Determination of Energy of $nn$-Singlet Virtual State in $d + ^2H \rightarrow p + p + n + n$ Reaction

Abstract The $nn$ final state interaction has been investigated in $d + ^2H \rightarrow (pp)^S + (nn)^S \rightarrow p + p + n + n$ reaction going through a formation and breakup of singlet diproton and dineutron in the intermediate state. In the kinematically complete experiment performed at $E_d = 15$ MeV two protons and neutron were detected at angles close to those of emission of $(pp)^S$ and $(nn)^S$ systems. Simulation of the reaction showed that the shape of neutron energy (timing) spectrum depends on $E_{nn}$—the energy of virtual $^1S_0$ state of $nn$-system. The most likely value $E_{nn} = 0.076\pm 0.006$ MeV was obtained by fitting procedure using the experimental data and simulations. This low value of $E_{nn}$ evidently indicates on effective enhancement of $nn$-interaction in intermediate state of the studied reaction.

1 Introduction

Nucleon-nucleon interaction have been studied for nearly a century and a great amount of data on proton-proton ($pp$) as well as neutron–proton ($np$) interactions has been accumulated over this period. Careful analysis of these has led to the construction of NN interaction potentials describing the vast majority of experimental data. The situation around neutron–neutron ($nn$) interaction is more ambiguous. In the absence of a neutron target, data on this interaction are obtained primarily from reactions with two neutrons in the final state. But in many cases, there are serious discrepancies between available experimental data and the results of the current precise calculations on the base of the Faddeev equations.

The most pronounced discrepancies were found in quasifree neutron–neutron scattering. The experimental cross sections obtained at 25–26 MeV exceed the theoretical estimates by about 18% [1,2]. At the same time, the theory describes well the cross sections obtained for quasifree $np$ scattering at these energies. Since at low energies the quasifree-scattering cross section is dominated by the singlet $^1S_0$ potential component, it was concluded by Witala and Glöckle [3] that this very component was underestimated and this was a reason for the discrepancy between experiment and theory. An increase of about 8% in this component results in agreement between theory and experiment for quasifree $np$ and $nn$ scattering. However, one may notice that authors did not explain the reasons for the introduction of such increase.

According to the authors of Dibaryon model of NN-interaction [4], the strong discrepancies of experiment and theory observed in $nd$- and $pd$-breakup reactions can be explained by a significant strengthening of $nn$- and $pp$-correlations of attractive character in the third nucleon field in $^3H$ ($pnn$) and $^3He$ ($ppn$) systems. New
mechanism arising in the Dibaryon model-scalar $\sigma$-meson exchange between the nucleon and dibaryon—is presented as diagram in Fig. 1a. One can propose that such mechanism also may be induced by $\sigma$-exchange between two dibaryons ($^1S_0$) in $d + d \rightarrow (pp)^5 + (nn)^5 \rightarrow p + p + n + n$ reaction (Fig. 1b).

So we suggest a study of various few body reactions such as $n + ^3H \rightarrow ^2H + (nn), n + ^2H \rightarrow ^1H + (nn), d + ^2H \rightarrow (pp) + (nn)$. In these experiments the energy of the singlet $nn$-virtual state will be determined in various reactions. Analysis of these energies will allow us to estimate the degree of $nn$-correlations in various reactions and determine the mechanism itself of these correlations. As a first part of this investigation we present a study of $d + ^2H \rightarrow (pp) + (nn)$ reaction, in which $nn$-correlated pair can be produced dynamically in the intermediate state. Thus, measured $nn$-correlation, in particular energy of $nn$ virtual singlet state may be different from that for the free $nn$-system.

