Acta Physica Polonica B Proceedings Supplement **17**, 3-A35 (2024)

OBSERVATION OF A NEW DECAY CHANNEL OF THE DD THRESHOLD RESONANCE*

R. Dubey[a], K. Czerski[a], Gokul Das H[a], M. Kaczmarski[a]
A. Kowalska[b], N. Targosz-Ślęczka[a], M. Valat[a]

[a]Institute of Physics, University of Szczecin, 70-451 Szczecin, Poland
[b]Institute of Mathematics, Physics and Chemistry
Maritime University of Szczecin, 70-500 Szczecin, Poland

Received 18 November 2023, accepted 13 February 2024,

High-energy electron–positron (e^+e^-) emission in the deuteron–deuteron reaction supporting the existence of the single-particle threshold resonance in ^{4}He has been observed. This observation suggests a new decay channel in the deuteron–deuteron reaction at extremely low energies. The experiment was carried out by employing Si detectors of different thicknesses and various Al absorption foils placed in the front of the detector at the eLBRUS Ultra High Vacuum Accelerator Facility of the Szczecin University, Poland. A deuterium beam was accelerated to energies ranging between 7 and 14 keV. The measured electron energy spectrum and the electron–proton branching ratio show a strong alignment with our expectations for an e^+e^- pair creation decay from the deuteron–deuteron 0^+ threshold resonance to the ground state, which should be many orders of magnitude stronger than other electromagnetic channels. Our detailed Monte Carlo simulations of the experimental energy spectrum also confirmed this alignment and predict an increase in the electron–proton BR when lowering the deuteron energy.

DOI:10.5506/APhysPolBSupp.17.3-A35

1. Introduction

The deuteron–deuteron (DD) reaction branching ratios (BR) at very low deuteron energies could be significantly changed by a threshold resonance due to its internal structure, expressed generally by partial resonance widths. The total resonance width is a sum of a deuteron, proton, neutron, and electromagnetic partial widths, and is strongly energy-dependent due to the penetration factor in the deuteron channel. Theoretical calculations

---

[*] Presented at the XXXVII Mazurian Lakes Conference on Physics, Piaski, Poland, 3–9 September, 2023.

assuming $J^{\pi} = 0^{+}$, based on the energy-weighted E_0 sum rule, predict a significant partial width for $e^{+}e^{-}$ internal pair creation (IPC) in the DD threshold resonance [1]. Detecting emitted electrons with a continuous energy spectrum up to 23 MeV in the DD reactions could provide additional evidence for the existence of this resonance [2], which holds significant implications for nuclear reaction rates in astrophysical plasmas and commercial applications of DD fusion reactions. The $e^{+}e^{-}$ channel's contribution to the DD reaction cross section can be observed at energies as low as 10 keV, where electron screening also contributes to the enhancement of DD reactions by reducing the Coulomb barrier [3]. The latter effect is especially vital in dense, strongly coupled stellar plasma environments, such as giant planets, brown dwarfs, and white dwarfs, where it can lead to substantial increases in the nuclear reaction rates. Investigating low-energy nuclear reactions in metallic environments with quasi-free electrons offers a unique opportunity for comparisons of experiment with theory. Interestingly, the screening energy values for metallic targets strongly depend upon the crystal lattice defects [4]. Therefore, a precise determination of threshold resonance parameters is crucial for understanding the observed enhancement of the DD reaction cross section in the metallic environment within the energy range where electron screening and threshold resonance excitation occur.

In this work, we report on the observation of the electron emission in the low-energy DD reactions which can originate from the internal pair creation decay of the threshold resonance. The experimental results will be compared to the theoretical calculations of the reaction BR, showing that the $e^{+}e^{-}$ transition to the ground state of ^{4}He might be the strongest reaction channel at very low deuteron energies. The experimental analysis is also supported by careful Monte Carlo simulations using the `Geant4` code [5].

2. Experimental setup

The experiment was performed at the eLBRUS Ultra High Vacuum Accelerator Facility of the University of Szczecin, Poland [6]. A deuterium beam was accelerated to energies ranging between 7 and 14 keV, with the constant beam current of 40 μA, using the magnetically analyzed single-charged atomic and molecular deuterium ions. The beam impinged on a 0.5 mm thick ZrD_2 target that was tilted at 45° to the beam, resulting in the beam spot size of 7×12 mm. To reduce the systematic uncertainties, only one EG ORTEC silicon detector of the 2 mm thickness and 100 mm^2 detection area, situated at the backward angle 135°, was used for all charged particles emitted: protons, tritons, and ^{3}He particles as well as electrons and positrons produced by the DD reactions. The traditional analog NIM bin system was used to process energy signals from the detector, and data were acquired via the TUKAN MCA. The experimental energy spectrum measured at deuteron energy of 14 keV using a 2 mm thick Si detector and 46 μm thick Al absorption foil is shown in Fig. 1. Instrumental methodology is discussed in detail in Ref. [7].

