SEARCH FOR NUCLEAR ETA STATES AT COSY AND GSI

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Based on the attractive η-nucleon interaction, the possible existence of η-mesic nuclear states has been discussed since some time. Nevertheless these states have not been seen clearly in experiments. The current status of experiments at COSY and at GSI searching for signals of η-mesic states in light nuclear systems, by using different methods, is presented.

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1 Introduction

The excistence of η-mesic nuclear states was first discussed by Haider and Liu [1] based on the attractive ηN interaction with an ηN scattering length $a_\eta N = 0.27 + i0.22$ fm or $a_\eta N = 0.28 + i0.19$ fm [2]. In other analyses of η production data close to threshold, different values of the ηN scattering length, ranging from 0.2 to 1 fm in the real part, and from 0.2 to 0.35 fm in the imaginary part, were deduced [3–7]. The value of the ηN scattering length (mainly $\mathrm{Re}\, a_{\eta N}$) determines the size of the nucleus required to form a quasi-bound system together with an η meson. Note that a scattering length $a_{\eta N} = 1$ fm translates to a quite deep optical potential depth of $V_\eta = -120$ MeV at normal nuclear matter density. A quasi-bound ηNN state was predicted by Ueda [8], whereas the strong energy dependence of the near-threshold amplitude seen in the reaction $pd \to {}^3\mathrm{He}\,\eta$ $[9, 10]$ was interpreted as an indication for a quasi-bound ${}^3\mathrm{He}\,\eta$ system by Wilkin [3]. Garcia-Recio et al. predict the energies and widths of η bound states in various nuclei from ^{12}C up, and conclude that medium-heavy nuclei are the most promising candidates to search for η bound states. A more comprehensive overview on the η nucleon and nucleus interaction is given by Hanhart in these proceedings [11].

First experiments searching for η-mesic nuclei at BNL [12] and LAMPF [13] based on a missing mass technique in using the (π^+, p) reaction came to negative or inconclusive results. This might be due to the fact that these experiments were planned to search for narrow states, and were probably not sensitive enough to observe broader states in line with theoretical predictions. At the LPI Moscow the reaction $\gamma^{12}\mathrm{C} \to \pi^+ nX$ at excitation energies close to the η mass was studied with a back-to-back π^+ neutron pair emitted in transverse direction to the photon beam [14]. An enhancement at excitation energy below the η threshold was interpreted as an indication for the excistence of a bound ${}^{12}\mathrm{C}_\eta$ state. Very recently, the existence of η-mesic

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^{3}He was claimed to have been observed in the reaction $\gamma ^3\mathrm{He} \rightarrow \pi^0 pX$ using the photon beam at MAMI [15]. In this experiment a peak in the photon energy spectrum corresponding to an excitation energy below the the $^3\mathrm{He}\,\eta$ threshold was observed if the $\pi^0 p$ pair was emitted back-to-back. It has however been pointed out [11, 16] that the data of Ref. [15] do not allow to unambiguously deduce the existence of a $^3\mathrm{He}_\eta$ bound state. In this contribution the search for light η-mesic nuclei using recoil-free transfer reactions at GSI [17, 18] and COSY [19] and the study of η-mesic ^{3}He in exclusive measurements at COSY [20] will be discussed.

2 Bound η production in recoil-free transfer reactions

The study of transfer reactions at recoil-free kinematics is a powerful method to produce mesons in a bound state with a nucleus. In particular, this was demonstrated in the discovery and study of deeply bound pionic states in Pb and Sn nuclei by measuring the (d,^{3}He) reaction at 0^o [21]. The same reaction can be used to implant an η meson at rest into a nucleus, in this case by creating a proton hole in the target nucleus, as illustrated in Figure 1 (left). The incident d beam kinetic energy required in order to achieve the recoil-free condition is around 3.5 GeV depending on the η binding energy, as shown in Figure 1 (right). This energy, corresponding to $p_d \approx 5\,\mathrm{GeV/c}$, is beyond the COSY limit, but available at the GSI heavy ion synchrotron SIS.

