SEARCH FOR THE η-MESIC NUCLEI BY MEANS OF COSY-11, WASA-AT-COSY AND COSY-TOF DETECTOR SYSTEMS*

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We review status and perspectives of the search for the light η-mesic nuclei using COSY-11, WASA-at-COSY and COSY-TOF detector systems.

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1. Introduction

The negatively charged pions and kaons can be trapped in the Coulomb potential of atomic nucleus forming so-called pionic (kaonic) atoms. Observations of such atoms allows for studies of strong interaction of pions and kaons with atomic nuclei on the basis of shifts and widths of the energy levels [1, 2].

It is also conceivable that a neutral meson could be bound to a nucleus. In this case the binding is exclusively due to the strong interaction and hence such an object can be called a *mesic nucleus*. Here the most promising candidate is the η-mesic nucleus since the ηN interaction is strongly attractive. As discussed in the contribution by Wycech [3] the nuclear states of η may be bound by a similar mechanism as states of $\overline{K}$ with the difference that in the case of $\overline{K}$, nucleons are excited to the $\Lambda(1405)$ and in the case of η meson to the $N^*(1535)$ resonant state. We may thus picture [4] the formation and decay of the η-mesic nucleus as the η-meson absorption by one of the nucleons leading to the creation of the $N^*(1535)$ and then its propagation through the nucleus until it decays into the pion–nucleon pair which escapes

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from the nucleus. Predicted values of the width of such states range from ~ 7 to ~ 40 MeV [5–7]. However, it is important to stress that the width and binding energy of the η-nucleus bound states depends strongly on the not well known subthreshold η-nucleon interaction [6] making impossible an unambiguous prediction as regards the bound states, and, therefore, direct measurements are necessary [6].

The search for the η-mesic nucleus was conducted in many inclusive experiments [8–14] via reactions induced by pions [8, 9], protons [11, 13], and photons [10, 14]. Many promising indications of the existence of such an object were reported [10, 13, 14], but so far none was independently confirmed. Experimental investigations with high statistical sensitivity and the detection of the $N^*(1535)$ decay products are being continued at the COSY [15, 16], JINR [11], J-PARC [17], and MAMI [18] laboratories. In this contribution we report on searches of the η-mesic helium in exclusive measurements carried out at the cooler synchrotron COSY by means of the WASA-at-COSY [15, 16] and COSY-11 [19–22] detector setups. We present also suggestion of studies of η-mesic tritium with quasi-free reactions at the COSY-TOF facility.

We consider the study of the η-mesic nuclei as interesting on its own account, but additionally it is useful for investigations of *(i)* the ηN interaction, *(ii)* the $N^*(1535)$ properties in nuclear matter [23], *(iii)* the properties of the η meson in the nuclear medium [24], and *(iv)* the flavor singlet component of the η meson [25, 26].

2. Indications for the existence of the η-mesic helium

In 1985 Bhalerao and Liu [27] performed a coupled-channel analysis of the $\pi N \to \pi N$, $\pi N \to \pi\pi N$ and $\pi N \to \eta N$ reactions and came to conclusion that the interaction between the nucleon and the η meson is attractive. Based on this finding Haider and Liu postulated the existence of the η-mesic nuclei [28], in which the electrically neutral η meson might be bound with the nucleons by the strong interaction. The formation of such a bound state can only take place if the real part of the η-nucleus scattering length is negative (attraction), and the magnitude of the real part is greater than the magnitude of the imaginary part [6,29]. In the 1980s the η-mesic nuclei were considered to exist for $A \geq 12$ only [28] due to the relatively small value of the ηN scattering length ($a_{\eta N} = (0.28 + i0.19)$ fm [27]). However, recent theoretical investigations of hadronic- and photo-production of the η meson result in values of the real part of $a_{\eta N}$ which, depending on the analysis method, range from 0.25 fm up to 1.05 fm [30], and which do not exclude the formation of bound η-nucleus states for such light nuclei as helium [31–33] or even for deuteron [34]. According to the calculations including multiple scattering theory [33] or Skyrme model [35] an especially good candidate for binding is the ^{4}He-η system. Recent calculations by Haider [7] or Tryasuchev and Isaev [36] also indicate the binding in the ^{4}He-η system, while they rather exclude the existence of the ^{3}He-η state. On the other hand, there are promising experimental signals which may be interpreted as indications of the the ^{3}He-η bound state, as, for example, the shape of the excitation function for the $dp \rightarrow ^3\mathrm{He}\,\eta$ reaction [31] determined by the SPES-4 [37], SPES-2 [38], COSY-11 [39], and COSY-ANKE [40] collaborations (Fig. 1 (left)). It has been indicated by Wilkin [42, 43] that a steep rise of the total cross-section in the very close-to-threshold region followed by a plateau may be due to the existence of a pole of the $\eta^3\mathrm{He} \rightarrow \eta^3\mathrm{He}$ scattering amplitude in the complex excess energy plane Q with $\mathrm{Im}\,(Q) < 0$ [42]. This reference shows that the occurrence of the pole changes the phase and the magnitude of the s-wave production amplitude. And indeed, the momentum dependence of the asymmetry in the angular distributions of $\cos\theta_\eta$ expressed in terms of the asymmetry parameter α [39], can only be satisfactorily described (solid and dashed lines in Fig. 1 (right)) if a very strong phase variation associated with the pole is included in the fits [42, 43]. Otherwise, there is a significant discrepancy between the experimental data and the theoretical description (dotted line in Fig. 1 (right)).

