FOUR-BODY $d+d$ REACTION AT 46.7 MeV*

B. Struzhko

Institute for Nuclear Researches of the Ukrainian Academy of Science
Kyiv, Ukraine

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Two-dimensional proton–proton (pp) and proton–proton–neutron (ppn) coincidence spectra from d + d reaction were calculated, taking into account quasi free scattering (QFS) of protons and final state interaction (FSI) of neutron–proton pairs. Deuteron beam energy $E_0 = 46.7$ MeV, proton emission angles $\vartheta_1 = \vartheta_2 = 38.75°$, $\varphi_1 - \varphi_2 = 180°$ and a neutron one $\vartheta_n = 0°$ are the pp QFS kinematic conditions. The results are compared to appropriate experimental data. Contribution from singlet deuterons disintegration seems to prevail in coincidence spectra and about one fourth part of all coincidence events is from pp QFS.

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Some researches of four-body $d+d$ reaction are known at present [1–6]. It was found that quasi free scattering (QFS) and final state interaction (FSI) processes are important. Neutron–neutron (nn) and proton–proton (pp) FSI effects were observed in experiments [1,2]. QFS of protons was identified in the proton–proton–neutron (ppn) coincidence spectrum [6]. The increased yield of pp coincidence events was noticed at energies of pp QFS as well [3–6]. On the other hand, such interpretation of the double coincidence spectra cannot be only possible because np FSI processes are allowed, moreover proton angular and energy distributions from the $^2\mathrm{H}(d,d^*)d^*$ reaction are similar to those from pp QFS [7,8].

In this work the attempt is undertaken to estimate the contribution of various mechanisms, simulating pp and ppn coincidence spectra taking into account the np FSI and pp QFS and comparing them with the experimental data [6]. Effects of the target and detector dimensions and resolutions are taken into account. Beam energy $E_0 = 46.7$ MeV and emission angles of

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protons $\vartheta_1 = \vartheta_2 = 38.75°$, $\varphi_1 - \varphi_2 = 180°$ and a neutron one $\vartheta_n = 0°$ correspond to the pp QFS kinematic condition. The differential cross sections of the four-particle ^{2}H(d, pp) reaction are calculated by using the prescription [7]:

$$\frac{d^4\sigma(E_1, E_2, \vartheta_1, \varphi_1, \vartheta_2, \varphi_2)}{d\Omega_1 d\Omega_2 dE_1 dE_2} = \frac{(2\pi)^4}{v} \int \rho |F|^2 \sin\vartheta d\vartheta d\varphi \,. \tag{1}$$

E_1 and E_2 are energies of protons, $v = p_0/2m$ is a velocity of the deuteron in the beam, $\boldsymbol{p}_0$ is a deuteron momentum, m is the nucleon mass, ρ is a phase space factor [9], ϑ and φ are angles of a relative neutron–neutron momentum $\boldsymbol{k}_{nn}$. In calculations of the double coincidence spectrum $N_{pp}(E_1, E_2)$ an integration domain covers all possible directions $\boldsymbol{k}_{nn}$ (*i.e.* within of 4π), and for threefold coincidence N_{ppn} it is defined by a solid angle of the neutron detector. Transition matrix element is approximated as a sum

$$|F|^2 = c_1 |F_{\mathrm{QF}}|^2 + c_2 |F_{\mathrm{S}}|^2 + c_3 |F_{\mathrm{T}}|^2 \,. \tag{2}$$

F_{S} and F_{T} are the ^{1}S$_0$ and ^{3}S$_1$ np FSI amplitudes, F_{QF} is the pp QFS amplitude evaluated in the plain wave impulse approximation (PWIA) [10]:

$$|F_{\mathrm{QF}}|^2 = |\psi(\boldsymbol{p}_{pp}/2 - \boldsymbol{k}_{nn})|^2 |\psi(\boldsymbol{k}_{nn} - \boldsymbol{p}_{nn}/2)|^2 \frac{d\sigma_{pp}(k_{pp})}{d\Omega} \,.$$

$\boldsymbol{p}_{pp} = \boldsymbol{p}_1 + \boldsymbol{p}_2$, $\boldsymbol{p}_1$, $\boldsymbol{p}_2$ are momenta of protons in the laboratory system, $\boldsymbol{p}_{nn} = \boldsymbol{p}_0 - \boldsymbol{p}_{pp}$, $k_{nn} = \sqrt{mE_{nn}}$, $E_{nn} = E_0 + Q - E_1 - E_2 - p_{nn}^2/4m$, $Q = -4.449$ MeV, $\boldsymbol{k}_{pp} = (\boldsymbol{p}_1 - \boldsymbol{p}_2)/2$, $\boldsymbol{\psi}(\boldsymbol{k})$ is a Fourier component of the deuteron wave function. It is taken in the Hulthen form :

$$\psi(r) = \frac{\sqrt{ab(a+b)/2\pi}}{a-b} \frac{\exp(-ar) - \exp(-br)}{r} \,,$$

$h^2a^2 = mE_a$, $E_a = 2.2245$ MeV, $h^2b^2 = mE_b$, $E_b = 59.8$ MeV. Calculations are carried out in the simple impulse approximation (SIA) [10, 11] and in the modified one (MIA) [12] with $R = 4.6$ fm chosen.