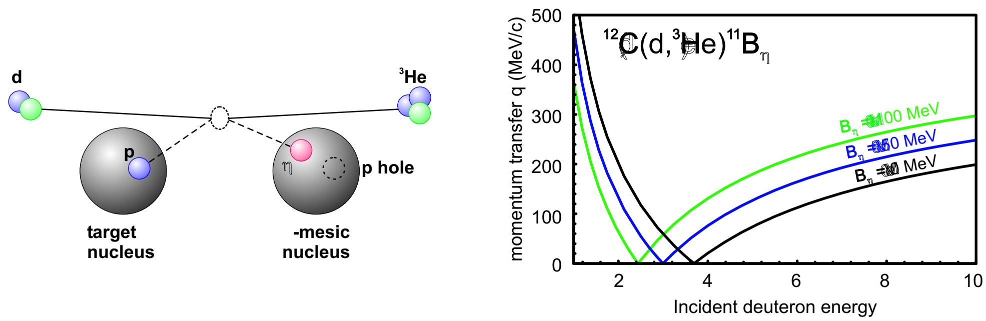

Fig. 1. (Left) Schematic illustration of the formation of an η mesic nucleus in the (d,^{3}He) reaction. (Right) Momentum transfer as a function of the d kinetic energy for the ^{12}C(d,^{3}He)^{11}B$_\eta$ reaction for different η binding energies B_η.

The η binding energy is deduced from the missing mass of the residual nuclear system which is determined from a momentum measurement of the ^{3}He particles emitted at 0^o. In the ideal case a bound η state would be visible in a peak-like structure at excitation energies of the residual $(A-1,\ Z-1)$ system below the η threshold. However as a complication, this system, apart from its η mesic excitation, is not necessarily in its nuclear ground state, since different proton hole states can be created in the target nucleus. Their contributions to the excitation spectrum can, in principle, be disentangled if their relative strength is known. Fortunately, at the recoil-free condition all contributions with finite angular momentum transfer are strongly suppressed, and for light target nuclei only few proton hole states are relevant. Thus for the considered nuclei ^{7}Li and ^{12}C the expected contributions are $(0p_{3/2})_p^{-1} \otimes p_\eta$ and $(0s_{1/2})_p^{-1} \otimes s_\eta$. This expectation has been supported by a DWIA calculation [18], using experimental data on the "elementary" reaction $pd \rightarrow {}^3\mathrm{He}\,\eta$ [22], and taking into account the nuclear excitation spectrum and the distortion for the incoming d and outgoing ^{3}He. The same type of calculation was successfully used in describing the shape of the excitation spectrum in the formation of deeply bound pionic states [23], and found to predict the measured cross section within a factor of two. For nuclear bound η states a maximum cross section of the order of $d^2\sigma/d\Omega/dE \simeq 1\,\mathrm{nb/sr/MeV}$ is predicted. The calculated excitation spectrum is clearly sensitive to the depth of the η-nucleus potential (for details see Ref. [18]).

For the (p,^{3}He) reaction, the condition of recoil-free kinematics is fulfilled at $p_p \approx 1.75\,\mathrm{GeV/c}$ well within the range of beam energies at COSY. The formation of η-mesic states using this reaction on nuclear targets has been studied theoretically by Liu [24]. For $T_p = 1.0\,\mathrm{GeV}$ and $\theta_{^3\mathrm{He}} = 0^o$, this calculation predicts cross sections for the formation of η-mesic states $d\sigma/d\Omega$ between 0.2 and 2 μb/sr, depending on the used ηN scattering length.