2 Kinematical Simulation of $d + ^2H \rightarrow p + p + n + n$ Reaction

The kinematical simulation of the $d + ^2H \rightarrow (pp)^5 + (nn)^5 \rightarrow p + p + n + n$ reaction was performed using a program intended for studying reactions with three or more particles in the final state [5]. At first we perform simulation of “quasi-binary” reaction $d + ^2H \rightarrow (pp)^5 + (nn)^5$ at neutron energy of 15 MeV. Thus, masses of two-nucleon systems are taken in a fairly wide range relative to the estimated masses of virtual singlet states of $pp$- and $nn$-pair. The simulation results for quasi-binary reaction kinematics shown in Fig. 2 allow us to define the registration angles for the final protons and neutrons. Of the various combinations of angles, we chose those at which the energy of $pp$-system would be large enough to decrease the ionization losses of final protons, while the energy of $nn$-system would be relatively small to reduce the uncertainty in neutron energy determined by time-of-flight technique. On the other hand, it was necessary to take into account the experimental impossibility of proton registration at angles close to $0^\circ$ as well as a significant decrease in detection efficiency at low neutron energy. Therefore, the compromise registration angles and corresponding energies of $pp$ and $nn$ pairs were chosen (see, Fig. 2). It was assumed also that the both protons will be detected by the same detector and the neutron will be detected at the angle close to the angle of emission of $nn$-system.

Further simulation was performed for four-body kinematics at emission angles of neutrons and protons selected at the first stage ($\Theta_{p1,2} = 27^\circ \pm 1.5^\circ, \Theta_n = -36^\circ \pm 1.2^\circ$). As a result of simulation, we get an array of events with all parameters of four final particles (energies and emission angles). Additionally, using the information on the angles and energies of both neutrons we can construct the value of relative energy of two neutrons that is the excess energy of $nn$-system above the threshold of its breakup into two neutrons:

Fig. 1 The graphs illustrating the scalar force induced by $\sigma$-exchange between the $^1S_0$ dibaryon and third nucleon (a) and between two $^1S_0$ dibaryons (b)
Fig. 2 Kinematics of “quasi-binary” reaction $d + ^2H \rightarrow (pp)^S + (nn)^S$. Grey areas correspond to chosen angles: $\Theta_{pp} = 27^\circ$, $\Theta_{nn} = 36^\circ$.

Fig. 3 Simulation of $d + ^2H \rightarrow p + p + n + n$ reaction. a $E_{n1}-E_{n2}$ diagram, grey areas—events with $E_{nn} = 120 \pm 50$ keV. b Neutron spectra for democratic breakup and two variants of selection on $E_{nn}$.

$$E_{nn} = \frac{1}{2} \left( E_{n1} + E_{n2} - 2\sqrt{E_{n1}E_{n2} \cos \Delta \Theta} \right)$$

The data for all values of $E_{nn}$ correspond to the so-called democratic breakup. Two-dimensional $E_{n1} - E_{n2}$ diagram and neutron energy spectrum for all simulated events are shown in Fig. 3. Selection of events with predetermined values of $E_{nn} = E_{nn} \pm \Gamma_{nn}$ leads to structures both in two-dimensional $E_{n1} - E_{n2}$ diagram (Fig. 3a) and in neutron energy spectra (Fig. 3b). The presence of two peaks in these spectra is due to the fact that in reactions with formation and breakup of NN intermediate state, and under the condition that the breakup particle is detected at the angle of emission of NN-system, to hit the detector may only particles emitted in c.m. system either in the forward ($\sim 0^\circ$) or backward ($\sim 180^\circ$) directions. In general, it can be noted that the shape of the energy (and accordingly timing) neutron spectrum is sensitive to both $E_{nn}$ and $\Gamma_{nn}$ values that will allow us to determine them from a comparison of experimental and simulated spectra.

