COSY Proposal /Letter of Intent /Beam Request

For Lab. use

Exp. No.:	Session No.
186.3	42

Title of Experiment: **Search for the η -mesic ^{3}He with WASA at COSY**

Collaborators: The WASA-at-COSY collaboration

Institute:

(Continue on separate sheet if necessary)

Spokesperson for collaboration: Name: P. Moskal, W. Krzemien, M. Skurzok

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Is support from the LSF program of the EC requested?

Yes ~~No~~

Date: 07.01.2014

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Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second) minimum needed	maximum useful
p Intensity > 10^{10} unpolarized	1.468 GeV/c to 1.867 GeV/c	L = $5x10^{30}$ $cm^{-2}s^{-1}$	
Type of target	**Safety aspects (if any)**	**Earliest date of Installation**	**Total beam time (weeks)**
D_2 pellet target		August 2014	2 weeks

What equipment, floorspace etc. is expected from Forschungszentrum Jülich/IKP?

WASA-at-COSY installation

Summary of experiment (do not exceed this space):

We propose to conduct a search for the ^{3}He-η bound state by the energy scan at the final states ppNπ, ^{3}He6γ and ^{3}He2γ measuring excitation functions of its production cross section in proton-deuteron reactions for processes corresponding to two anticipated mechanisms:(i) absorption of the η meson by one of the nucleons, which subsequently decays into N-π pair e.g.: pd-> $(^3\text{He-}\eta)_{bound}$ ->pppπ^-, and (ii) decay of the η-meson while it is still "orbiting" around a nucleus e.g.: pd-> $(^3\text{He-}\eta)_{bound}$ -> ^{3}He6γ reactions. In the first case we estimate a cross section for the bound state formation in the order of 80 nb, and from the previous experiments we estimate a background to about 2500 nb. In the case of the second considered mechanism, we expect a cross section for the signal in the order 0.4 nb and background in the order of 16 nb. Recent theoretical investigations show, independent of the model, that the binding energy of the possible η-mesic helium is small (in the order of 1 MeV). Therefore, we assume that the pole is very close to the threshold, in the range of few MeV. The predicted value of the width of the mesic nucleus is strongly model-dependent and varies from about 1 MeV to about 20 MeV. Therefore, we intend to scan the excess energy range around the ^{3}He-η threshold from -50 to 20 MeV. In order to decrease the systematic uncertainties we plan to change beam momentum continuously for each measurement cycle. In order to reach a sensitivity for a width in the order of MeV, we need to collect statistics, that will permit the binning into intervals of 1 MeV. Taking into account the expected background cross section, we can reach a sensitivity of 10 nb for the measurement of the pd-> $(^3\text{He-}\eta)_{bound}$ ->pppπ^- reaction and a sensitivity of 0.5 nb for the pd-> $(^3\text{He-}\eta)_{bound}$ -> ^{3}He6γ reaction within 10 days of continous measurement with an average luminosity of $5\text{x}10^{30}\text{cm}^{-2}\text{s}^{-1}$.

In the most pessimistic case the measurement will permit to lower the upper bound for the cross section of the production of the ^{3}He-η nucleus in the case of the pd-> $(^3\text{He-}\eta)_{bound}$ ->pppπ^- reaction from the present limit of 270 nb down to a value of 10 nb and to put the first limits on the pd-> $(^3\text{He-}\eta)_{bound}$ -> ^{3}He6γ reaction. It is important to stress that such a sensitivity will permit to reach the range of values of the cross section expected for the creation of the η-mesic ^{3}He. The normalisation will be determined based on the simultaneous measurement of the reactions pd-> ^{3}Heη, pd-> ^{3}Heπ^0, and proton-deuteron elastic scattering, and the absolute value of excess energy will be determined via missing mass method using the pd-> ^{3}He-η reaction.

In order to realize the proposed studies we would like to ask for two weeks of the proton beamtime in the slow ramping mode.

Attach scientific justification and a description of the experiment providing the following information:

For proposals:
Total beam time (or number of particles) needed; specification of all necessary resources
For beam requests:
Remaining beam time (allocations minus time already taken)

Scientific justification:
- What are you trying to learn?
- What is the relation to theory?
- Why is this experiment unique?

Details of experiment:
- Description of apparatus.
- What is the status of the apparatus?
- What targets will be used and who will supply them?
- What parameters are to be measured and how are they measured?
- Estimates of solid angle, counting rate, background, etc., and assumptions used to make these estimates.
- Details which determine the time requested.
- How will the analysis be performed and where?

General information:
- Status of data taken in previous studies.
- What makes COSY suitable for the experiment?
- Other considerations relevant to the review of the proposal by the PAC.

