

Spontaneous nuclear fusion

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We present the first experimental investigation of deuteron fusion at thermal energy performed underground. Using deuterated palladium targets, we measured spontaneous proton emission attributed to nuclear fusion reactions between deuterons. Protons with energies around 3 MeV, consistent with the expected signature of the deuteron-deuteron fusion reaction, were observed in palladium foils. Despite extensive efforts, we found no evidence for the predicted 0^+ resonance near the reaction threshold.

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I. INTRODUCTION

An experimental observation of the deuteron-deuteron (DD) fusion reaction at thermal energies is challenging due to the very low reaction rate. At these low particle energies, the probability of penetrating the repulsive Coulomb barrier, which must be overcome for fusion to occur, is extremely low. However, the electron screening effect enhances reaction rates between positively charged nuclei at low energies due to the lowering of the Coulomb barrier by atomic electrons surrounding the nuclei [1–3]. The effect is particularly strong for reactions with hydrogen isotopes when implanted into a solid lattice [4,5]. It can be further enhanced by introducing lattice defects that can trap target nuclei in regions of higher electron density, compared to the case when target nuclei occupy regular interstitial positions in the crystals [4,5]. An example of this behaviour is observed in palladium, where two different palladium targets were studied [5,6]. One target was annealed, resulting in a nearly defect-free sample. In the second target, crystal defects were introduced by the cold-rolling process and ion-beam bombardment. The annealed, undamaged sample did not produce significant electron screening. In contrast, a large screening energy was reported in the second palladium target, where the cold rolling increased the number of crystal defects into which hydrogen and deuterium atoms can be trapped [5,6]. Another independent study of the d+d reaction [7] showed similar lattice-dependent effects of electron screening induced by implanted deuterium and small amounts of oxygen impurities.

For the reaction between two deuterons, electron screening potentials, U_e , up to 800 eV have been measured [3]. According to the theory of electron screening [2], this means that the nuclear reaction cross section in the absence of resonances is

almost constant for all energies below the electron screening potential and its value is close to the one at 800 eV [4]. This would make the reaction measurable down to very low energies.

It was also suggested in Ref. [8] that electron screening alone may be insufficient to fully explain the experimentally measured DD fusion cross sections at the lowest energies. In that work, it was theorized that the presence of a near-threshold resonance could explain the obtained reaction rate. Although the products of deuteron fusion at high energies are protons, tritons, neutrons, and ^3He in equal amounts [9,10], the existence of the predicted 0^+ resonance close to the reaction threshold (23.85 MeV excitation energy) could open a new reaction channel leading directly to the ground state of ^4He nucleus at low deuteron energies [8,11–13]. This state is theorized to be a single-particle resonance having the d+d cluster structure, which results in a very small and energy-dependent resonance width (on the order of ~ 1 eV) having a large partial width for the internal electron-positron (e^-e^+) pair creation. The contribution of this channel to the d+d reaction cross section is expected to increase for decreasing deuteron energies far below the Coulomb barrier (with a height of about 320 keV [11,12]) and it is expected that the contribution of this channel becomes dominant below 5 keV [12,13]. The experimental observation of 0^+ threshold resonance has recently been reported in Refs. [12,13].

In this study, we present the first experimental results of the deuteron fusion at thermal energy conducted in underground laboratories. We have measured spontaneous proton emission from deuterated palladium targets induced by a nuclear fusion reaction between two deuterons. The energy of emitted protons was consistent with their emission from regions where ^{16}O and ^{19}F impurities had been previously implanted in palladium. However, despite extensive efforts, we found no evidence for the predicted 0^+ resonance near the reaction threshold.

II. METHODS

The experimental study was performed at Jožef Stefan Institute in Ljubljana. Spontaneous nuclear fusion was observed

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in two separate experiments. In both cases, our equipment was placed underground to decrease cosmic-ray background.