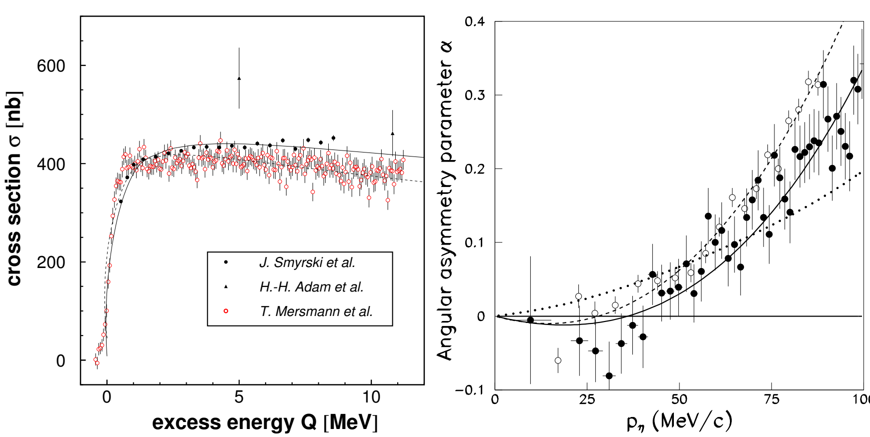

Fig. 1. (Left) Total cross-section for the $dp \rightarrow ^3\mathrm{He}\,\eta$ reaction as determined by the COSY-ANKE [40] (open circles) and the COSY-11 [39] (full dots) and [41] (triangles). The solid and dashed lines represent the scattering length fit to the COSY-11 and COSY-ANKE data, respectively. (Right) Angular asymmetry parameter α. Closed and open circles represent results of COSY-ANKE [40] and COSY-11 [39], respectively. The dashed and solid lines denote results [42] of the fit (allowing for the phase variation) to the COSY-11 and COSY-ANKE data, respectively. The dotted line denotes the result of the fit without the phase variation. The figure is adapted from Ref. [42].

3. Study of the η-^{3}He system in d–p collisions at COSY-11

Details of the experimental technique [44–46] and a comprehensive description of results concerning the search of the η-mesic ^{3}He nucleus conducted by the COSY-11 group were described elsewhere [19–22]. Therefore, here we only summarize the main results. The measurements were carried out using the deuteron beam of COSY which was circulating through the stream of the internal hydrogen target of the cluster-jet type [44]. Data were taken during a slow acceleration of the beam from $3.095\,\mathrm{GeV}/c$ to $3.180\,\mathrm{GeV}/c$, crossing the kinematical threshold for the η production in the $dp \to^3 \mathrm{He}\,\eta$ reaction at $3.141\,\mathrm{GeV}/c$. The corresponding variation of the excess energy in the $\eta-^3$He system ranged from -10 MeV to $+9$ MeV. For the scanned beam momentum interval we determined excitation functions for the pion production in the $dp \to {}^3\mathrm{He}\,\pi^0$ and $dp \to ppp\pi^-$ reaction which were chosen out of possible decay channels of the η-mesic ^{3}He. A signature of existence of the η-^{3}He bound state was based on observation of a resonance like structure with the center lying below the η production threshold in the measured excitation curves.