Keeping in mind that k_{pp} is rather moderate for S wave interaction to be used and rather high for Coulomb terms to be neglected the cross section of proton–proton elastic scattering is calculated as [13]:

$$\frac{d\sigma_{pp}(k)}{d\Omega} = \frac{1}{k^2 + (-1/a + rk^2/2)^2}$$

with $a = -7.813$ fm and $r = 2.78$ fm [14].

F_S and F_T terms in (2) are calculated by using the Watson–Migdal approximation:

$$|F_S|^2 = |F_{1S}|^2 |F_{2S}|^2 .$$

F_{1S} and F_{2S} are for neutron–proton pairs emitted to the left and to the right of a beam direction,

$$\begin{aligned} F_{1(2)S}(k) &= \frac{r(k^2+\alpha^2)}{2(-1/a + rk^2/2 - ik)}, \\ \alpha &= \frac{1+\sqrt{1-2r/a}}{r}, \quad hk = \sqrt{mE_{np}}. \end{aligned} \tag{3}$$

The expressions for ${F_T}^2$ are similar. Parameters a and r are equal -23.748 and 2.75 fm for the $^1S_0$ np state and 5.424 and 1.759 fm for $^3S_1$ [14]. As

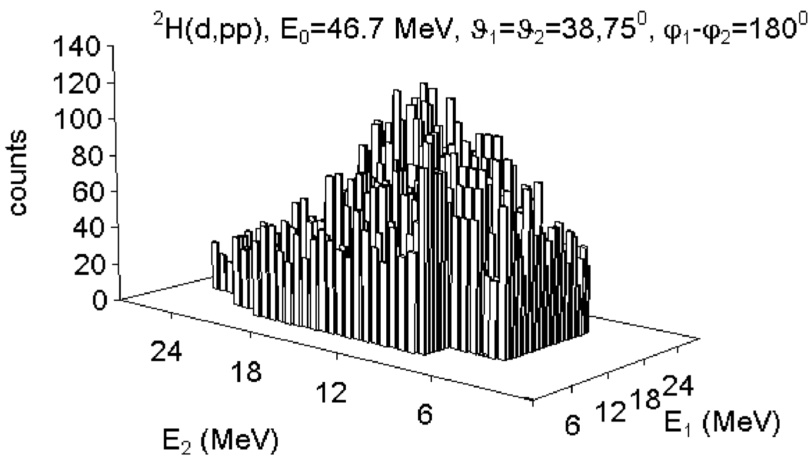

Fig. 1. Two–dimensional *pp* coincidence spectrum [6]

we know, at our energies SIA does not reproduce absolute values of cross sections [15], but the relative distributions of spectator momenta are consistent with experimental ones [13], so it is possible to estimate the QFS contribution to the double pp coincidence spectrum from the threefold ppn coincidence one. The experimental *pp* coincidence spectrum is shown in the Fig. 1. Calculated cross sections and data on the cut along a diagonal $E_1 = E_2$ are shown in Fig. 2. Only the first term in the sum (2) was taken into account. Calculated cross sections are multiplied with a factor

$c_{\rm norm} = 0.2$. SIA and MIA calculations without target and detector dimensions and resolutions taken into account are shown as dashed and dotted lines. Factors $c_{\rm norm}$ are 0.2 and 1.0 respectively. Angular distribution of neutrons — 'spectators' from ^{2}H(d, ppn) reaction is strongly directed forward. Function $dN/d(\cos\vartheta) \sim 1/(0.0019 + \sin^3\vartheta)$ is a good approximation for angular distribution at angles $\theta_n < 20°$. Equally Gaussian function $dN/dE_n \sim \exp\{-\ln 2(E_0 - E_n)^2/H^2\}$ is a good approximation for the neutron spectrum at $\theta_n = 0°$ with $E_0 = 23.4$ MeV and $H = 5.5$ MeV. The average efficiency η of the neutron detector is calculated with the adapted Stanton code [16]. Calculated ratio $\eta N_{ppn}/N_{pp} = 0.026$, that 4 times exceeds the experimental value 0.0061 ± 0.0007 [6]. This result can be interpreted assuming that pp QFS contribution to the pp coincidence spectrum in Fig. 1 really exists but amounts only to about quarter of all events. By the way the value $c_{\rm norm}/4 = 0.05$ almost coincides with a factor 0.049 obtained for ^{3}He$(^3$He$, dd)pp$ reaction at beam energy 50 MeV [10].