A. Detection system

We studied the deuteron fusion reaction with a ΔE -E telescope detector, placed in a high vacuum chamber. The detector was produced according to our specifications by Canberra Industries. It consists of a 300 μm thick Si detector and behind it a 1 cm thick Ge detector. Both detectors are placed in a common cryostat and cooled to the liquid nitrogen temperature. The cryostat is windowless and constantly kept under a vacuum. The active area of the Si detector has a diameter of 8 mm and the Ge detector has a diameter of 1.6 cm. The distance between the two detectors is 6.6 mm. In this setup, the electron detection efficiency was $(1.30 \pm 0.02) \times 10^{-4}$ and the resolution was (6.3 ± 0.1) keV at 976 keV. This was calibrated with a ^{207}Bi conversion electron source [14]. The energy range of the Ge detector was between 50 keV and 24 MeV and of the Si detector between 40 keV and 8.5 MeV. Electrons and positrons cannot be distinguished from each other in this setup, but are detected by demanding the signals from both detectors to reach the CAEN DT5780 digital multichannel analyzer within 200 ns of each other. Signal amplitudes and times from both detectors are written as list-mode data. In the offline analysis, an additional demand is set that the Si detector signal has to be between 40 and 200 keV to accept electron or positron events corresponding to the decay of the predicted threshold 0^+ resonance, according to Refs. [12,13].

B. Targets

Two different deuterium loaded Pd foils were used. Both palladium foils were produced by Zlatarna Celje goldsmith company by cold rolling Pd metal sheet from about 2.5 mm thickness to 0.1 mm. The foils had final dimensions of 2.5×2.5 cm and were labeled as 99.9% pure. They were loaded with deuterium at 1 bar pressure and 25 °C temperature for about 24 h. The deuterium gas contained 85% of D_2 molecules and 15% of H_2 ones. The palladium foil loses hydrogen in vacuum. A typical deuterium loss profile in vacuum is shown in Fig. 1. Deuterium concentration was determined gravimetrically. After palladium lost most hydrogen, the loading procedure was repeated. When maximally filled, the first target contained 0.47 and the second one 0.70 hydrogen atoms compared to palladium.

A uniform deuterium depth distribution was found in both targets. The deuterium depth distribution was determined with the nuclear reaction analysis (NRA) technique measuring high-energy protons emitted in the $^2\text{H}(^3\text{He}, p)^4\text{He}$ reaction [15] at six ^3He energies, in an energy range from 0.629 to 4.297 MeV. The deuterium depth profiles (see Ref. [5] for more details) were obtained by fitting the NRA spectra using the SIMNRA code [16].

C. The experimental procedure

In the first experiment, the telescope detector was placed at an angle of 45°, 9.1 cm from the target. In the second experiment, the detector was placed parallel to the target at a distance of 3.0 cm. Since the detector had to be refilled

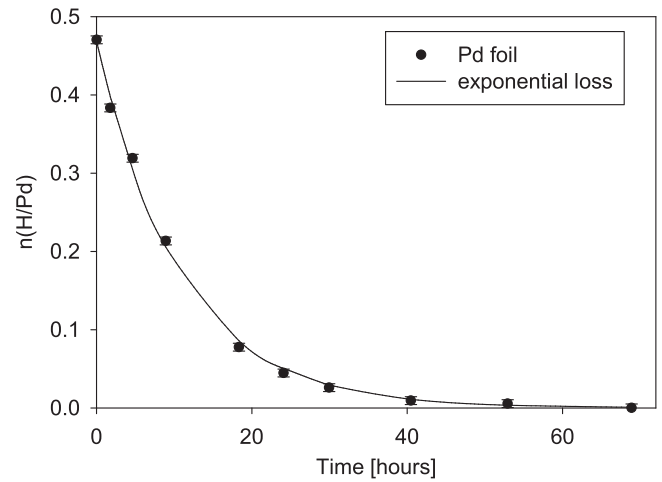


FIG. 1. The number of hydrogen atoms compared to palladium ones as a function of time the palladium foil spent in vacuum. The concentration closely follows the exponential decay law with a decay time of 10.8 h.