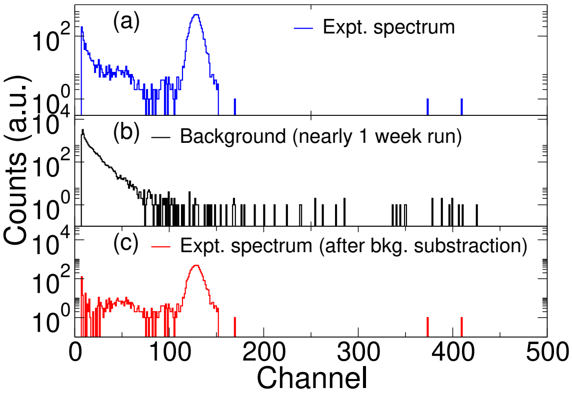

Fig. 1. Experimental energy spectrum measured at deuteron energy of 14 keV using a 2 mm thick Si detector and 46 μm thick Al absorption foil: (a) total experimental spectrum, (b) background, (c) experimental spectrum.

3. Results

In Fig. 2 (left panel), the response energy spectra of Si detectors with thicknesses of 1000–3000 μm, obtained for electrons and positrons produced in the DD reaction, simulated with Geant4, are presented. The comparison between the charged particle spectra measured at 14 and 7 keV deuteron energies and the simulated ones is shown in Fig. 2 (right panel). For both data sets, the average energy loss of electrons and positrons in the detector is about 625 keV. The theoretical spectra were normalized to the experimental counting rate observed in the energy region of 0.6–1.5 MeV, corresponding to the electron absorption bump.

The experimentally determined electron–proton BR for the deuteron energies of 7 keV and 14 keV are presented in Table 1. A clear increase in its value for the lower energy is observed. In the case of the DD reaction going through the known broad overlapping resonances of ^{4}He, we would expect a constant value of the studied BR. Thus, it is convincing to describe the experimental data with the IPC decay of the 0^+ threshold resonance.

In the case of neglecting the contributions of broad resonances, the BR IPC/protons is a ratio of the Lorenz resonance curves

$$R = \frac{\Gamma_{\mathrm{IPC}}}{(E-E_R)^2+1/4\Gamma^2} \Big/ \frac{\Gamma_P}{(E-E_R)^2+1/4\Gamma^2} = \frac{\Gamma_{\mathrm{IPC}}}{\Gamma_P} = \mathrm{const}\,. \qquad (1)$$

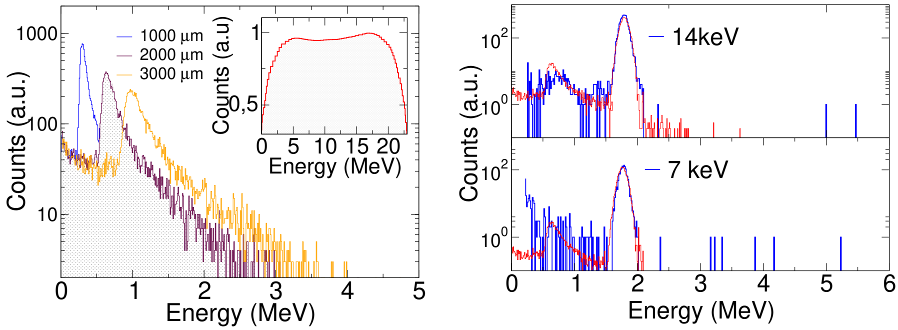

Fig. 2. (Colour on-line) Left panel: Response energy spectra of Si detectors with thicknesses of 1000–3000 μm obtained for electrons and positrons produced in the DD reaction, simulated with Geant4 [7]. In the inset, the original e^+e^- energy spectrum employed in the simulation, originating from the theoretically predicted internal pair creation process, is presented. Right panel: Experimental energy spectrum measured at deuteron energies of 14 and 7 keV using a 2 mm thick Si detector and 46 μm thick absorption Al foil (in blue/black). The electron spectrum calculated with Geant4 is presented in red/grey.

Table 1. The electron–proton BR determined for the deuteron energies of 14 keV and 7 keV compared with theoretical calculations.

Energy [keV]	BR (expt.)	$\varGamma_{\mathrm{IPC}}$ [meV]		$\varGamma_{\mathrm{IPC}}/\varGamma_p$
		incoherent	coherent	coherent*
14	0.08 ± 0.012	136 ± 20	127 ± 19	3.3 ± 0.6
7	0.60 ± 0.23	275 ± 105	155 ± 60	

*Weighted average.