For the $dp \to {}^3\mathrm{He}\,\pi^0$ channel we concentrated on differential cross-sections for the forward pion angles ($\Theta^{\mathrm{cm}}_{d-\pi} = 0°$). This choice was dictated by the fact that the $dp \to {}^3\mathrm{He}\,\pi^0$ cross-section is up to two orders of magnitude smaller at the forward angles than at the most backward angles. Assuming that the searched structure is produced isotropically, one can expect that it can be best seen just at the forward angles since it appears on the level of small "non-resonant" cross-section. The determined excitation function for the $dp \to {}^3\mathrm{He}\,\pi^0$ process does not show any structure which could originate from a decay of η-^{3}He bound state [21]. The estimated upper limit for the cross-section of the $dp \to (\eta^3\mathrm{He})_{\mathrm{bound}} \to {}^3\mathrm{He}\,\pi^0$ reaction chain is equal to 70 nb. This limit appears not very restrictive at least under assumption that the cross-sections for the ^{3}He-η bound state formation are of the same order as the $dp \to {}^3\mathrm{He}\,\eta$ cross-sections near threshold ($0.4\,\mu$b), and that other possible decay channels like $dp\pi^0$ or $ppp\pi^-$are more favorable.

We expect that $ppp\pi^-$ is one of the favorable decay channels of the η-^{3}He bound state since it corresponds to one step process of absorption of the η meson on the neutron inside the ^{3}He nucleus in the reaction $\eta n \to N^*(1535) \to p\pi^-$. In the N^* rest frame the pion and the proton are emitted back-to-back with momenta of about 430 MeV$/c$. In the center-of-mass (c.m.) system these momenta are smeared due to the Fermi motion of the neutron inside the ^{3}He nucleus. However, they are significantly larger than the momenta of the two remaining protons which are in the order of 100 MeV$/c$, and which play the role of "spectators". The counting rate of all identified $dp \to ppp\pi^-$ events including the quasi-free π^- production stays constant in the scanned range of the beam momentum (see Fig. 2 (a)). However, after rejection of the quasi-free events, the number of $dp \to ppp\pi^-$ counts in the beam momentum interval above the η threshold is higher than the number of counts in the interval of equal width below the threshold (see Fig. 2 (b)). This difference is equal to $23-9=14$ and its statistical significance is of $2.5\,\sigma$. The observation of this effect was reported in Ref. [20]. As a possible reaction mechanism explaining the observed enhancement we suggested the production of "on-shell" η mesons in the reaction $dp \to {}^3\mathrm{He}\,\eta$ which subsequently are absorbed in the ^{3}He nucleus and converted to negatively charged pions in the interaction with the neutron.

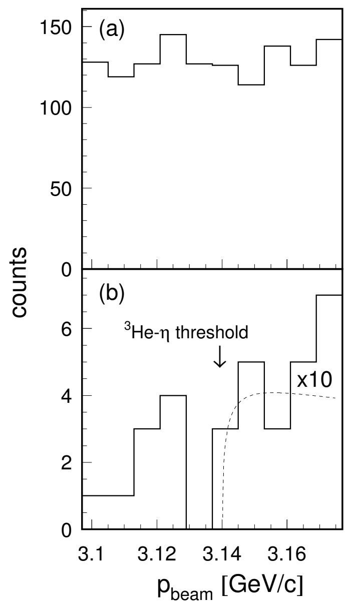

Fig. 2. Number of $dp \to ppp\pi^-$ events as a function of the beam momentum without any cuts (a) and after rejection of events corresponding to the quasi-free π^- production (b). The dashed line represents calculations of the η absorption described in the text.

For testing the η absorption hypothesis we estimated the counting rate of the $dp \to ppp\pi^-$ events assuming that the absorption cross-section σ_{abs} is equal to the cross-section for the $dp \to {}^3\mathrm{He}\,\eta$ reaction (for more details see Ref. [19]). This assumption is justified by the observation that the real and imaginary part of the ^{3}He-η scattering length [39] have comparable values. The result of our estimation multiplied by a factor of 10 is shown by the dashed line in Fig. 2 (b). It underestimates the experimental counts roughly by an order of magnitude and thus it does not corroborate the η absorption hypothesis.