2.1 Search for light η-mesic nuclei with the (d,^{3}He) reaction

It was proposed [17] to search for η-mesic states by studying the (d,^{3}He) reaction at the recoil-free energy $T_d = 3.5\,\mathrm{GeV}$ on ^{7}Li and ^{12}C at the GSI Fragment Separator (FRS) [25], in a similar technique as used for the measurements of deeply bound pionic states [21]. Figure 2 shows a simulated excitation energy spectrum for the $d + {}^7\mathrm{Li} \rightarrow {}^3\mathrm{He} + X$ reaction close to the $^6\mathrm{He}\,\eta$ threshold, based on the DWIA calculation of Ref. [18] within 100 h running time, using a d beam intensity of $3 \times 10^{10}/\mathrm{s}$ and a target thickness of 1 g/cm^2.

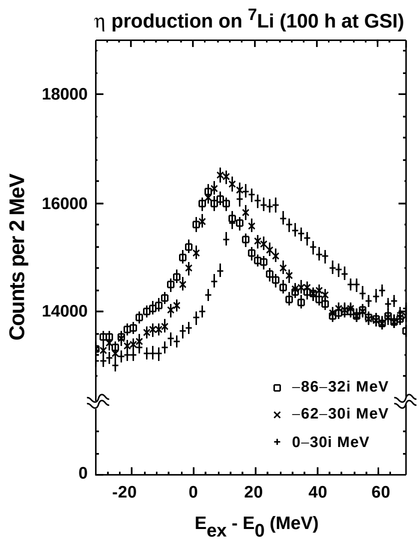

Fig. 2. Expected excitation energy spectrum for the ^{7}Li(d,^{3}He) reaction around the η production threshold for 100 h running. The continuum background below the peak is due to multi-pion production.

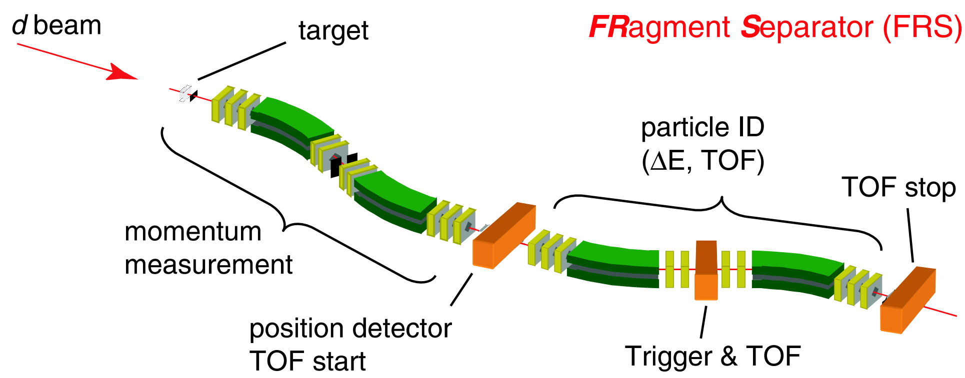

Fig. 3. Schematic layout of the experiment at the GSI Fragment Separator.

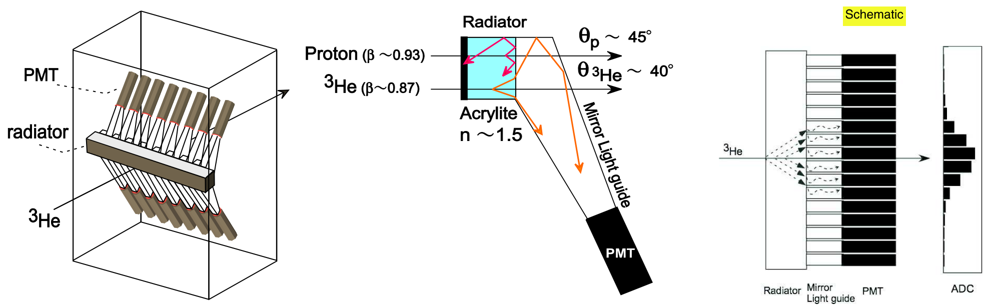

Fig. 4. The position sensitive total reflection Cerenkov detector: (left) overall schematic view, (middle) vertical cross section of one element, (right) top view with distribution of signal height across the focal plane.