with liquid nitrogen every two to three days, the targets were also changed and refilled with deuterium at the same time. In the first experiment, only the first Pd foil was used (containing 47 at.% of deuterium at maximum), while in the second one the foil containing maximally 70 at.% of deuterium was used. Each measurement was in turn followed by a background measurement with the targets removed from the vacuum chamber. The same procedure was repeated for about three months in each case. Since the background in the germanium detector above 3 MeV represent cosmic muons, the entire setup was in the first experiment placed in a military bunker Škrilj near Kočevje, Slovenia. The bunker was built as a nuclear bomb shelter in the 1950s. The underground chamber was about 140 m from the entrance horizontally and 72 m below the surface vertically. This resulted in a decrease in cosmic-ray count rate by about a factor of 50 compared to the surface, while the number of horizontal cosmic rays that pass through both detectors decreased by a factor of about 35. The total measuring time on the palladium target was 34.49 days and the background was measured for 42.89 days. In the second experiment, the experimental setup was placed in a former mercury mine in Idrija, Slovenia. The underground chamber was in this case reached by a vertical elevator down to 122 m below the surface. This resulted in a decrease in cosmic-ray count rate by about a factor of 300 compared to the surface. The total measuring time on the palladium target was 38.87 days and the background was measured for 27.39 days.

III. RESULTS

Two silicon detector spectra from the first experiment are shown in Fig. 2. The black spectrum shows the background measurement and the red one the measurement on the Pd target. Only the first 31 h of each measurement were considered for the palladium foil data, resulting in an effective measuring time with the target of 16.67 days out of the total 34.49 days. This selection was made because, as shown in Fig. 1, the foil had lost nearly all of the deuterium after approximately 30 h

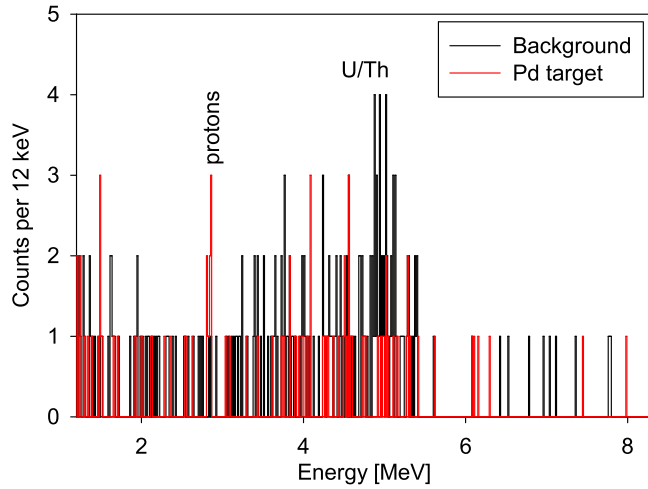


FIG. 2. Silicon detector spectra measured on palladium target in red color and without a target (background) in black color. 3 MeV protons from d+d reaction and α particles from the decay of natural uranium and thorium decay chains are marked. The measurements are from the military bunker. The spectrum with palladium foil was measured for 16.67 days and the background for 42.89 days.

in vacuum. The silicon detector spectrum measured on the palladium foil shows a peak at about 3 MeV (see Sec. IV). The same peak is not seen in the background spectrum, which contains mostly α particles belonging to the decays of natural $^{238,235}\text{U}$, ^{232}Th , and their daughters. There are 9 ± 3 counts in this peak after background subtraction.

The silicon detector spectrum from the second experiment on the palladium foils is shown in Fig. 3. The spectrum again shows a peak at about 3 MeV, but this time the peak is wider and has a slightly smaller energy than in Fig. 2. There are 12 ± 3.5 counts in this peak. The shown data correspond to 7 days of measurements, since only the first day of each measurement was taken into account. No background subtraction was

