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Bound Diproton: An "Illusive" Particle or Exotic Nucleus?

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This paper considers the possible existence of a bound diproton. The study was inspired by the predictions of Migdal (*Sov. J. Nucl. Phys.* **16**, 238 (1973)), who solved a theoretical task for two identical particles to become bound in the potential field established by heavy nuclei. Earlier, the possibility of bound particles was confirmed experimentally in the case of the dineutron. We report the search for a bound diproton, or ^{2}He nucleus, analyzing the results of irradiation of several samples with protons with energies just below the thresholds in the corresponding $(p, 2p)$ nuclear reaction channel. The irradiated ^{159}Tb and ^{181}Ta samples were then counted by applying an HPGe gamma-spectrometer and featured a significant intensity of the 511 keV gamma-ray peaks. After acquiring data sets with peak intensities versus sample cooling times, the results were fitted with one or two exponential functions, and two experimentally determined half-lives were obtained for Ta sample, i.e., 6336 ± 220 s and 1224 ± 40 s. These values were in good agreement with the results of theoretical calculation based on the assumption of the 384 keV binding energy of the diproton. In addition, the radius and possible configuration and reaction mechanism were estimated and presented to serve together as a preliminary basis for confirming the existence of a bound diproton.

topics: diproton, positron decay, diproton half-life

1. Introduction

A bound diproton is one of three representatives of possible two-nucleon systems, including also its charge symmetric partners: the deuteron and the dineutron. By definition, such a unique nucleus should consist of two protons only with its total mass being less than the mass of the two separate protons. If such a two-proton system is to be observed, it will have far-reaching consequences for our understanding of nucleon–nucleon interactions, the structure of nuclei, theoretical predictions [1, 2] and even the stellar evolution [3]. Among these possible two-nucleon bound configurations, according to a hierarchy of their masses, the deuteron is most likely to be the lightest nucleus potentially allowing a corresponding beta decay of the dineutron or the diproton with the formation of the deuteron instead. However, for decades such a nucleus formed by two identical bound nucleons was considered non-existing due to the Pauli exclusion principle and the additional Coulomb repulsion for the diproton. At the same time, some theoretical studies do not rule out the bound diproton [4, 5], as well as the bound dineutron [5]. The main experimental search for the two-proton system were targeted at nuclei for which the subtle equilibrium between the numbers of neutrons and protons is violated with the greater amount of the latter. Then the limits of stability for such nuclei were exceeded, allowing their radioactive disintegrations via β^+, proton and two-proton decay. The last mode is predicted to occur since 1960 [1, 2] in the even-Z proton-rich isotopes beyond the beta-stability drip line and has been intensively studied over the last decades [6–9] in order to discover rather simultaneous two-proton emission. This emission can be realized in the following two different ways: either isotropic emission of two protons without angular correlation, or correlated emission, when a ^{2}He resonance is formed and which may decay easily penetrating the Coulomb and centrifugal barriers of the daughter nucleus or outside the barrier [6]. Even though in both cases a zero energy difference between the energies of the two protons is the most probable, and additionally for the emission of ^{2}He a small relative angle between the two correlated protons can be observable, as in the case of the dineutron emission [10].

However, it was never stated what these observations imply for a bound diproton. As predicted in [5], we have observed a bound dineutron [11, 12]. The same publication of Migdal [5] implicitly pointed out that " an analogous mechanism leads to bound states which are more complicated than the dineutron". Then, further more complicated bound states can be realized in a nuclear reaction and represent a nuclear system consisting of the residual nucleus and the diproton, which is located within a few fm from the nuclear surface of the residual nucleus. Such a configuration is different from the classical description of nuclear reactions at low energies when it is assumed that all particles lighter than the residual nucleus in the output channel are well separated by the distance from the residual nucleus itself [13].

Our success with the discovery of a bound dineutron made us follow the same idea to search for a bound diproton as a nuclear particle or ^{2}He nucleus in the nuclear reaction of a new type and a channel $(p, {}^2p)$.