For testing this hypothesis we analysed also momentum and angular distributions of the final state particles in the $dp \to ppp\pi^-$ reaction. The experimental distribution of the pion momentum in the c.m. system is centered around 430 MeV/c as expected for pions originating from the decay of the $N^*(1535)$. It agrees with results of simulations of the η absorption. However, the momentum distribution of the proton with the highest momentum, which we call the leading proton, is centered at around 300 MeV/c and is lower than the corresponding distribution for the η absorption grouped around 430 MeV/c. A disagreement takes place also in the case of the distribution of the center-of-mass angles between the pion momentum vector and the momentum vector of the leading proton which in the case of simulations of the η absorption are close to 180° and for the experiment lie around 160°.

One can expect, that due to very similar kinematical conditions, absorption of the η mesons bound in the ^{3}He nucleus is characterized by differential distributions which are very close to ones predicted in our simulations for the absorption of "on-shell" η mesons. In particular, one can expect that the $\pi^- - p$ pairs originating from the decay of the η-mesic ^{3}He are emitted at c.m. angles concentrated predominately in the range 150°–180° as it is the case for the η-meson absorption. In this angular range, there are only two experimental counts. Assuming, that these two counts originate from the decay of the ^{3}He-η bound state, we estimated the cross-section for the production of such a state in d–p collisions close to the η production threshold. The resulting cross-section of $0.27 \pm 0.19\,\mu$b should be considered as an upper limit for the production cross-section of the η-mesic ^{3}He since the observed two events might originate from other processes than the bound state decay.

Data collected in the COSY-11 measurements with the ramped deuteron beam were also used to investigate the cusp effect observed at SATURNE in the threshold excitation curve for the process $dp \to {}^3\mathrm{He}\,X$ [47]. As suggested by Wilkin [48], the cusp visible in the SATURNE data below the η threshold could be caused by an interference between an intermediate state including the η meson and the non-resonant background corresponding to the multi-pion production. In the SATURNE experiment the ^{3}He ejectiles were measured with the SPES IV spectrometer which was set in such a way that it registered the ^{3}He which was approximately at rest in the c.m. frame. Since the COSY-11 momentum and angular acceptance was much larger than one of the SPES IV spectrometer, the limitation on the c.m. momenta of ^{3}He was realized by means of corresponding cuts during the data analysis [22]. Contrary to the SATURNE result no cusp below the η threshold was observed [21].

4. Search for the η-^{4}He state with WASA-at-COSY

The installation of the WASA detector at COSY opened a unique possibility to search for the ^{4}He-η bound state with high statistics and high acceptance. We conduct a search via an exclusive measurement of the excitation function for the $dd \to {}^3\mathrm{He}\, p\pi^-$ reaction varying continuously the beam momentum around the threshold for the $d\,d \to {}^4\mathrm{He}\,\eta$ reaction. Ramping of the beam momentum and taking advantage of the large acceptance of the WASA detector[1] allows to minimize systematical uncertainties making the WASA-at-COSY a unique facility [49] for such kind of exclusive experiments. The $^4\mathrm{He} - \eta$ bound state should manifest itself as a resonant like structure below the threshold for the $dd \to {}^4\mathrm{He}\,\eta$ reaction. If a peak below the $^4\mathrm{He}\,\eta$ threshold is found, then the profile of the excitation curve will allow to determine the binding energy and the width of the ^{4}He-η bound state. If, however, only an enhancement around the threshold is found, then it will enable to establish the relation between width and binding energy [5]. Finally, if no structure is seen the upper limit for the cross-section of the production of the η-helium nucleus will be set. In addition, when searching for the signal of the η-mesic state we may take advantage of the fact that the distribution of the relative angle between the nucleon–pion pair for the background (due to the prompt $dd \to {}^3\mathrm{He}\, p\pi^-$ reaction) is much broader than the one expected from the decay of the bound state. This is because the relative angle between the outgoing nucleon–pion pair originating from the decay of the $N^*(1535)$ resonance is equal to 180° in the N^* reference frame and it is smeared only by about 30° in the reaction center-of-mass frame due to