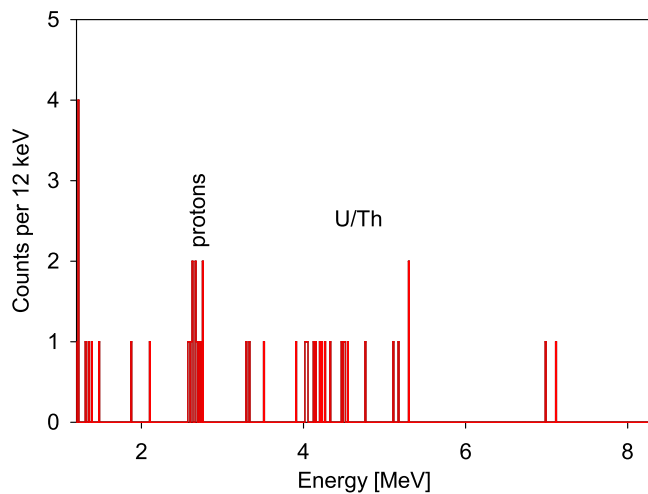


FIG. 3. Silicon detector spectrum measured on palladium target. 3 MeV protons from d+d reaction and α particles from the decay of natural uranium and thorium decay chains are marked. The measurement is from the mercury mine and shown data correspond to 7 days of measurements.

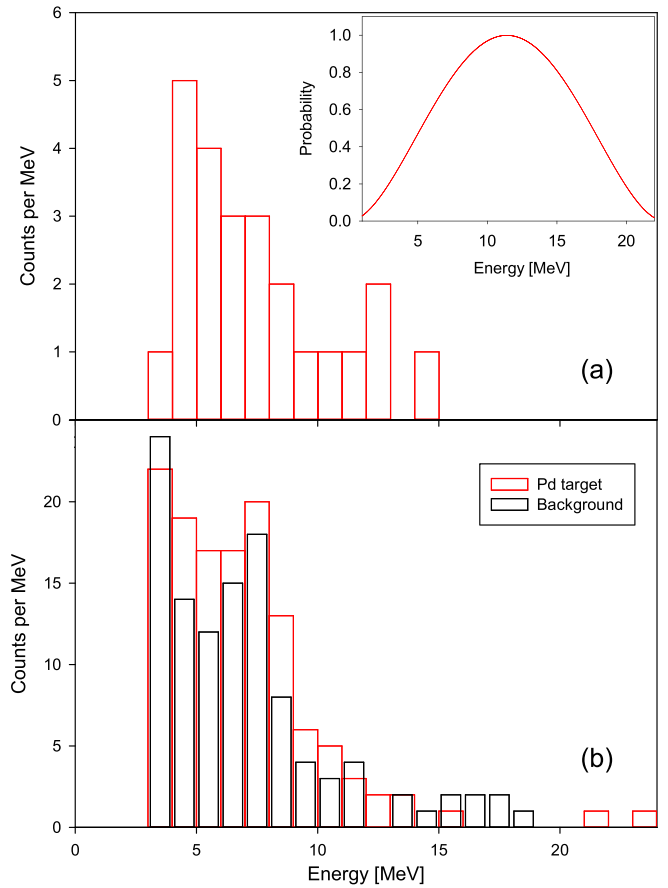


FIG. 4. Summed simultaneous Si and Ge detector events above 3 MeV. The expected electron-positron spectrum is shown as an insert in panel (a). The measurement [panel (a)] is on the Pd target from the mercury mine and lasted 38.87 days. The measurement [panel (b)] is from the military bunker. In this case, the Pd target was measured for 34.49 days and the background for 42.89 days.

needed, since the spectrum is relatively clean at energies of the protons and no background was detected at these energies.

Since the observation of the e^-e^+ pair emission from the d+d reaction was recently reported [12,13], we expected to measure more e^-e^+ pairs than protons. Therefore, we employed our ΔE -E telescope detector. The spectra were obtained by summing the energies of simultaneous signals from both silicon and germanium detectors. The Si detector energy was required to lie between 40 and 200 keV and the time window was 200 ns. Figure 4 shows in red color the electron spectrum measured on the palladium target and in black color the background. The expected electron-positron spectrum is shown as an insert [12,13]. Since the measured electron-positron spectrum shows no resemblance to the expected one, we conclude that it is due to cosmic rays and not due to the expected electrons or positrons deexciting the predicted 0^+ resonance in ^4He . In the military bunker, the target and background measurements did not show a statistically significant difference. The difference between the measurements in the bunker and the mine is due to different depths under the ground. The number of cosmic rays and their energies are lower in the deeper mercury mine.