2. Theoretical prerequisites

In line with the prediction made by Migdal [5], who theoretically confirmed the appearance of bound states for two identical particles, such as neutrons or protons, these states correspond to the single-particle levels at the additional energy branch, which ends up at an energy of about $\varepsilon_c \simeq 0.4$ MeV. Then any single-particle states are in the range of 0–0.4 MeV, and it would then be possible to directly observe one or both $(p,^2 p)$ nuclear reaction products under some specific conditions. It is important for diproton experiments to fix proton energies 0.05–0.1 MeV below the threshold of the corresponding $(p, 2p)$ nuclear reaction. Currently, taking into account that the diproton is a proton-rich or excessive nucleus, one can assume its β^+ decay, resulting in the appearance of a 511 keV annihilation peak in the instrumental gamma-spectrum of proton-irradiated samples. If this annihilation peak is observed in the corresponding spectra, then it will be the very first evidence that two interacting protons can form a bound state, even though their own interaction is insufficient for this to occur. Other evidence may come from the electron capture (EC) process and the observation of intense K_α/K_β transitions with the half-life, different from nuclear database values.

3. Experiments

To search for the bound diproton in the $(p, {}^2p)$ nuclear reaction (i.e., when proton energy $E_p \sim E_{\rm thr}(p, 2p)$ — threshold energy), we used the following samples with heavy nuclei: Tb, Ho, Er, Ta and Au with natural abundances. The irradiations of the samples were performed using the low-energy 11 MeV cyclotron Eclipse RD (Siemens).

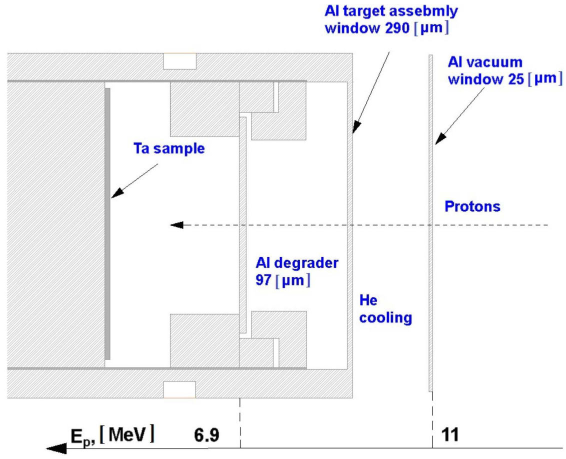

Fig. 1. Scheme of the experimental set-up for the Ta sample irradiated with the 6.9 MeV protons.

The energy of the protons E_p striking the investigated samples was ensured to be below the thresholds of the corresponding $(p, 2p)$ nuclear reactions by Al degraders installed between the vacuum window and the samples inside the target assembly. The value E_p and the energy straggling after degradation ΔE were determined by the SRIM-2013 code [14] for the initial energy of protons outgoing the cyclotron's tank ($E_{\rm in} = 11$ MeV). Figure 1 shows a scheme of the irradiation of Ta sample in the form of a disc with a diameter of 10 mm and thickness of 110 μm.

For this study, a gamma spectrometer with HPGe detector was used, namely, the GC2020 Canberra detector at the Department of Nuclear and High Energy Physics, Taras Shevchenko National University of Kyiv, Ukraine (TSNUK), for off-line measurements after irradiation of the samples and the obtained results are as follows:

– there was no broadened 511 keV peak of significant intensity in the instrumental gamma-ray spectra of the $^{\rm nat}$Er and ^{197}Au samples;

– there was a broadened 511 keV peak of significant intensity detected in the instrumental gamma-ray spectra of the ^{159}Tb, ^{165}Ho and ^{181}Ta samples.

In this experiment, the 97 μm Al degrader was applied, resulting in the energy of the protons bombarding the Ta sample to be $E_p = 6.9 \pm 0.2$ MeV. In such conditions, there were 120 irradiation iterations with 4.7 μA proton current, including 8 s for irradiation and 10 s for cooling time per iteration. Therefore, the overall time of the experiment was about 36 min with the total number of protons $\simeq 2.8 \times 10^{16}$ on the Ta sample. Along with Ta sample, similar irradiations were performed for the samples ^{159}Tb ($E_p = 6.1 \pm 0.3$ MeV), $^{\rm nat}$Er ($E_p = 8.0 \pm 0.1$ MeV), ^{197}Au ($E_p = 5.6 \pm 0.3$ MeV) and ^{165}Ho ($E_p = 5.8 \pm 0.4$ MeV).