### 3 Experiment and Results

The experiment was performed at 15 MeV deuteron beam of SINP MSU. In the measurement the CD$_2$-target with thickness of 2 mg/cm$^2$ was used. Two protons were detected by a $\Delta E-E$ telescope at the angle of 27$^\circ$ while the neutron was detected at $-36^\circ$ (on the other side relative to the deuteron beam) with time-of-flight distance of 0.79 m. These angles correspond to angles of $(pp)^S$ and $(nn)^S$ emission in two body reaction. Thus,
Fig. 4 Simulation of passage of protons, deuterons, $^3$He and pp-pairs (grey points) through the $\Delta E–E$ telescope

in the $\Delta E–E$ telescope the total energy of two protons was determined. The neutron energy was determined by the time-of-flight technique.

The two-proton events in the $\Delta E–E$ telescope were selected by the ionization losses other than those for protons and deuterons events. Figure 4 shows the calculation results for passage of two secondary protons through the $\Delta E–E$ telescope as well as those for single protons, deuterons, and $^3$He. Since the energies of the two protons may differ significantly ($E_{p1} - E_{p2}$ two-dimensional distribution, in principle, is similar to that of $E_{n1} - E_{n2}$, shown in Fig 3a), the loss in $\Delta E$-detector may extend from $^2$He loss down to that of single proton, provided the second proton with low energy is not detected in the detector.

Thus, from the events corresponding to detection of two protons at $27^\circ$ and the neutron at $-36^\circ$ the timing spectrum of neutrons was formed. Figure 3a presents this experimental spectrum in comparison with simulated spectra for three values of $\epsilon_{nn} = E_{nn} \pm \Gamma_{nn}$. This figure shows the shape dependence of the neutron timing spectrum as a function of $\epsilon_{nn}$.

For determining the most likely value for $\epsilon_{nn}$ which is consistent with experimental data we calculated $\chi^2$ using the experimental data and simulations. In the process of fitting for each value of $E_{nn}$ the optimum value of width $\Gamma_{nn}$ was determined by a minimum value of $\chi^2$. Thus, for each value $E_{nn}$ the minimum value of $\chi^2$ has been found. Figure 5b shows a parabolic fit to the minimum $\chi^2$ values obtained at discrete values of $E_{nn}$. From this fit a value of $E_{nn} = 0.076 \pm 0.006$ MeV was determined, where the quoted uncertainty is based on the $\chi^2_{min} + 1$ criterion.

The $E_{nn}$ energy is related to the scattering length $a_{nn}$ and the effective range $r_{nn}$ by the equation:

$$\frac{1}{a_{nn}} = -\left(\frac{m_n E_{nn}}{\hbar^2}\right)^{1/2} - \frac{1}{2} r_{nn} \frac{m_n E_{nn}}{\hbar^2} + \cdots$$

(2)
According to Eq. (2), the obtained value of the virtual energy $E_{nn} = 0.076 \pm 0.006$ MeV corresponds to the value of the singlet $nn$-scattering length $a_{nn} = -22.2 \pm 0.6$ fm. This value of $nn$-scattering length significantly differs from the experimental values of $^1S_0$ $nn$-scattering length obtained in $nd$-breakup reaction $-16.2 \pm 0.4$ [6], $-16.5 \pm 0.9$ [7], $-17.6 \pm 0.4$ [8], $-18.7 \pm 0.6$ [9], $-18.8 \pm 0.4$ [10].

4 Conclusions

We investigated the $d + ^2H \rightarrow (pp)^S + (nn)^S \rightarrow p + p + n + n$ breakup reaction, passing through a formation in the intermediate state of dineutron and diproton singlet pairs. For the first time, in a kinematically complete experiment the energy of virtual state of $nn$-system $E_{nn}$ is determined. The most likely value $E_{nn} = 0.076 \pm 0.006$ MeV was obtained from the $\chi^2$ fit using the experimental data and simulations. The corresponding value of the $nn$-scattering length is much larger than values obtained in $nd$-reaction. This evidently indicates an effective enhancement of $nn$-interaction in the intermediate state of the studied reaction. In the future, it would be desirable to compare our experimental results with rigorous four-body calculations.

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