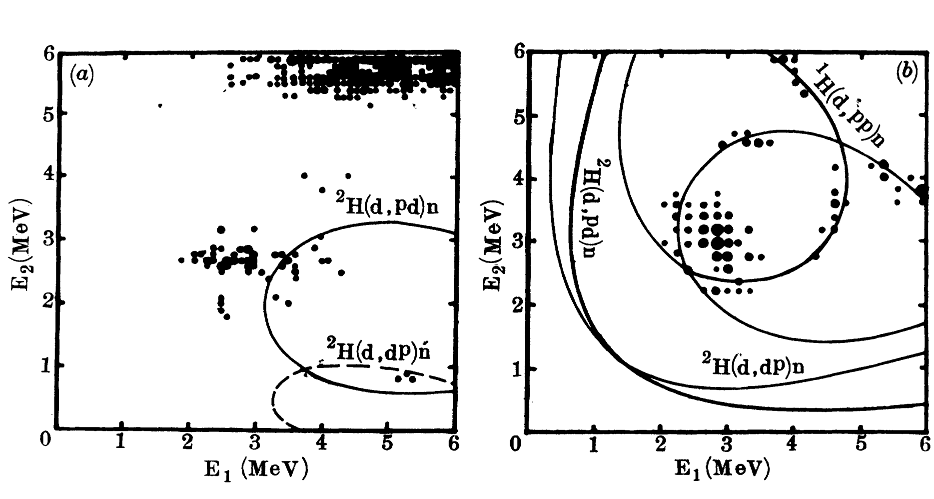

FIG. 2. Two-dimensional spectra: (a) coplanar geometry, $\Delta\theta=32.3°$; (b) noncoplanar geometry, $\Delta\theta=29.3°$.

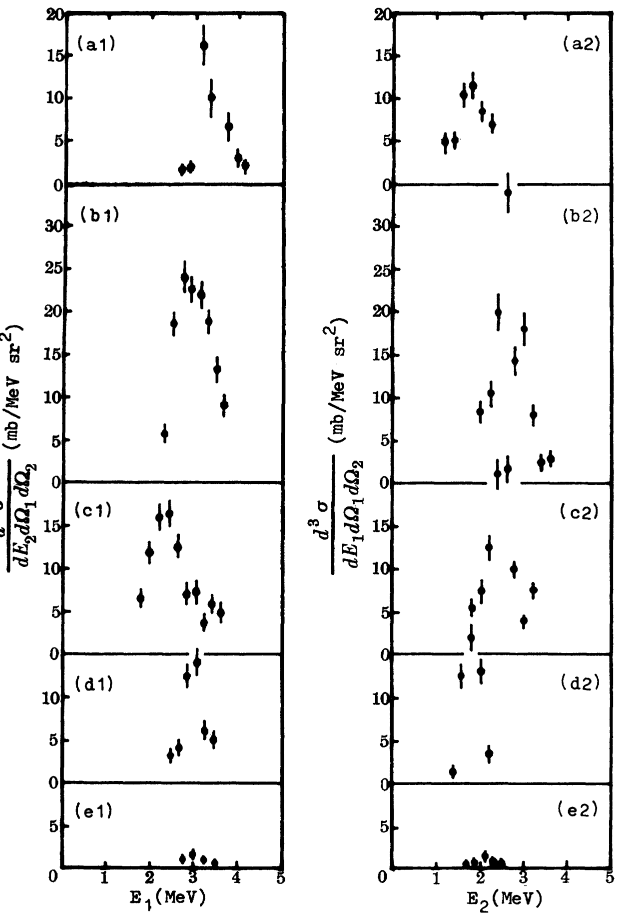

FIG. 3. Projected spectra of five angle pairs of coplanar set: (a) $\Delta\theta=25.6°$, $\theta_1=24.1°$, $\theta_2=49.7°$; (b) $\Delta\theta=32.3°$, $\theta_1=19.9°$, $\theta_2=52.2°$; (c) $\Delta\theta=35.9°$, $\theta_1=17.8°$, $\theta_2=53.7°$; (d) $\Delta\theta=39.9°$, $\theta_1=15.2°$, $\theta_2=55.1°$; (e) $\Delta\theta=43.5°$, $\theta_1=12.8°$, $\theta_2=56.3°$.

of the projected proton spectra, and the differential cross section $d^2\sigma/(d\Omega_1 d\Omega_2)$ was calculated from integration of the area under the projected spectrum.