EC-Support:
The European Commission supports access of new users from member and associated states to COSY. Travel and subsistence costs can be granted in the frame of the program Access to Large Scale Facilities (LSF).

Search for the η-mesic ^{3}He with WASA at COSY

Spokesperson: P. Moskal[a]
Contributors: W. Krzemień[a], M. Skurzok[a]
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January 14, 2014

Abstract

We propose to conduct a search for the ^{3}He-η bound state by measuring excitation functions of its production cross sections in proton-deuteron reactions for processes corresponding to two anticipated mechanisms: (i) absorption of the η meson by one of the nucleons, which subsequently decays into $N-\pi$ pair e.g.: $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$, and (ii) decay of the η-meson while it is still "orbiting" around a nucleus e.g.: $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\,6\gamma$ reactions. In the first case we estimate a cross section for the bound state formation in the order of 80 nb, and from the previous experiments we estimate a background to about 2500 nb. In the case of the second considered mechanism, we expect a cross section for the signal in the order 0.4 nb and background in the order of 16 nb. Recent theoretical investigations show, independent of the model, that the binding energy of the possible η-mesic helium is small (in the order of 1 MeV). Therefore, we assume that a pole is very close to the threshold, in the range of few MeV. The predicted value of the width of the mesic nucleus is strongly model-dependent and varies from about 1 MeV to about 20 MeV. Therefore, we intend to scan the excess energy range around the $^3\text{He}-\eta$ threshold from -50 to 20 MeV. In order to decrease the systematic uncertainties we plan to change beam momentum continuously for each measurement cycle. In order to reach a sensitivity for a width in the order of MeV, we need to collect statistics, that will permit the binning into intervals of 1 MeV. Taking into account the expected background cross section, we can reach a sensitivity of 10 nb for the measurement of the $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$ reaction and a sensitivity of 0.5 nb for the $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\,6\gamma$ reaction within two weeks of measurement with an average luminosity of $5 \cdot 10^{30}\ cm^{-2}s^{-1}$.

In the most pessimistic scenario the measurement will permit to lower the upper bound for the cross section of the production of the η–^{3}He nucleus in the case of the $pd \rightarrow (^3\text{He}\eta)_{bound} \rightarrow ppp\pi^-$ reaction from the present limit of 270 nb down to a value of 10 nb and to put the first limits on the $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\,6\gamma$ reaction. It is important to stress that such a sensitivity will permit to reach the range of values of the cross section expected for the creation of the η-mesic ^3He. The normalisation will be determined based on the simultaneous measurement of the reactions $pd \rightarrow {}^3\text{He}\eta$, $pd \rightarrow {}^3\text{He}\pi^0$, as well as proton-deuteron elastic scattering, and the absolute value of excess energy will be determined via missing mass method using the $pd \rightarrow {}^3\text{He}\eta$ reaction.

In order to realize the proposed studies we would like to ask for two weeks of the proton beamtime in the slow ramping mode.

1 Introduction

In 2008 we have presented a proposal for the search of the mesic nucleus in ^{3}He-η and ^{4}He-η systems with the WASA detector at COSY (see 186.1 and 186.2 at http://donald.cc.kfa-juelich.de/wochenplan/List_of_all_COSY-Proposals.shtml)

The observation of a bound state of meson and nucleus would be interesting in its own account, and the determination of its properties would be valuable for the determination of the eta-nucleon interaction, for studies of the N*(1535) properties in nuclear matter [1, 2], the properties of the η meson in the nuclear medium [3, 4, 5], for the determination of the flavour singlet component of the η meson [6], and in general for studies of the chiral and axial U(1) symmetry breaking in low energy QCD [2, 6, 7].

According to the recommendation of the PAC36 and next PAC37 (beam request) we have conducted a search for the $^4He-\eta$ bound state measuring the excitation functions for the $dd \to {}^3\mathrm{He}\, p\pi^-$ and $dd \to {}^3\mathrm{He}\, n\pi^0$ reactions. The main experimental campaign was completed in November 2010 and as promised in the proposal we have reached the sensitivity on the level of few nb. Results based on the first data sample were published recently [8], and the status of the analysis of the full sample with 20-times larger statistics is described below in section 2.

Due to the limitations in the available beam-time the PAC has recommended to concentrate on the studies of only one out of the ^{3}He-η and ^{4}He-η states. We decided to investigate the ^{4}He-η system via the $dd \to ({}^4\mathrm{He}-\eta)_{bound} \to {}^3\mathrm{He}N\pi$ reactions. The choice was rather arbitrary and was based mainly on the fact that ^{3}He identification with the WASA detector allows for a less involved analysis and cleaner triggering compared to the case of the $pd \to ({}^3\mathrm{He}-\eta)_{bound} \to ppN\pi$ reactions.