The schematic layout of the experiment at the FRS is illustrated in Figure 3. The first half of the 72 m long FRS is used as magnetic spectrometer which allows to measure the momentum of particles detected by a position sensitive detector at the dispersive central focal plane, whereas the second half serves for the identification of the ^{3}He particles by time-of-flight measurement. An additional time-of-flight and trigger detector was required at the third focal plane. The main problem of the experiment is the huge proton background from deuteron break-up which at the recoil-free condition is transmitted through the spectrometer, since in this case both ^{3}He and protons have nearly the same magnetic rigidity. At the required d beam intensities of $10^{10}/\mathrm{spill}$ (spill length $\sim 1\mathrm{s}$, duty cycle ~ 0.3) this results in a proton rate of more than $10^8/\mathrm{s}$ at the central focal plane detector during extraction. As a solution detectors which are sensitive to ^{3}He but blind to protons had to be developed. This was achieved with Cerenkov detectors with acrylite radiators using total reflection, as illustrated in Figure 4 (left and middle). Due to the higher velocity of protons ($\beta = 0.93$) their Cerenkov light is totally reflected at the front surface of

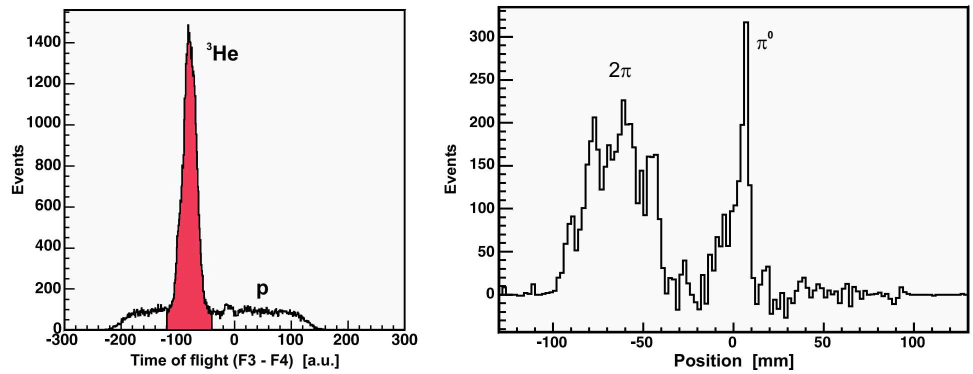

Fig. 5. (Left) Time-of-flight spectrum between the total reflection Cerenkov detectors at the third and forth focal planes of the Fragment Separator (18 m flight path), demonstrating the suppression of the background of protons from deuteron break-up. (Right) Position spectrum at the central focal plane of the Fragment Separator in the reaction $d + (\mathrm{CH}_2)_\mathrm{n} \rightarrow {}^3\mathrm{He} + X$. The peak in center of the focal plane corresponds to quasi-monoenergetic ^{3}He in the reaction $d + p \rightarrow {}^3\mathrm{He} + \pi^0$ with $\theta_{c.m.}(\pi^0) = 180^o$.

the radiator whereas the light from ^{3}He ($\beta = 0.87$) is transmitted through the front surface and guided to PMT's above or below the active region covered by the radiator. The light collection system of the central Cerenkov detector is subdivided into 16 light guides which allows to deduce the horizontal coordinate of the ^{3}He track by the distribution of light among these cells, as shown in Figure 4 (right). Clearly, this requires a careful relative calibration of the PMT pulse height spectra. In tests it was found that each Cerenkov detector has a suppression factor of about 10^3 for the protons while the ^{3}He particles are detected without measurable losses, and that a postion resolution of $3.5\,\mathrm{mm}$ (fwhm) could be achieved.