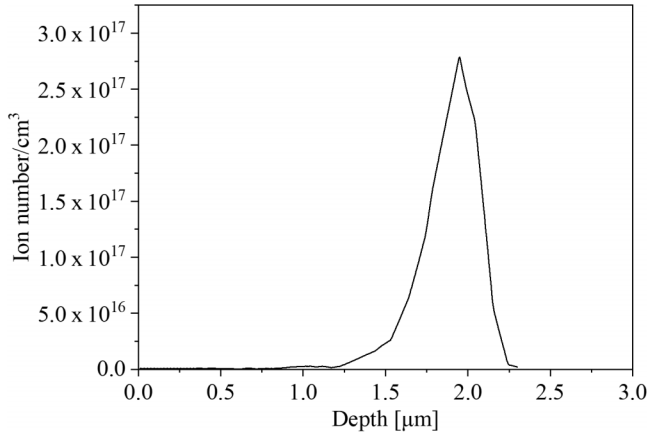


FIG. 5. Simulated distribution of ^{19}F in the first palladium target bombarded with 6.5 MeV ions. The simulation was performed with the SRIM code [18]. The number of implanted ^{19}F ions was $(2.1 \pm 0.1) \times 10^{15}$.

IV. DISCUSSION

The results can be interpreted using conventional knowledge of nuclear physics. The d+d fusion reaction proceeds at low deuteron energies through two main reaction channels $^2\text{H} + ^2\text{H} \rightarrow p + ^3\text{H}$ and $^2\text{H} + ^2\text{H} \rightarrow n + ^3\text{He}$ with a similar probability (0.5). In the first case, the reaction Q value is 4.03 MeV, which is carried away by the two reaction products. The energy is shared in proportion of their masses and the resulting protons have an energy of 3.0 MeV [17]. The protons from the military bunker have an energy of 2.82 MeV, since they lost about 180 keV in the palladium target. This means that they come from a target depth of 2.9 μm [18]. Taking into account that the target had an angle of 45° with respect to the detector, this corresponds to a depth of 2.0 μm in the target. At slightly lower depth, we see a peak in Fig. 5 that shows our simulation of ^{19}F distribution in the Pd target. The ^{19}F ions had been previously implanted into palladium, since we had used the same target for other experiments [5,6]. The simulation was performed using the SRIM code [18] with known implantation doses.

The second target used in the mercury mine contained no fluorine, since it was freshly prepared before the experiment. However, this target was prepared differently. Despite our explicit demand not to anneal the palladium, the manufacturer annealed it in air before cold rolling. This resulted in a layer of oxygen inside palladium. This was checked with the proton induced gamma-ray emission analysis technique, where at least a factor of 28 more oxygen was found in the 5 μm deep drilled hole compared to the surface of palladium. The protons from this target have a central energy of 2.63 MeV, corresponding to the energy loss of 370 keV in the palladium target. FWHM of the peak was 170 keV. This means that protons come from a target depth between 4.5 and 7 μm [17].

Cross-section estimation

The nuclear reaction occurs between deuterons jumping among the interstitial positions and deuterons that are trapped by impurities. The latter are more strongly bound in the

crystal than the first ones and cannot move between trapping positions [19]. Based on this assumption, we can calculate the cross section for the d+d reaction at thermal energies in the palladium target. The following estimate is based on a simplified phenomenological model that relates the measured proton yield to the density of trapped deuterium and the flux of mobile deuterium atoms. The purpose of this model is not to provide a complete description of the fusion process in palladium, but rather to obtain a first-order estimate of the effective reaction cross section from the experimentally measured data. The number of implanted ^{19}F ions was $(2.1 \pm 0.1) \times 10^{15}$. Assuming that each fluorine traps one deuterium atom, the above number is the number of target atoms N_t ; therefore, we can use the standard formula