Now encouraged by the statements by the previous PAC meetings that "the possible existence of the meson-nucleus bound states is one of the current issues in hadron and nuclear physics which is of high physics interest", and by the recent theoretical and experimental results [4, 9, 10, 11, 12, 13, 14, 15, 16] we would like to complete the studies proposed in the original proposal and to measure the excitation function for the $pd \to ({}^3\mathbf{He}\text{-}\eta)_{bound} \to ppp\pi^-$, $pd \to ({}^3\mathbf{He}\text{-}\eta)_{bound} \to ppn\pi^0$, $pd \to ({}^3\mathbf{He}\text{-}\eta)_{bound} \to dp\pi^0$, $pd \to ({}^3\mathbf{He}\text{-}\eta)_{bound} \to {}^3\mathbf{He}\, 2\gamma$ and $pd \to ({}^3\mathbf{He}\text{-}\eta)_{bound} \to {}^3\mathbf{He}\, 6\gamma$ systems in the excess energy range near threshold (below and above threshold for ^{3}He-η production).

With respect to the state of the knowledge in the year 2008 we have now new and stronger arguments in favour of carrying out the search for the ^{3}He-η bound state. Moreover, thanks to articles [4, 7, 9, 11, 16, 17] and vigorous discussions carried out at the symposium dedicated to the η-mesic nuclei http://koza.if.uj.edu.pl/mesic-nuclei-2013/ we have elaborated a new experimental approach complementary to the one presented in the original proposal.

The main arguments in favour of the search for the η-mesic-^{3}He systems are:

1. The extremely steep rise of the total cross section for the $pd \to {}^3\mathrm{He}\eta$ reaction in the very close-to-threshold region followed by a plateau may originate from a pole of the $\eta^3\mathrm{He} \to \eta^3\mathrm{He}$ scattering amplitude in the complex excess energy plane Q with $Im(Q) < 0$ [18] (see left panel of Fig 1).

2. A steep increase of the total cross section for ^{3}He-η photo-production at threshold via the $\gamma^3He \to \eta^3He$ reaction [16, 19] (see Fig. 2) shows that the rise of the cross section above threshold is independent of the initial channel and can therefore be assigned to the $^3He-\eta$ interaction.

3. The recent determination of the energy dependence of the tensor analysing power t_{20} by the ANKE collaboration confirmed that the s-wave production amplitude in the $pd \to {}^3\mathrm{He}\,\eta$ reaction is fairly energy independent [20] (see Fig 3); again indicating that the steep threshold enhancement is due to the $^3He-\eta$ interaction.

4. The asymmetry in the angular distribution of the η meson emission [21, 22] indicates strong changes of the phase of the s-wave production amplitude with energy, as expected from the occurrence of the bound or virtual η^3He state [18] (see right panel of Fig. 1).

5. The evolution with energy of the angular dependence of $\gamma^3He \rightarrow \eta^3He$ [19] is "similar to that of the $pd \rightarrow {}^3$Heη reaction which indicates changing of s-wave amplitude associated with the η^3He pole" [9].

6. An often stated argument that the extracted ηN scattering length is too low for the η-helium binding is weakened in view of new theoretical results. Estimates of sub-threshold amplitudes are model dependent and recently Gal et al., has concluded that: "Calculations of η-nuclear bound states show, in particular, that the η-N scattering length is not a useful indicator of whether or not η meson bind in nuclei"[11]. Moreover, differences in the value of ηN scattering lengths obtained in different analyses are at least to some extent explained by the recent observation that the flavour singlet component induces greater binding than the flavour-octet one. Therefore, the $\eta - \eta'$ mixing, which is neglected in many of the former analyses, increase the η-nucleon scattering length relative to the pure octet η by a factor of about 2 [7]. The importance of the $\eta - \eta'$ mixing is also stressed [23].

Despite the rapid increase of theoretical efforts in recent years there are still no model independent calculations which would really help to judge which out of the ^{4}He-η and ^{3}He-η systems is more likely to form a bound state. However, indications and claims exist in favour of the ^{3}He-η system. For example the rise of the cross section at threshold and hence the strength of the eta-nucleus interaction is much stronger in the case of the ^{3}He-η system than in the case of the ^{4}He-η one. This is clearly seen in Fig 3. Furthermore, Colin Wilkin concludes in a recent article: "There is very good experimental evidence that the strong final state interaction seen in the $\vec{d}d \rightarrow {}^3He\eta$ and γ^3He $\rightarrow \eta^3$He reactions near threshold must be associated with a pole in the excess energy plane for |Q|<1MeV. In contrast, any FSI in ${}^4He\eta$ system is less obvious"[9].