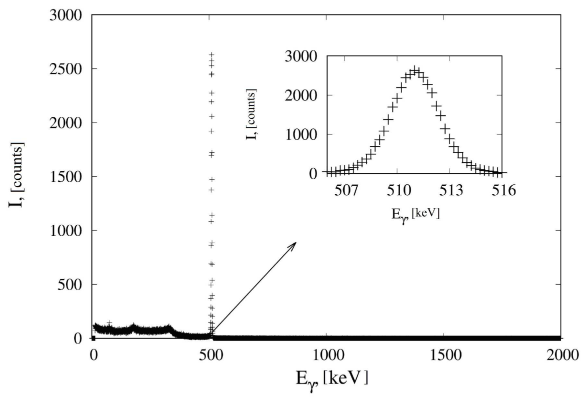

Fig. 2. Instrumental gamma-ray spectra of the irradiated Ta sample with the 6.9 MeV protons. The measurement time is 120 s.

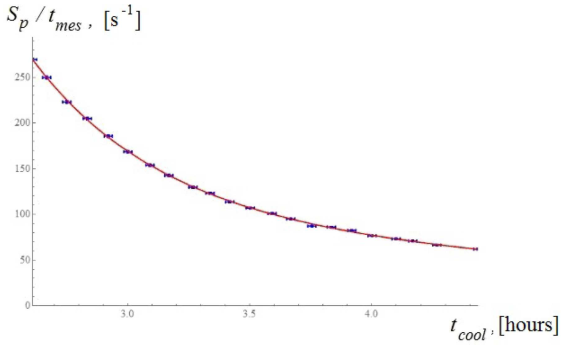

Fig. 3. Dependence of the intensity of the 511 keV gamma line versus time of cooling t_{cool}.

The peak of 511 keV in a typical instrumental gamma-ray spectrum is presented in Fig. 2 after irradiation of the Ta sample with $E_p = 6.9 \pm 0.2$ MeV $< E_{\rm thr}(p, 2p)$. By keeping the same geometry of the sample, and then having a set of 511 keV peak intensities as a function of time, this dependence was fitted with single and two exponential functions. The fit of the intensity set S_p/t_{mes} of the 511 keV gamma line with a single exponent function ($y(t_{cool}) = A \exp[-\ln(2) t_{cool}/T_{1/2}]$) for certain time of cooling (t_{cool}) gives the χ^2 value equal to 1430.6. The fit with two exponential functions $y(t_{cool}) = A_1 \exp[-\ln(2) t_{cool}/T_{1/2;1}] + A_2 \exp[-\ln(2) t_{cool}/T_{1/2;2}]$ gives $\chi^2 = 1.5$. Here, χ^2 is defined as follows

$$\chi^2 = \frac{\sum_{i=1}^{N_{\rm points}} \left[S_{p,i}/t_{mes,i} - y_{N_{\rm par}}(t_{cool,i})\right]^2}{\left[N_{\rm points} - m\right]\left[\Delta S_{p,i}/t_{mes,i}\right]^2}, \tag{1}$$

where $N_{\rm points}$ is the number of the points in Fig. 3 ($N_{\rm points} = 35$); m is the number of parameters for the fitting, $m = 2$ or $m = 4$ for one or two exponent expression $y_{N_{\rm par}}(t_{cool,i})$, respectively; S_p and ΔS_p are the number of counts in the peak of 511 keV gamma line and its uncertainty, respectively; t_{mes} is the measurement time of the instrumental gamma spectrum; t_{cool} is the cooling time of the Ta sample by protons before the next subsequent counting; $y_{N_{\rm par}}(t_{cool,i})$ is the fitted value for the corresponding experimental point.

TABLE I

Parameters of the fitted line with two exponents $y(t_{cool}) = A_1 \exp[-\ln(2) t_{cool}/T_{1/2;1}] + A_2 \exp[-\ln(2) t_{cool}/T_{1/2;2}]$ to the 511 keV gamma intensity.