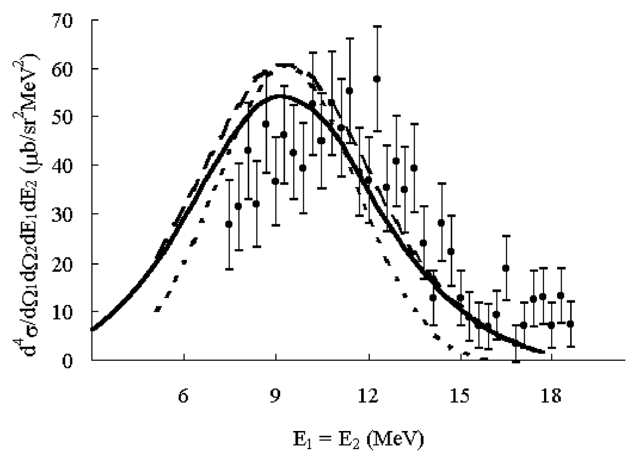

Fig. 2. Simulated cross sections for pp QFS and data along the diagonal $E_1 = E_2$. Dashed and dotted lines are SIA and MIA calculations for dot geometry and ideal resolution.

Simulated spectrum with all three amplitudes in the sum (2) taken into account is given in Fig. 3. The fitting area in a plane E_1–E_2 is bounded with thresholds E_1, $E_2 = 7.8$ MeV and four-body limit of the $d+d \to p+p+n+n$ reaction and contains $m = 2694$ elements $N_{ij\,{\rm exp}}$ of an experimental matrix with errors $dN_{ij\,{\rm exp}}$ and simulated ones $N_{ij\,{\rm sim}}$. The value

$$\chi^2 = \frac{1}{m-3}\sum \frac{(N_{ij\,{\rm exp}} - N_{ij\,{\rm sim}})^2}{dN^2_{ij\,{\rm exp}}}$$

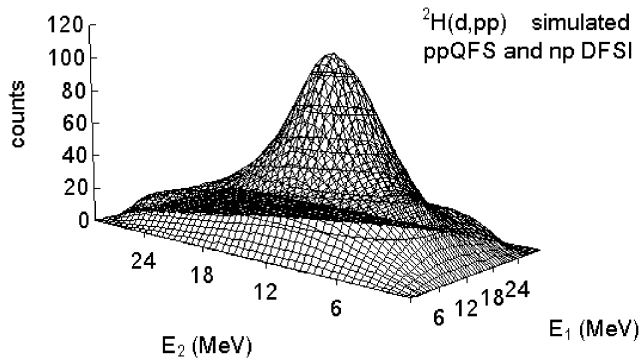

Fig. 3. Simulated pp coincidence spectrum with pp QFS and np FSI amplitudes taken into account. Fitting with the least squares method.

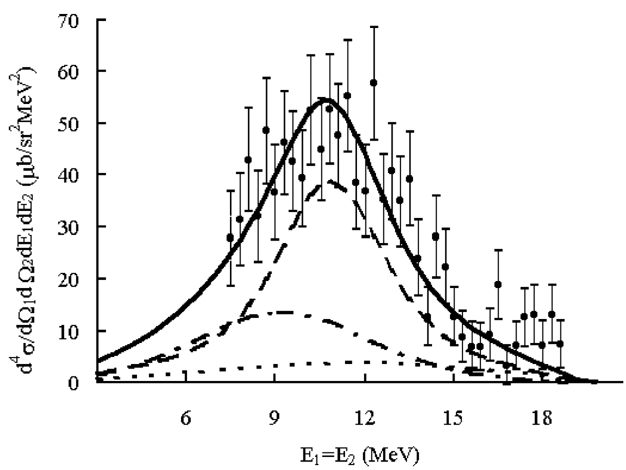

Fig. 4. Cuts of surfaces in Fig. 1 and 3 along a diagonal $E_1 = E_2$. Dashed–dotted, dashed and dotted lines are for the pp QFS (SIA), singlet and triplet *np* FSI respectively and solid line is their total contribution.

has appeared to be equal 1.5, and ratio of contributions from the separate terms in (2) on this area is $(0.20 \pm 0.04) : (0.65 \pm 0.07) : (0.15 \pm 0.03)$ in agreement with the value N_{ppn}/N_{pp}. Calculated cross sections and data [6] on the cut along $E_1 = E_2$ are shown in Fig. 4. The dash–dotted, dashed and dotted lines show the QFS component and FSI ones for ${}^1S_0$ and ${}^3S_1$ np states, respectively. So in an incomplete ${}^2\mathrm{H}(d,pp)$ experiments FSI effects are rather essential even at angles of pp QFS. It should be taken into account in interpretation of the data [3–6], and in the projects of future experiments.

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