In the proposed experiment we plan to search for the decay of the η-mesic helium via two mechanisms:

1. As discussed in the original proposal: absorption of the eta meson and excitation of one of the nucleons to an N* resonance, which subsequently decays into an $N - \pi$ pair:

   $pd \rightarrow ({}^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$,

   $pd \rightarrow ({}^3\text{He-}\eta)_{bound} \rightarrow ppn\pi^0$,

   $pd \rightarrow ({}^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$,

2. Decay of the η-meson while "orbiting" around a nucleus [9] via:

   $pd \rightarrow ({}^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\, 2\gamma$ and $pd \rightarrow ({}^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\, 6\gamma$.

For the first reaction we estimate a cross section in the order of 80 nb and the background of about 2500 nb, and for the second decay mechanism we estimate the cross section in the order of 0.4 nb with background of about 16 nb. However, these are crude estimates (see Section 3).

The importance of the studies of mesic nuclei is reflected also in the ongoing research programs on the η and η'-mesic nuclei in many laboratories as e.g.: ELSA [24], MAMI [15], GSI [25, 26], JINR and LPI [27], and JPARC [28, 29].

It is worth to point out that this proposal is complementary to the above mentioned programs and that WASA detector at COSY gives unique possibilities to conduct the proposed studies of the hadronic production of ^{3}He-η system with the continuous change of the beam momentum and the exclusive measurement of all ejectiles.

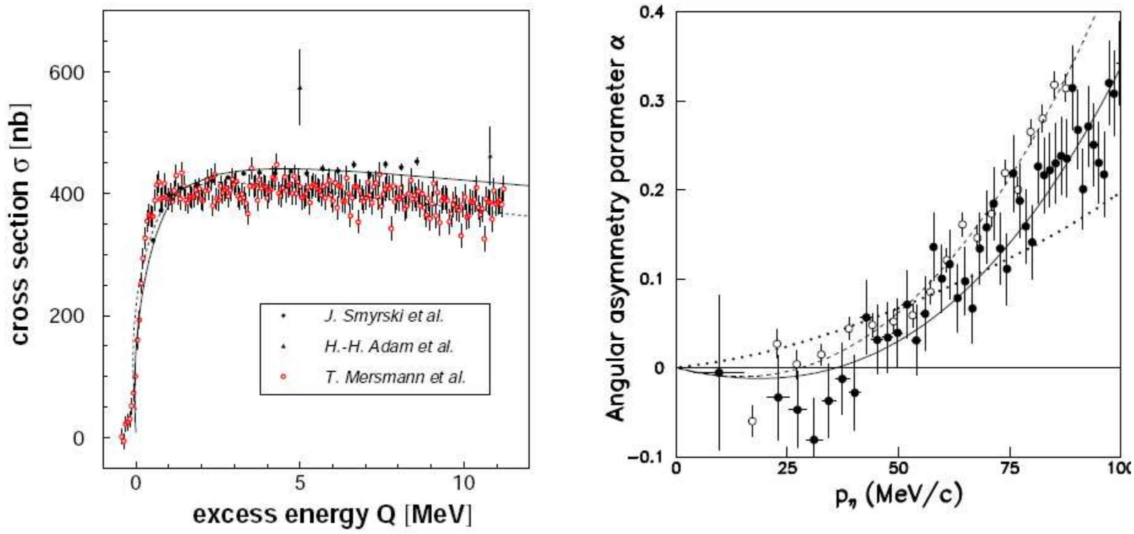

Figure 1: Left: Close-to-threshold total cross-section for the $dp \to {}^3\mathrm{He}\eta$ reaction plotted as a function of the excess energy Q. Shown are the measurements performed by ANKE collaboration [30] (open circles) and COSY-11 group: [31] (full dots) and [32] (triangles). The solid line represents the scattering length fit to the COSY-11 data [31], while the dashed line is the analogous fit to the data set of Ref. [30]. Right: Angular asymmetry parameter α plotted as a function of CM momentum. Filled circles are the experimental data from ANKE [30], whereas open circles represent the data set of COSY-11 group [31]. The solid and dashed lines correspond respectively to fit to the ANKE and COSY-11 data, including the phase variation of the s-wave scattering amplitude, whereas the dotted line is obtained neglecting the phase variation of the amplitude. The Figure is adopted from Ref. [18] .