Parameters	Data
A_1	331 ± 18 s^{-1}
$T_{1/1;1}$	6336 ± 220 s
A_2	30517 ± 233 s^{-1}
$T_{1/2;2}$	1224 ± 40 s
χ^2	1.5

Two exponential components were identified with one order of value different initial intensities and the parameters of the experimental data fit, given in Table I.

The dependence of the intensity $I = S_p/t_{mes}$ of the 511 keV gamma line vs time t_{cool} is presented in Fig. 3.

In order to make sure that the source of positrons does not belong to any other reaction products, we analyzed all open reaction channels and the corresponding reaction products on the main isotopes. First, we checked out the isotopes produced in the (p, n) nuclear reactions on main isotopes such as:

- ^{159}Tb $(p, n)^{159}$Dy — EC decay only;
- ^{165}Ho $(p, n)^{165}$Er — EC decay only;
- ^{181}Ta $(p, n)^{168}$W — EC decay only.

The impurities in the Ta sample contained the following chemical elements:

- $^{\rm nat}$Mo — $0.0019 \pm 0.0036\%$;
- ^{93}Nb — $0.0151 \pm 0.0046\%$;
- $^{\rm nat}$Fe — $0.1326 \pm 0.0380\%$.

Second, the open channels of (p, x) reactions and the produced nuclides on main and impurity isotopes were analyzed (where x means all possible particles in the outgoing channel of a nuclear reaction). Based on the results of our analysis, no positron emitters were identified as reaction products with a similar half-live neither on the main elements nor on the impurities. In similar experiments with sample ^{159}Tb, we got the following half-life results: 5759 ± 131 s and 1120 ± 51 s using

- theoretical model;
- decay modes of the diproton/^{2}He and binding energies.

Then, due to no obvious sources of positrons generated in our samples after irradiation with protons, our "working hypothesis" became the formation of a bound diproton in the potential well of the residual nucleus with an atomic number $(A-1)$ and charge $(Z-1)$. The diproton consists of two protons only, so it should be susceptible to two possible decay modes, (i) EC: $^2p + e^- \to d + \nu_e$ and (ii) positron decay: $^2p \to d + e^+ + \nu_e$.

The binding energies for different processes have different values, i.e., $B_{dp} < 1.442$ MeV for EC decay; $B_{dp} < 0.420$ MeV for positron decay (nuclear process); $B_{dp} < 0.931$ MeV for an atomic-nuclear process (positron decay $^2\mathrm{He} \to {}^2\mathrm{H} + e^+ + \nu_e$). The last decay mode is the one most likely observed by our team.

4. Radius and half-lives of the diproton

The interval assessment for the diproton radius was performed based on these binding energy limits and a very well-known theoretical expression from the theory of nucleus

$$r_{dp}^2 = \frac{\hbar^2}{m_p\, B_{dp}}, \tag{2}$$

where m_p is the proton mass. An estimate of the diproton radius r_{dp} interval can be then obtained as follows

- for EC: $r_{dp} > 5.36$ fm;
- for nuclear positron decay: $r_{dp} > 9.94$ fm;
- for atomic–nuclear positron decay: $r_{dp} > 6.67$ fm.

To determine the half-life of the diproton, in a very first approximation, one can follow an approach according to which the diproton is assumed to be bound but it decays into the deuteron, positron, and the electron neutrino. To estimate its decay constant, the following expression can be used to describe the allowed and superallowed transitions [15]

$$f\, t_{1/2} = \frac{\tau_{1/2}}{B\,(\mathrm{F}) + \lambda^2\, B\,(\mathrm{GT})}, \tag{3}$$

where f is the phase space factor; $t_{1/2}$ is the half-life of the diproton; $\tau_{1/2}$ is 6145 s; $B(\mathrm{F})$ is the Fermi strength; $B(\mathrm{GT})$ is the Gamow–Teller strength; $\lambda = 1.27$ is a constant. For the diproton phase space factor determination, we used the following semi-empirical expression [16]

$$\log(f) = 4\log(E_{\max}) + 0.79 - 0.007\, A_d$$
$$-0.009\ (A_d{+}1)\ \frac{\left(\log(E_{\max})\right)^2}{9}, \tag{4}$$

where $E_{\max}$ is the endpoint energy of the positron spectrum; A_d is an atomic number of the product isotope, i.e., the deuteron.