Very recently two weeks of data on the reaction $d+{}^{12}\mathrm{C} \rightarrow {}^3\mathrm{He}+X$ at $T_d = 3.5\,\mathrm{GeV/c}$ were taken at GSI with the FRS tuned to ^{3}He emitted at the η threshold. As Figure 5 (left) shows, ^{3}He is clearly identified in a time-of-flight measurement between Cerenkov detectors at the third and forth focal plane, while the proton background is almost completely suppressed. The position measurement was verified with quasi mono-energetic ^{3}He emitted within the FRS acceptance in the $dp \rightarrow {}^3\mathrm{He}\pi^0$ reaction by using a $(\mathrm{CH}_2)_n$ target, as illustrated in Figure 5 (right). Similarly, also the reaction $dp \rightarrow {}^3\mathrm{He}\eta$ was measured. The data analysis is in progress.

2.2 Search for light η-mesic nuclei with the (p,^{3}He) reaction

At COSY the study of the (p,^{3}He) reaction at the Big Karl magnetic spectrometer [26] on light targets (^{6}Li, ^{12}C, ^{27}Al) was proposed in the search for η-mesic nuclei [19]. The ^{3}He particles are identified in the Big Karl focal plane scintillation detectors by time-of-flight and ΔE measurement, their momentum determined from the position in the MWDC's (see Figure 6 (left)). This allows for a missing mass measurement of the $(A-2, Z-1)$ residual system around the η threshold. In order to reduce the substantial multi-pion continuum background, the large acceptance segmented scintillation detector ENSTAR [27], which encloses the target, has been built.

By requiring $p\pi^-$ coincidences in almost back-to-back geometry in the ENSTAR detector events with bound η production according to the channel $\eta n \to N^{\star 0}(1535) \to p\pi^-$ are expected to be considerably enhanced relative to multi-pion events. The layout of the experiment is shown in Figure 6 (left), schematic views of the ENSTAR detector are given in Figure 6 (right).

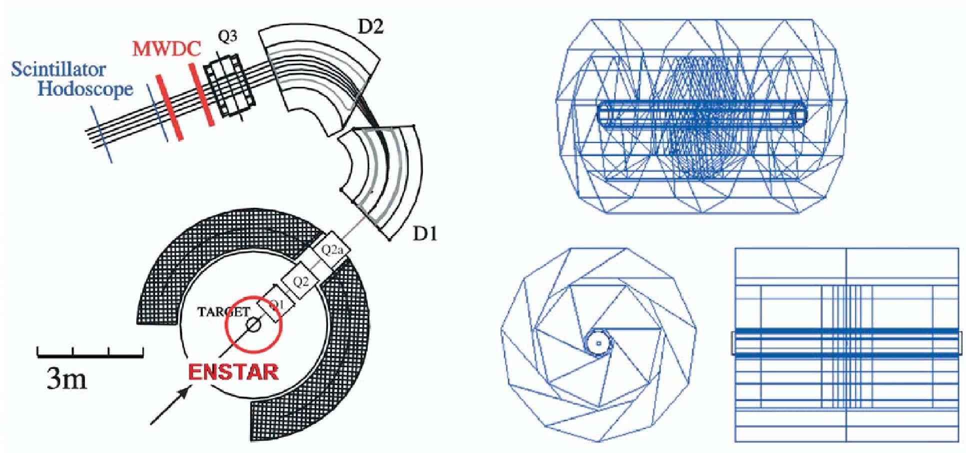

Fig. 6. Layout of the search experiment for nuclear bound η states at the Big Karl spectrometer (left) and schematic view of the ENSTAR detector (right).