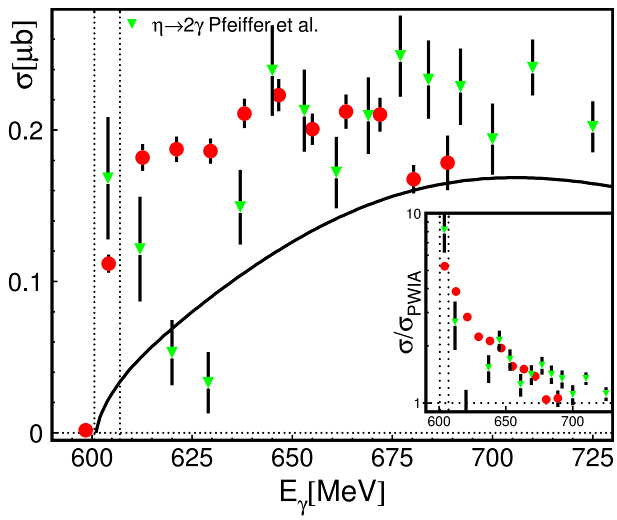

Figure 2: Total cross section for the $\gamma^3\mathrm{He} \to \eta^3\mathrm{He}$ coherent η-production reactions [19, 33]. The curves are from PWIA modelling. The dotted lines indicate coherent and breakup thresholds. The inserts show the ratio of data and PWIA prediction (figure from [16]).

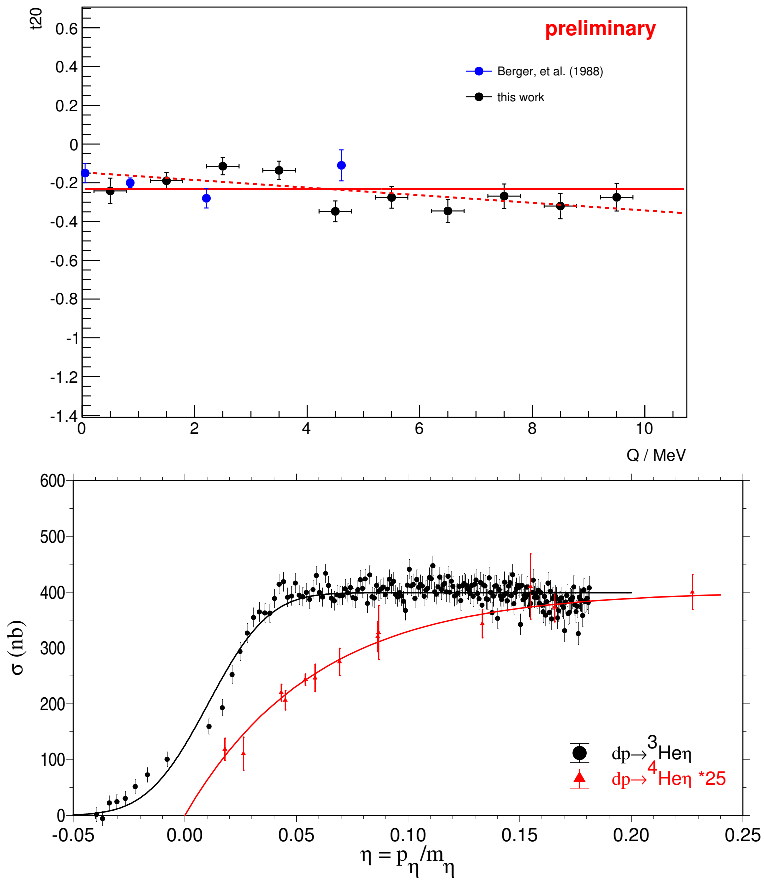

Figure 3: Top: Energy dependence of the deuteron tensor analysing power t_{20} close to the production threshold. The solid line corresponds to a fit to the data assuming a constant analysing power while the fit indicated by the dashed line allows for a linear energy dependence (figure from [20]). Bottom: Comparison of the excitation functions for the $dp \rightarrow {}^3\mathrm{He}\eta$ and $dd \rightarrow {}^4He\eta$. The dd data have been scaled by a factor of 25. The solid curves are to guide the eye (figure from [34]).

2 Status of the search for the signal from the ${}^4He - \eta$ bound state in the excitation function of the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow {}^3\mathrm{He}n\pi^0$ reactions

Two experiments dedicated to the search of η-mesic helium were conducted up to now using the WASA-at-COSY detector. Both of the experiments focused on the bound state decay into the ^{3}He and a nucleon- pion pair.