To achieve an energy dependence of the BR, a contribution of broad resonances, which is relatively strong for the proton channel, should be obviously involved. The resulting formula for the BR taking into account also an interference effect between the broad resonances and the threshold resonance reads as follows [1]:

$$R=\frac{2\hbar^2}{\mu a}\frac{\varGamma_{\mathrm{IPC}}}{E^2}\Big/\left[\frac{k}{\pi}\frac{1}{\sqrt{EE_{\mathrm{G}}}}S(E)+\frac{2\hbar^2}{\mu a}\frac{\varGamma_p}{E^2}+2\left(\frac{k}{\pi}\frac{S(E)}{3}\frac{1}{\sqrt{EE_{\mathrm{G}}}}\frac{2\hbar^2}{\mu a}\frac{\varGamma_p}{E^2}\right)^{1/2}\cos\left(\phi^{0+}\right)\right]. \tag{2}$$

Here, we have assumed that the broad resonance contribution can be described by the astrophysical S-factor for the (d,p) reaction which is known and can be approximated by a constant value $S(E) = 57$ keV barn. Only one third of its value associated with the broad 0^+ resonances in ^{4}He can interfere with the threshold resonance, taking into account the 0^+ DD phase shift $(\phi) = 115°$. The threshold resonance terms corresponding to the IPC and proton channels could be simplified as the studied deuteron energies E are much larger than the resonance energy and the total resonance width. The wave number is denoted by k, and the channel radius a of the deuteron channel is equal to 7 fm [8]. The Gamow energy E_{G} equal to 986 keV describes penetration through the DD Coulomb barrier. The proton partial width of the threshold resonance is equal to 40 meV and was determined in the study of the $^2\mathrm{H}(d,p)^3\mathrm{He}$ reaction at very low energies [3]. Therefore, only one parameter remains free and can be fitted to the experimental BR. The results of calculations taking into account the interference term and neglecting it are presented in Table 1.

4. Discussion and conclusions

High-energy electron/positron emission in DD reactions at extremely low energies has been detected using a relatively thin Si detector, based on the observation of the characteristic absorption bump and the Geant4 Monte Carlo simulations. It is likely explained by the decay of a 0^+ threshold resonance through IPC which should be many the order of magnitude stronger than other electromagnetic transitions [8]. The branching ratio between γ rays and protons in the DD reactions was experimentally determined to be about 10^{-7} [9]. The internal electron conversion (IEC) and internal pair creation should be much weaker compared to the γ-ray transitions. Therefore, the electron/proton branching ratio of about 10 percent estimated from the present experiment can only be explained by the 0^+ threshold resonance in ^{4}He observed previously in the $^2\mathrm{H}(d,p)^3\mathrm{He}$ reaction [1, 3]. Additionally, the IEC transition probability is linear with the energy, oppositely to the internal pair creation for which an E^5 dependence is observed [10]. Therefore, the IEC transitions are many orders of magnitude less probable than IPC to the ground state corresponding to the 24 MeV transition energy.

Table 1 presents experimental data on the electron–proton BR, which was measured for electron energy losses ranging from 0.6 to 1.5 MeV. These measurements were conducted using a thin Si detector (2 mm thick) at deuteron energies of 14 keV and 7 keV and showed an increase in the electron–proton BR by a factor of seven for the latter. In addition, we compared these experimental results with theoretical calculations from Refs. [1, 2], taking into account (or neglecting) the interference effect between the threshold resonance and the known broad resonances in the compound nucleus ^{4}He. The IPC partial resonance widths calculated for the incoherent case differ strongly for two studied deuteron energies. Only, in the coherent case, the low-energy value could be corrected and agrees now with the 14 keV value, demonstrating importance of the destructive resonance interference effect that was previously observed in the $^2\mathrm{H}(d,p)^3\mathrm{He}$ reaction [3].

The experimentally observed increase in the electron–proton BR when lowering the deuteron energy could be explained by the IPC partial resonance width of about 140 meV which is more than 3 times larger than the proton partial width. This result agrees with the theoretical prediction of the IPC transition strength based on the energy-weighted E_0 sum rule [1]. The presented approach of measuring the electron–proton BR is independent of the electron screening effect which affects the penetration factor through the Coulomb barrier being equal for both studied channels and is eliminated from the expression for the BR. More exact data are expected for measurements of the BR for deuteron energies below 5 keV, which will be, however, very difficult due to the dropping cross-section values.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 951974.

REFERENCES

[1] K. Czerski, *Phys. Rev. C* **106**, L011601 (2022).

[2] K. Czerski *et al.*, *Phys. Rev. C* **109**, L021601 (2024).

[3] K. Czerski *et al.*, *Europhys. Lett.* **113**, 22001 (2016).

[4] A. Kowalska *et al.*, *Materials* **16**, 6255 (2023).

[5] S. Agostinelli *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **506**, 186 (2003).

[6] M. Kaczmarski *et al.*, *Acta Phys. Pol. B* **45**, 509 (2014).

[7] Gokul Das H *et al.*, *Measurement* **228**, 114392 (2024).

[8] D.R. Tilley, H.R. Weller, G.M. Hale, *Nucl. Phys. A* **541**, 1 (1992).

[9] F.J. Wilkinson III, F.E. Cecil, *Phys. Rev. C* **31**, 2036 (1985).

[10] J.T.H. Dowie, T. Kibedi, T.K. Eriksen, A.E. Stuchbery, *At. Data. Nucl. Data Tables* **131**, 101283 (2020).