Recently a beamtime of two weeks was performed in which the reaction $p + {}^{27}\mathrm{Al} \to {}^{3}\mathrm{He} + p + \pi^- + X$ at proton beam momentum $p_p = 1.745\,\mathrm{GeV/c}$ was studied. For calibration purpose also $(\mathrm{CH}_2)_n$ targets were irradiated in order to detect particle production in pp and $p\mathrm{C}$ collisions. Figure 7 shows energy loss versus time-of-flight spectra measured for both targets at the Big Karl focal plane, and demonstrates that ^{3}He is clearly identified.

The ^{3}He momentum calibration was done with the reaction $pd \to {}^{3}\mathrm{He}\,\eta$. The ENSTAR detector was calibrated with cosmic rays offline, and with pp elastic scattering during the experiment. The ^{27}Al(p,^{3}He) reaction was measured for two different magnet settings of Big Karl corresponding to missing mass windows between 23.7 and 23.8 GeV/c^2 and between 23.74 and 23.84 GeV/c^2, respectively, around the $^{25}\mathrm{Mg}\,\eta$ threshold of 23.8 GeV/c^2. True coincidences between the focal plane detectors and the ENSTAR detector were observed. The data analysis is in progress.

3 Study of the ^{3}He-η system below threshold

In studies of the $pd \to {}^{3}\mathrm{He}\,\eta$ reaction at SATURNE [9, 10] it was found that the squared amplitude increases by about a factor 10 within an energy range of a few MeV as one approaches the threshold. This has been interpreted as an indication for the existence of a quasi-bound $^{3}\mathrm{He}\,\eta$ state [3] but this interpretation is not unique. In order to obtain an unambiguous answer to the question whether or not ^{3}He and η form a bound system, one has to study the system at subthreshold energies, and consequently look for signatures in final states without an η meson. As

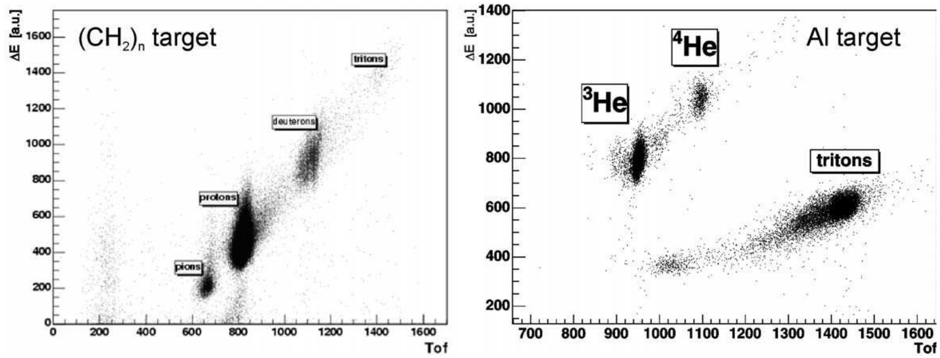

Fig. 7. ΔE versus time-of-flight spectra measured at the Big Karl focal plane with 1745 GeV/c protons impinging on a (CH$_2$)$_n$ target (left) and a ^{27}Al target (right). Note that in the right spectrum the gain of the ΔE signal is reduced by a factor two, and a ΔE lower threshold is applied which suppresses pions, protons and deuterons.

already discussed above, in a nuclear environment the $\eta N \to \pi N$ channel is open where initial and final state strongly couple via the $N^\star(1535)$ resonance. This absorption mode which is expected to be the dominant one results in a in-medium width of the η meson of several 10 MeV at nuclear density, much larger that the free η width of 1.3 keV.