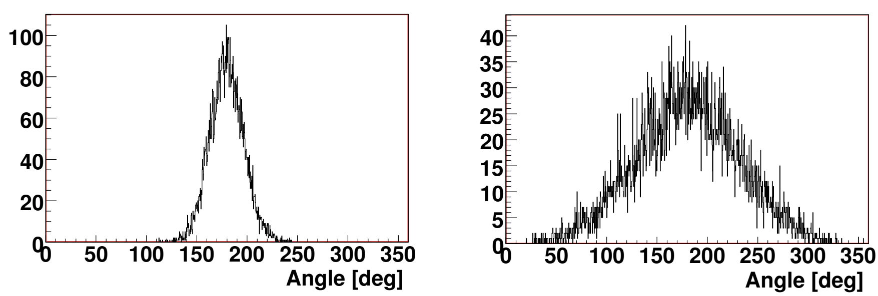

Fig. 3. Distribution of the relative p–π angle seen in the reaction c.m. system as simulated for the processes leading to the creation of the eta–helium bound state: $dd \to ({}^4\mathrm{He}\,\eta)_{\mathrm{bound}} \to {}^3\mathrm{He}\,p\pi$ (left), and for the prompt production of the $^3\mathrm{He}\,p\pi$ system assuming a homogeneous population of the phase space for the $dd \to {}^3\mathrm{He}\,p\pi$ reaction (right). The figure is adapted from reference [16].

[1] For the coincidence registration of all ejectiles from the $dd \to (\eta\,{}^4\mathrm{He})_{\mathrm{bound}} \to {}^3\mathrm{He}\,p\,\pi^-$ reaction the acceptance of the WASA-at-COSY detector equals to almost 70%.

the Fermi motion of the nucleons inside the He nucleus. Fig. 3 shows the distribution of the relative proton–pion angle as expected for the signal and for the background due to the prompt $dd \to {}^{3}\mathrm{He}\, p\, \pi^{-}$ reaction.

In the first experiment conducted in June 2008, we used a deuteron pellet target and the COSY deuteron beam with a ramped momentum corresponding to a variation of the excess energy for the ^{4}He-η system from -51.4 MeV to 22 MeV. At present the data are evaluated and preliminary excitation curves determined for few intervals of the $\Theta^{\mathrm{cm}}_{p-\pi}$ angle are shown in the left panel of Fig. 4. The figure indicates no structure in the angular range close to the 180 degree where the signal is expected. The ratio of excitation functions from various angular ranges is also constant as indicated in the right panel of Fig. 4. Therefore, taking into account the luminosity and the detector acceptance we preliminary estimated that an upper limit for the η-mesic helium production via the $dd \to (\eta\, {}^{4}\mathrm{He})_{\mathrm{bound}} \to {}^{3}\mathrm{He}\, p\, \pi^{-}$ reaction is equal to about 20 nb on a one sigma level. The experiment will be continued in November 2010. However, we cannot estimate the statistics required for the observation of the signal since it is *a priori* impossible to predict in a model independent way a cross-section for the creation of the η-mesic nucleus, which strongly depends on the strength of the relatively poorly known η-nucleon interaction, and which involves computations of the behavior of the many-body system. Therefore, based on the fact that the real and imaginary part of the helium-η scattering length are almost of the same value, we estimate the cross-section for the creation of the η-mesic helium applying the assumption that the probability of the production of the η meson in continuum and its absorption on the helium nucleus is of the same order. This leads to the hypothesis that the cross-section for the creation of the bound state below the threshold (which is than con-

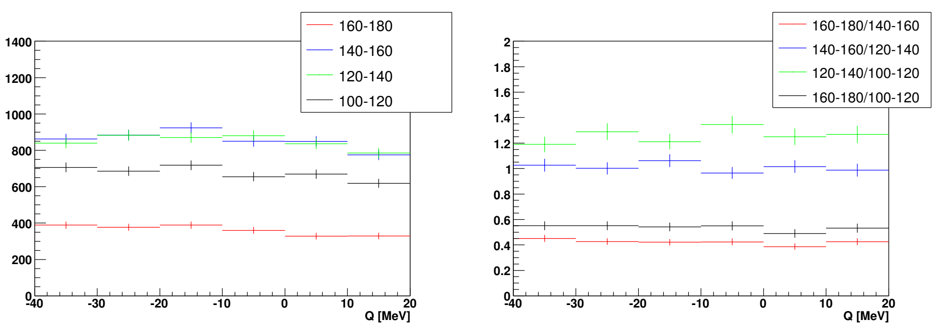

Fig. 4. (Left) Excitation function for the $dd \to^{3}$ He $p\pi$ reaction measured in the 20 degrees intervals of the $\Theta^{\mathrm{cm}}_{p-\pi}$ angle. Courtesy to [50]. (Right) Ratio of excitation functions from angular ranges as indicated in the figure.