$$N_p = \eta N_b N_t \sigma / S, \quad (1)$$

where N_p is the number of detected protons, η is the detection efficiency, and N_b/S is the number of beam particles per unit area. From Fig. 1, we estimate that the average deuterium concentration during our measurement was $C = 8.28$ at.% compared to palladium. The diffusion coefficient of deuterium in palladium at the constant temperature in the bunker of 289 K is $4.34 \times 10^{-8} \text{ cm}^2/\text{s}$ [19]. This diffusion coefficient corresponds to an effective deuterium transport velocity of approximately $v = 13.4 \text{ cm/s}$, which is used solely to estimate the flux of mobile deuterium atoms through the lattice. It does not represent the instantaneous velocity of an individual deuterium jump between neighboring interstitial sites. We can calculate the cross section σ as

$$\sigma = \frac{N_p}{t \eta N_t} \times \frac{M}{N_A \rho v} = (3.0 \pm 1.0) \times 10^{-16} \text{ b}. \quad (2)$$

Here, ρ and M are the density and molar mass of palladium, N_A is the Avogadro's number, and t is the time of the measurement (16.67 days). The proton detection efficiency η equalled $(1.30 \pm 0.02) \times 10^{-4}$ in the bunker experiment.

The detection efficiency in the mercury mine experiment was $(9.1 \pm 0.1) \times 10^{-4}$.

Assuming an astrophysical $S(E)$ factor of 59 b keV from Ref. [10] for the reaction between bare nuclei, we can also calculate the cross section using the equation [11,12]

$$\sigma = \frac{S(E)}{\sqrt{E(E + U_e)}} e^{-2\pi\alpha\sqrt{\mu c^2/2(E + U_e)}}, \quad (3)$$

where $E = 0.025 \text{ eV}$, α is the fine structure constant, and μ is the reduced mass, and we obtain that our derived cross section equals the experimental one at $U_e = (475 \pm 10) \text{ eV}$. This means that the electron screening potential equals 475 eV for our fluorine implanted palladium target. Such an electron screening potential is to be expected from other measurements in various metals, where electron screening potentials even up to 800 eV have been reported in palladium for the same reaction [3,20,21]. Reactions between two deuterium nuclei moving in the lattice are clearly much less likely than those involving trapped deuterium. This is because deuterium jumps occur in a correlated way. Long range correlations up to 1 μm in length have been reported [19]. This precludes us from estimating how likely such reactions would be. We could only calculate the cross section for the first target containing ^{19}F , since the amount of oxygen in the second target could not be

precisely determined due to its small concentration. We can only say that the reactions in the second target were less likely than in the first one.

V. CONCLUSIONS

We have for the first time seen spontaneous proton emission from palladium foils filled with deuterium. The protons come from the nuclear fusion reaction of two deuterons at thermal energy. The proton energy supports the emission from areas implanted with ^{16}O and ^{19}F impurities in palladium targets. The deduced cross section agrees nicely with other measurements of electron screening in metallic targets. Despite our best efforts, we could not confirm the existence of the predicted $J^\pi = 0^+$ narrow resonance at an excitation energy of 23.85 MeV in ^4He . We detected 12 protons in the mercury mine. According to the prediction of Ref. [12], the e^+/e^- reaction channel should be about 5 times stronger than the proton channel. Since the electron and proton detection efficiencies are very similar and since there are two leptons in the exit channel, we expected to detect about 120 electrons