The first experiment was performed in June 2008 by measuring the excitation function of the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction near the η meson production threshold [8]. During the experimental run the momentum of the deuteron beam was varied continuously within each acceleration cycle from 2.185 GeV/c to 2.400 GeV/c, crossing the kinematic threshold for η production in the $dd \rightarrow {}^4\mathrm{He}\,\eta$ reaction at 2.336 GeV/c. This range of beam momenta corresponds to a variation of the ${}^4\mathrm{He} - \eta$ excess energy from -51.4 MeV to 22 MeV.

Unfortunately out of nine allocated days, due to problems with the pellet target and the COSY beam we could collect data only for one day which in part had to be used to adjust and optimize the trigger conditions. The total time of effective data taking was 16.5 hours. We reached an averaged luminosity of about $2{\cdot}10^{30} s^{-1} cm^{-2}$. At the time of the experiment the cooling of the solenoid was broken and the measurement was carried out without magnetic field. That fact excluded the possibility of a direct momentum determination as well as the usage of the standard identification method for the charged particles registered in the Central Detector. Instead, momenta were determined with worse accuracy using the measured track angles and the He momentum. In spite of the mentioned difficulties, the performed measurement provided a data sample enabling us to check and optimize the trigger settings. The analysis of this test data also permitted to determine an upper limit of about 25 nb for the cross-section for the formation and decay of the bound state in the process $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ at the 90% confidence level (see below).

The so far performed analysis exhibits no structure which could be interpreted as a resonance originating from the decay of the η-mesic ^{4}He. The final excitation function obtained after the correction for the efficiency and the normalization to the luminosity is presented in Fig. 4. It can be well described by a second order polynomial (dashed line) resulting in a chi-squared value per degree of freedom of 0.98 and slightly worse by a straight line (solid line).

The data show no signal of the ^{4}He-η bound state in the excitation function. The results were published in [8]. The upper limit for the cross-section for the bound state formation and decay in the process $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ was determined at the 90 % confidence level and it varies from 20 nb to 27 nb for the bound state width ranging from 5 MeV to 35 MeV, respectively. The upper limits depend mainly on the width of the bound state and only slightly on the binding energy.

During the second experiment, in November 2010, two channels of the η-mesic helium decay were searched for: $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ and $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$ [35]. During the experimental run the momentum of the deuteron beam was varied continuously within each acceleration cycle from 2.127 GeV/c to 2.422 GeV/c, crossing the kinematic threshold for η production in the $dd \rightarrow {}^4\text{He}\,\eta$ reaction at 2.336 GeV/c. This range of beam momenta corresponds to a variation of the ^{4}He-η excess energy from -70 MeV to 30 MeV.

Data were taken for about 155 hours. The average luminosity was estimated based on the trigger rate for the elastic proton-proton scattering ($L=8.15{\cdot}10^{30} cm^{-2} s^{-1}$). Taking into account the fact that two reactions were measured, in total more than 20 times higher statistics were collected than in the 2008 run.

Independent analyses for the $dd \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$ and $dd \rightarrow {}^3\text{He}p\pi^-$ reactions were carried out. The ^{3}He for both cases was identified in the Forward Detector based on the ΔE-E method. The π^0 was reconstructed in the Central Detector from the invariant mass of two decay photons while the π^- identification in Central Detector was based on the measurement of the energy loss in the Plastic Scintillator combined with the energy deposited in the Electromagnetic Calorimeter. Neutrons and protons were identified via the missing mass technique. The corresponding spectra with applied cuts are presented in Fig. 5.