nected with the absorption of the η meson on the helium nucleus) is in the first order the same as the close-to-threshold cross-section for the η-meson production. Therefore, for the estimation of the counting rate in the future measurements we assume that the cross-section in the maximum of the Breit–Wigner distribution for the $dd \to (^4\text{He-}\eta)_{\text{bound}}$ production is about 15 nb as measured for the $dd \to ^4\text{He}\,\eta$ reaction [51–53]. Further on, we assume that the probability of decay of the ^{4}He-η bound state into the $^3\text{He}\,p\pi^-$ channel is equal to $\frac{1}{4} \times \frac{1}{2} = \frac{1}{8}$. The factor $\frac{1}{4}$ takes into account the fact that there are four possible η absorption channels: $\eta p \to p\pi^0$, $\eta p \to n\pi^+$, $\eta n \to n\pi^0$, $\eta n \to p\pi^-$. In turns, the factor 1/2 represents our guess of the probability that the three observer nucleons (ppn), in the process of the η absorption on the neutron in ^{4}He, form ^{3}He in the final state. Estimation of this effect needs, in our understanding of the problem, projection of the ^{4}He wave function on the wave function of the ^{3}He–n pair and inclusion of the pion and proton rescattering on the observer nucleons. Since this kind of estimations is not at present in our reach, we justify our guess using an analogy between the decay of the $^4\text{He} - \eta$ nuclei and the $^4_\Lambda$He-hypernuclei. For the latter case it was observed namely that in the π^- decay channel the decay mode $^4_\Lambda\text{He} \to \pi^- p\,^3\text{He}$ is dominant [54]. The above considerations imply that the cross-section for the $dd \to (^4\text{He}\,\eta)_{\text{bound}} \to ^3\text{He}\,p\pi^-$ reaction should be of the order of 2 nb. This level of sensitivity can be reached in the experiment which will be continued in November 2010 [15].

5. Search of the bound state with quasi-free beams

The systematic uncertainties in establishing of the shape of excitation functions discussed in the previous sections are significantly reduced by using

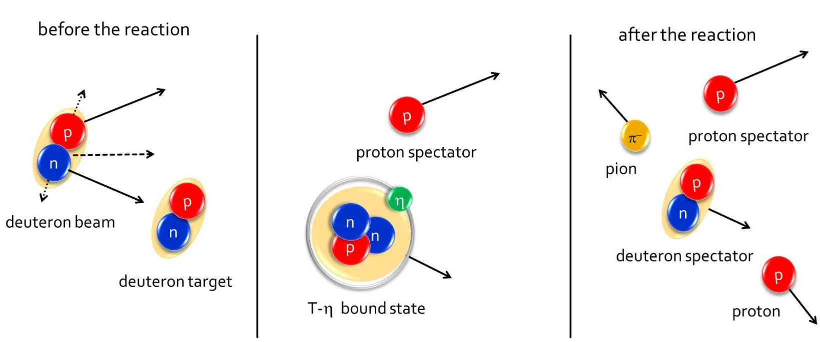

Fig. 5. Schematic picture of the quasi-free $nd \to (\eta\,T)_{\text{bound}} \to dp\pi^-$ reaction. The Fermi momentum of the nucleons inside the deuteron is presented by the dotted arrows and the beam momentum by the dashed one. The figure is adapted from reference [58].

the momentum ramping technique since the energy range of interest for the search of the η-mesic nucleus is scanned in each COSY cycle. A scan of the energy can also be achieved in the case of the fixed beam energy available for the external beam experiments. This may be realised by means of the quasi-free reactions as already successfully used at COSY for the study of the meson production in the quasi free proton–neutron collisions [55, 57]. For instance, a search of the η-mesic tritium may be realized by studying the excitation function of the $nd \to (\eta T)_{\rm bound} \to dp\pi^-$ reaction using a deuteron beam and tagging the nd reactions by the measurement of the spectator protons ($p_{\rm sp}$) from the $dd \to p_{\rm sp}\, nd \to p_{\rm sp}\,(\eta T)_{\rm bound} \to p_{\rm sp}\, dp\pi^-$ reaction. This reaction, shown schematically in Fig. 5, may be measured using the COSY-TOF detector. The Fermi motion of nucleons inside the deuteron beam will allow to scan a large range (in the order of 100 MeV) of excess energies in the nd reaction.

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