and positrons. This is certainly not the case, but due to the limited statistics, we cannot exclude that some electrons are buried among the cosmic-ray background.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] E. E. Salpeter, Electron screening and thermonuclear reactions, *Aust. J. Phys.* **7**, 373 (1954).
 - [2] H. J. Assenbaum, K. Langanke, and C. Rolfs, Effects of electron screening on low-energy fusion cross sections, *Z. Phys. A* **327**, 461 (1987).
 - [3] F. Raiola, L. Gang, C. Bonomo, G. Gyürky, M. Aliotta, H. W. Becker, *et al.*, Enhanced electron screening in d(d,p)t for deuterated metals, *Eur. Phys. J. A* **19**, 283 (2004).
 - [4] A. Cvetinović, M. Lipoglavšek, S. Markelj, and J. Vesić, Molecular screening in nuclear reactions, *Phys. Rev. C* **92**, 065801 (2015).
 - [5] A. Cvetinović, D. Đeordić, G. L. Guardo, M. Kelemen, M. La Cognata, L. Lamia, *et al.*, Electron screening in palladium, *Phys. Lett. B* **838**, 137684 (2023).
 - [6] A. Cvetinović, M. Lipoglavšek, D. Đukić, M. Kelemen, M. Čekada, J. Vesić, and S. Markelj, Electron screening in lithium-induced nuclear reactions, *Phys. Lett. B* **868**, 139816 (2025).
 - [7] K. Czerski, A. Huke, P. Heide, and G. Ruprecht, The $^2\text{H}(d,p)^3\text{H}$ reaction in metallic media at very low energies, *Europhys. Lett.* **68**, 363 (2004).
 - [8] K. Czerski, D. Weissbach, A. I. Kilic, G. Ruprecht, A. I. Huke, M. Kaczmariski, *et al.*, Screening and resonance enhancements of the $^2\text{H}(d,p)^3\text{H}$ reaction yield in metallic environments, *Europhys. Lett.* **113**, 22001 (2016).
 - [9] F. E. Cecil, H. Liu, J. S. Yan, and G. M. Hale, Measurement of branching ratios of low energy deuteron-induced nuclear reactions on ^2H , ^6Li , and ^{10}B , *Phys. Rev. C* **47**, 1178 (1993).
 - [10] U. Greife, F. Gorris, M. Junker, C. Rolfs, and D. Zahnow, Oppenheimer-Phillips effect and electron screening in d+d fusion reactions, *Z. Phys. A* **351**, 107 (1995).
 - [11] K. Czerski, Deuteron-deuteron nuclear reactions at extremely low energies, *Phys. Rev. C* **106**, L011601 (2022).
 - [12] K. Czerski, R. Dubey, M. Kaczmariski, A. Kowalska, N. Targosz-Ślęczka, G. Das Haridas, and M. Valat, Indications of electron emission from the deuteron-deuteron threshold resonance, *Phys. Rev. C* **109**, L021601 (2024).
 - [13] R. Dubey, K. Czerski, H. Gokul Das, A. Kowalska, N. Targosz-Ślęczka, M. Kaczmariski, and M. Valat, Experimental signatures of a new channel of the deuteron-deuteron reaction at very low energy, *Phys. Rev. X* **15**, 041004 (2025).
 - [14] F. G. Kondev and S. Lalkovski, Nuclear data sheets for $A = 207$, *Nucl. Data Sheets* **112**, 707 (2011).
 - [15] S. Markelj, A. Založnik, T. Schwarz-Selinger, M. Kelemen, P. Vavpetič, and P. Pelicon, *In situ* study of deuterium retention in self-ion damaged tungsten exposed to neutral atoms, *Nucl. Fusion* **59**, 086050 (2019).
 - [16] M. Mayer, SIMNRA, a simulation program for the analysis of NRA, RBS and ERDA, in *Proceedings of the 15th International Conference on the Application of Accelerators in Research and Industry*, edited by J. L. Duggan and I. L. Morgan (American Institute of Physics, College Park, Maryland, 1999), Vol 475, p. 541, <https://mam.home.ipp.mpg.de/>.
 - [17] P. J. Mohr, D. B. Newell, B. N. Taylor, and E. Tiesinga, CODATA recommended values of the fundamental physical constants: 2022, *Rev. Mod. Phys.* **97**, 025002 (2025).
 - [18] J. F. Ziegler, J. P. Biersack, and M. D. Ziegler, *The Stopping and Range of Ions in Matter* (Lulu Press, Morrisville, NC, 2008).
 - [19] Y. Fukai, *The Metal-Hydrogen System*, 2nd ed. (Springer, Berlin, 2005).
 - [20] J. Kasagi, Low-energy nuclear reactions in metals, *Prog. Theor. Phys. Suppl.* **154**, 365 (2004).
 - [21] A. Huke, K. Czerski, P. Heide, G. Ruprecht, N. Targosz-Ślęczka, and W. Żebrowski, Enhancement of deuteron-deuteron fusion reactions in metals and its relation to electron screening, *Phys. Rev. C* **78**, 015803 (2008).