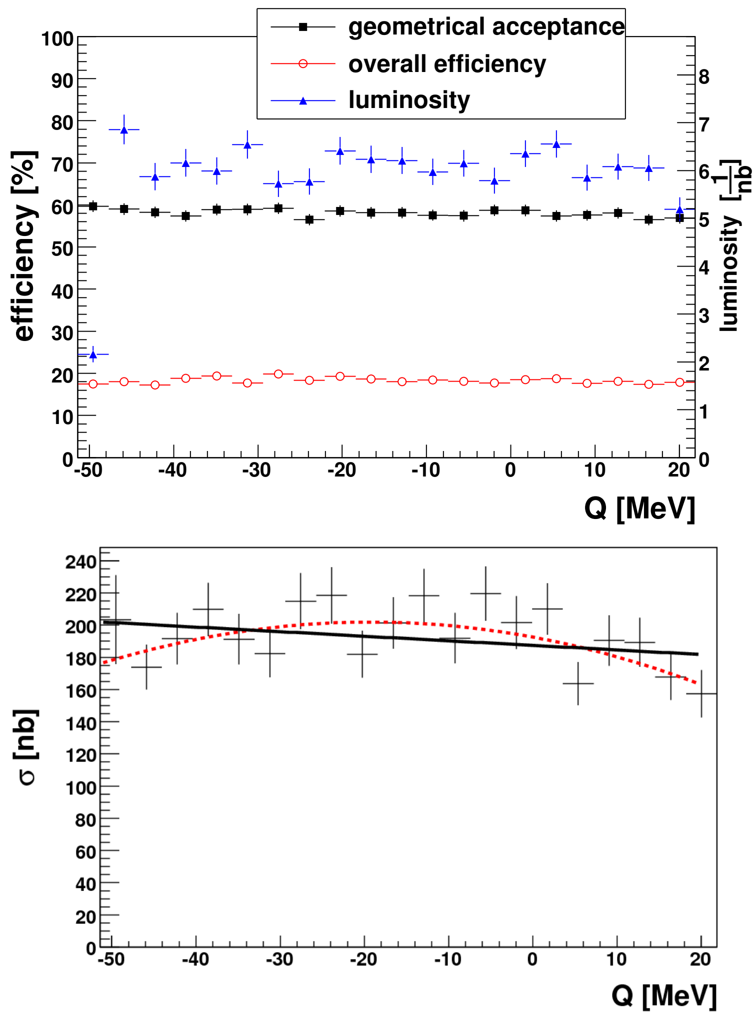

Figure 4: Top: Geometrical acceptance (full black squares), overall efficiency (open red circles) and luminosity (full blue triangles) as a function of the excess energy. The right axis denotes the luminosity. Bottom: Experimental excitation function for the $dd \rightarrow ^3\mathrm{He}p\pi^-$ reaction obtained after the normalization of the events selected in individual excess energy intervals by the corresponding integrated luminosities. The dotted and solid lines correspond to the second and the first order polynomials fitted to the data. The figures are adopted from Ref. [8].

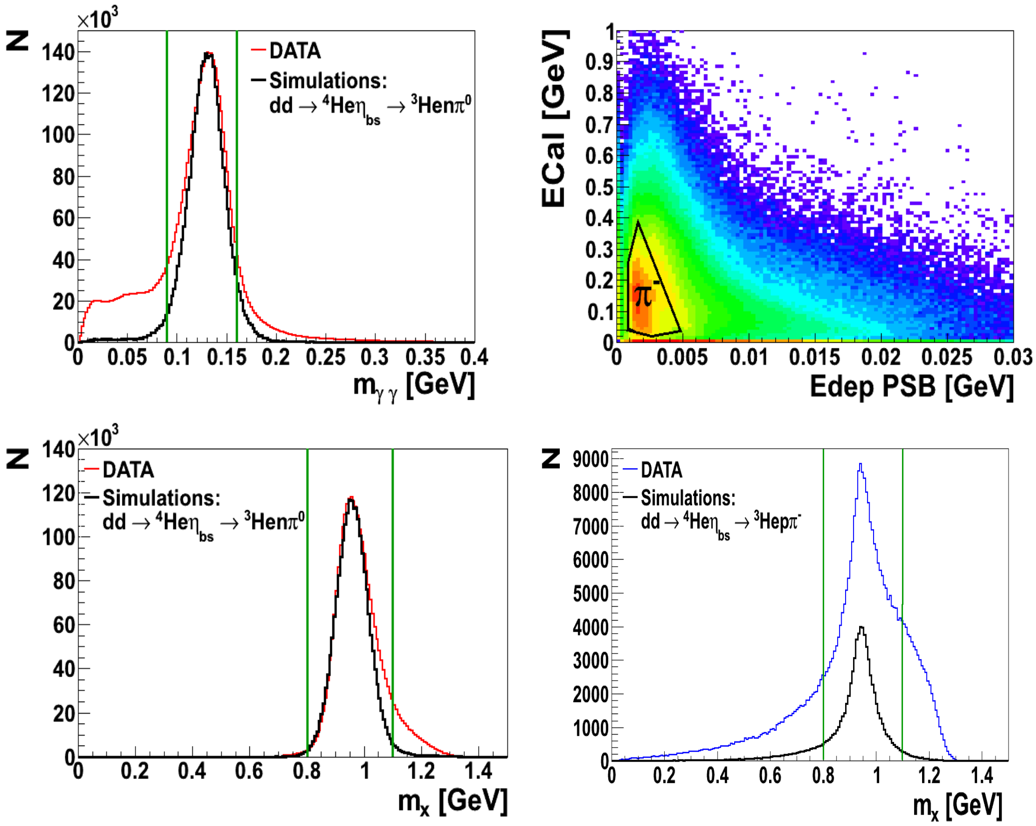

Figure 5: π^0 and π^- identification (upper panel). Proton and neutron identification (lower panel). The data are shown as red and blue histograms, the Monte Carlo simulations of the signal are marked with the black line, while the applied cuts are marked in green. m_x denotes the missing mass for the $dd \to {}^3\text{He}X$ reaction.