Figure 2 shows two two-dimensional spectra for the

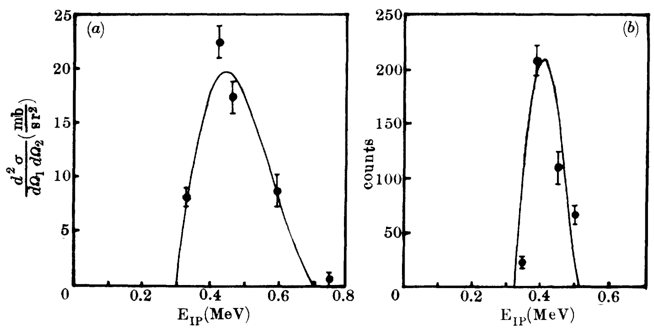

FIG. 4. Resonant diproton spectra: (a) coplanar geometry; (b) noncoplanar geometry.

two configurations. Figure 2(a) is the situation of a coplanar configuration at $\Delta\theta=32.3°$. There is an obvious enhancement of counts in the region of $E_1=2.9$ MeV and $E_2=2.5$ MeV, which belongs to the ^{2}H$(d,{}^2p)2n$ reaction. The real coincidences were found to be independent of background subtractions by choosing different flat parts of the time spectra. The large number of counts at the top of the spectrum came from *d*-*d* elastic scattering. The solid and dashed curves show the loci of ^{2}H$(d,pd)n$ and ^{2}H$(d,dp)n$ three-body breakup reactions, respectively. Both of these two reactions can be kinematically separated from the ^{2}H$(d,{}^2p)2n$ reaction. The ^{1}H$(d,pp)n$ reaction gives no contribution to the selected geometry area of Fig. 2(a). This is the reason that we have not used a counter telescope to identify particles. Figure 2(b) shows the two-dimensional spectrum of the noncoplanar configuration at $\Delta\theta$ of 29.3°. An obvious enhancement in the energy region around 2.9 MeV is considered to be the events from the ^{2}H$(d,{}^2p)2n$ reaction because all the kinematical loci of ^{1}H$(d,pp)n$, ^{2}H$(d,dp)n$, and ^{2}H$(d,pd)n$ reactions are far away from the region of interest. The projected spectra of the coplanar geometry are displayed as an example in Fig. 3. The maximum counts are 150 and the error bars are statistical only. The error of the absolute cross sections is less than 20%, which mainly comes from errors of the *d*-*d* elastic scattering cross sec-

TABLE I. Summary of experimental data in the measurement of the ^{2}H$(d,{}^2p)2n$ reaction.

Coplanar geometry

θ_1	θ_2	$\Delta\theta$	E_1 (MeV)	E_2 (MeV)	E_{IP} (MeV)	$d^2\sigma/(d\Omega_1 d\Omega_2)$ (mb/sr^2)
24.1°	49.7°	25.6°	3.1	1.8	0.32	8.2
19.9°	52.2°	32.3°	2.9	2.5	0.42	22.5
17.8°	53.7°	35.9°	2.5	2.3	0.46	17.4
15.2°	55.1°	39.9°	2.9	2.2	0.61	8.9
12.8°	56.3°	43.5°	3.1	2.2	0.75	0.7

Noncoplanar geometry ($\theta=34°$)

$\Delta\theta$	E_1 (MeV)	E_2 (MeV)	E_{IP} (MeV)	Counts
27.5°	3.0	3.2	0.35	25
29.3°	2.8	3.0	0.38	210
31.3°	3.1	3.0	0.45	112
32.8°	3.0	3.2	0.50	69

TABLE II. Results on the resonant diproton spectrum.

Datum set	Peak value (MeV)	Mean value (MeV)	Width (MeV)	Lifetime (10^{-21} s)
Coplaner	0.44±0.08	0.47±0.04	0.15±0.11	4.4±3.2
Noncoplanar	0.41±0.10	0.42±0.06	0.12±0.14	5.5±6.4
Final result	0.43±0.09	0.45±0.05	0.14±0.13	4.8±4.3

tion, solid angles, and coincidence efficiency.

The experimental data are summarized in Table I, where E_{IP} are calculated by using formulas (1) and (2). For the second configuration we were not able to obtain the absolute cross sections. Figure 4 shows the breakup energy distributions of the diproton, where (a) is for the coplanar geometry and (b) is for the noncoplanar geometry. Polynomial fits to the data are presented, from which the peak and mean values of the breakup energy of the diproton as well as the width of the distribution are obtained. The results are summarized in Table II. The lifetime of the resonant state is also listed. Since the two datum sets are statistically independent, we quote the weighted mean values as the final results. The quoted uncertainties are dominated by the errors of E_{IP} contributed by angle errors and the errors associated with the subtraction of proton energies E_1 and E_2 from measured spectra, but they also include statistical errors which appear in the fitting parameters.

The resonant spectra displayed in Fig. 4 are asymmetric. The long tail at higher energy is due to the Coulomb repulsion between two protons.

V. SUMMARY

The ^{2}H$(d,{}^2p)2n$ reaction was studied at 15.7 MeV bombarding energy. Two sets of angle pairs, coplanar and noncoplanar geometries, were selected to emphasize the final-state interaction of two protons. A series of two-dimensional spectra and corresponding projected spectra were acquired. Interaction energies of two protons were calculated from these spectra for each angle pair according to kinematics. Then the breakup energy distributions of the diproton were obtained. The experimental results show that the diproton is a resonant state. The peak and mean values of the breakup energy are 0.43±0.09 and 0.45±0.05 MeV, respectively. The resonant width and lifetime of the state are 0.14±0.13 MeV and $(4.8\pm4.3)\times10^{-21}$ s, respectively.

In addition, the experimental method for measuring the resonant spectrum developed in this work is feasible.

The authors would like to thank their colleagues of the target manufacturing, cyclotron, and computer groups for their help in the experiment.

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