For the Gamow–Teller transition, where a singlet state of the diproton transforms into a triplet state of the deuteron, it was obtained as follows: $B(\mathrm{F}) = 0$; $B(\mathrm{GT}) = 6$, then $f\ t_{1/2} = 634.98$ s. For the Fermi transition, where a singlet state of the diproton transforms into a singlet state of the deuteron, the results are as following: $B(\mathrm{F}) = 2$; $B(\mathrm{GT}) = 0$, then $f\ t_{1/2} = 3072.5$ s.

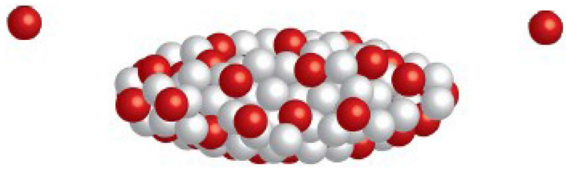

Fig. 4. Classical schematic representation of the diproton near the nuclear surface of the prolate deformed nucleus.

Based on the above indications, the interval estimated for r_{dp} is $9.94 < r_{dp} < 10.5$ fm and the interval estimated for B_{dp} is $0.376 < B_{dp} < 0.420$ MeV. Our assumption (guess) was $B_{dp} = 0.384$ MeV and $r_{dp} = 10.4$ fm.

Then, the Q values for three possible decay modes of the diproton/^{2}He were calculated and are

- for EC: $Q = 1058$ MeV;
- for nuclear positron decay: $Q = 0.036$ MeV;
- for atomic–nuclear positron decay: $Q = 0.547$ MeV.

Thus, the endpoint energy of the positron spectrum is equal to $E_{\beta+\max} = (0.931\ \text{MeV} - 0.384\ \text{MeV}) = 0.547$ MeV, and the half-lives of the diproton/^{2}He have the following values: $t_{1/2}(\mathrm{F}) = 5516 \pm 1030$ s (the experimental result obtained is 6336 ± 220 s); $t_{1/2}(\mathrm{GT}) = 1140 \pm 216$ s (the experimental result obtained is 1224 ± 40 s).

5. Nuclear configuration of the diproton

Simple classical interpretations based on the minimum of the energy of the $A-1$ $(Z-1)$ residual nuclei give the position of the diproton near the nuclear surface [5] of deformed prolate nuclei (^{180}Hf or ^{158}Gd) close to the poles as it is presented in Fig. 4.

6. Conclusions

It was indicated experimentally the possibility of the diproton existence in a bound state as a particle–satellite in the outgoing channel of a nuclear reaction with protons and odd (by proton numbers) heavy nuclei ^{159}Tb, ^{165}Ho, ^{181}Ta in the input channel. No such effect of diprotons generation was observed on Er isotopes with even number of protons. Most probably, this feature can be explained by the presence of the following nuclear reaction mechanism: a pick-up reaction with stripping off the target nucleus and the transfer of a proton to the projectile. For this to be expected to happen, the target nucleus must have one not paired-up proton.

Also, there was no such effect observed on ^{197}Au because of a "low deformation" of the ^{196}Pt residual nucleus to host the diproton ($\beta_2 = 0.139$, which is more than 2 times less than the values 0.279 for ^{180}Hf and 0.271 for ^{158}Gd [17]).

By our estimates the binding energy of the diproton $B_{dp} = 0.384$ MeV and the radius $r_{dp} \cong 10.4$ fm.

Two half-lives were determined and assigned for positron decay of ^{2}He into a triplet and a singlet state of the deuteron/^{2}H, namely 1224 ± 40 s and 6336 ± 220 s, respectively. In the same time, theoretical calculations present 1140 ± 216 s and 5516 ± 1030 s estimates.

Of course, the main question remains the following: how do these two protons, constituting a bound diproton but being separated for a so long distance, can still interact via the strong force? To answer this and other questions, further experimental and theoretical studies are necessary to perform in order to re-confirm the existence of a bound diproton as an exotic nucleus and not an "illusive" particle.

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