3.1 Study of the $pd \to ppp\pi^-$ reaction close to the ^{3}He-η threshold

In the decay of a small system like η-mesic ^{3}He the complete final state can be identified in an exclusive measurement if one uses a large acceptance detector system. The COSY-TOF detector [28], shown in Figure 8 (right), with its almost 2π acceptance in the laboratory frame, is ideally suited to detect the $^3\mathrm{He}_\eta \to ppp\pi^-$ decay with a characteristic event signature. A sketch of the reaction is given in Figure 8 (left). The final state is composed of a strongly forward peaked pair of spectator protons travelling at the velocity of the overall center of mass frame, and a $p\pi^-$ pair emitted back-to-back in the center of mass frame at invariant mass close to the $p\eta$ threshold. The finite angles of the spectator protons and the deviation from the back-to-back geometry of the $p\pi^-$ pair are due to internal momentum in the bound system. The spectator protons are almost exclusively emitted within the acceptance of the 3-layer "Quirl" scintillation detector of TOF and thus also of the forward calorimeter, which allows their energy measurement. The $p\pi^-$ pair is detected in coplanar "Barrel-Barrel" coincidences.

As a quasi-bound $^3\mathrm{He}\,\eta$ state is possibly formed directly as an intermediate resonance from the $p+d$ initial state, the proton beam energy must be matched to the mass of the $^3\mathrm{He}_\eta$ state. This has the disadvantage that the beam energy has to be scanned across the $^3\mathrm{He}_\eta$ resonance and thus its properties cannot be determined from a single measurement. On the other hand the advantage is that the energy resolution of such a measurement is not given by the energy resolution of the COSY-TOF detector but by the much more precicely defined COSY beam energy. In a first feasibility test the $pd \to ppp\pi^-$ reaction was studied at three beam momenta close to the

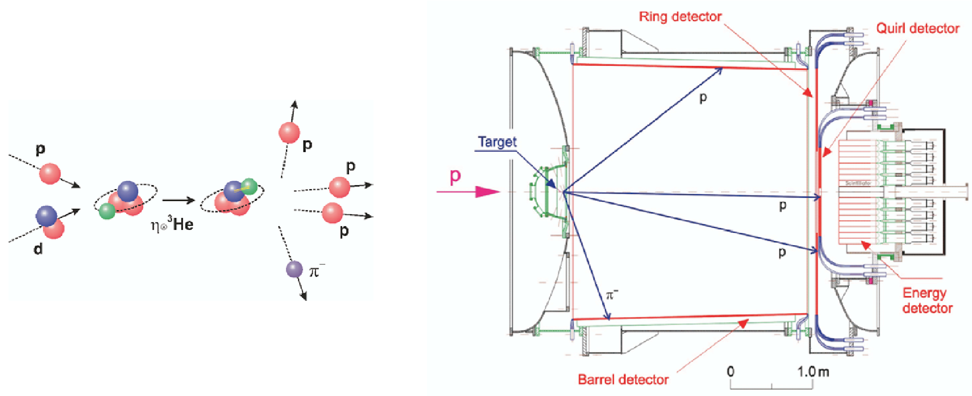

Fig. 8. (Left) Illustration of η-mesic ^{3}He formation in the reaction $pd \to {}^3\mathrm{He}_\eta \to ppp\pi^-$ with two forward spectator protons and a $p\pi^-$ pair back-to-back in the center of mass frame. (Right) Schematic view of the COSY-TOF detector.

$^3\mathrm{He}\,\eta$ threshold, namely 1552.3 MeV/c, 1567.3 MeV/c, and 1552.3 MeV/c. This corresponds to energies relative to the $^3\mathrm{He}\,\eta$ threshold of -8.7 MeV, -1.5 MeV, and +5.7 MeV, respectively. Provided the results are promising, a much finer scan with larger statistics is planned.

4 Summary

The question whether or not η-mesic nuclear states exist, is interesting in itself. In addition, the measurement of the η binding energy in different nuclei allows to determine the η-nucleus potential, and thus to deduce the real part of the η-nucleon scattering length with better accuracy. In experimental studies so far, indications for the existence of η-mesic nucear states have been seen, a conclusive result is however still missing. This is partially due to insufficient statistics, and partially to insufficient experimental information on the final state.

In this contribution, three different approaches in the study of η-mesic states at COSY and GSI were presented. After completion, these experiments will contribute to clarify the question of η-mesic nuclei.

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