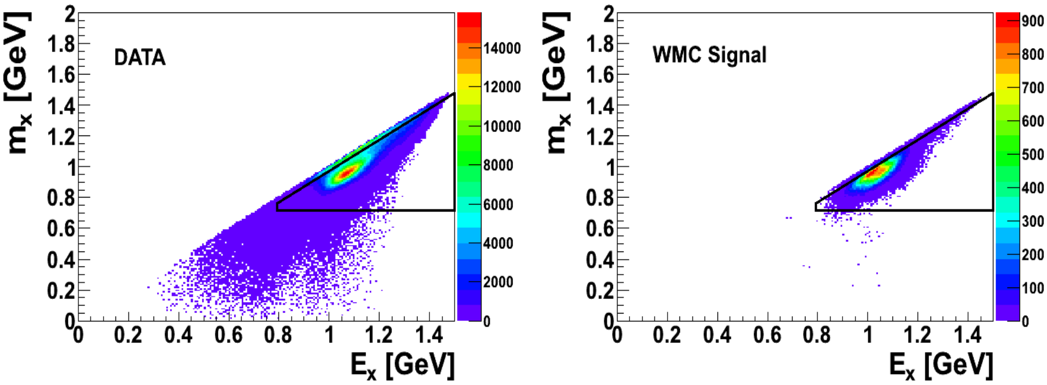

Figure 6: Missing mass m_x vs. missing energy E_x for $dd \to {}^3\text{He}X$ reaction. Data is presented in left panel while Monte Carlo in right panel. The applied cut is marked in black.

In case of the $dd \to {}^3\text{He}n\pi^0$ reaction, before particle identification, an additional cut on the $m_x(E_x)$ spectrum was applied as shown in Fig. 6 (left). The cut is based on Monte Carlo simulations and is presented in Fig. 6 (right).

In case of the $dd \to {}^3\text{He}p\pi^-$ reaction an additional coplanarity cut was applied. As a measure of the coplanarity the angle between the vector $\vec{p}_{beam} - \vec{p}_{^3He}$ and the cross product of the vectors $\vec{p}_1$ and $\vec{p}_2$: $\theta_{k,1x2} = \angle(\vec{p}_{beam} - \vec{p}_{^3He}, \vec{p}_1 \times \vec{p}_2)$ was defined. In the case of coplanarity $\theta_{k,1x2}$=90°. In data we applied a cut $\theta_{k,1x2} \in (90 \pm 5)^\circ$ which is presented in Fig. 7.

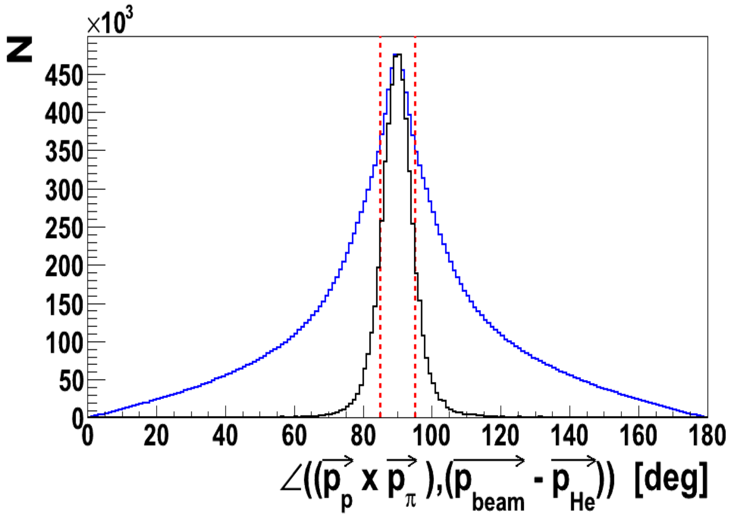

Figure 7: Distribution of the coplanarity observable determined for simulations of $dd \rightarrow$ ^{3}He$p\pi^-$ (black line) and for experimental data (blue line). The cut applied to the data - $\theta_{k,1x2} \in (90 \pm 5)^\circ$ - is marked by the vertical dotted red lines.

In order to select events corresponding to the production of bound states, cuts in the ^{3}He CM momentum, nucleon CM kinetic energy, pion CM kinetic energy and the opening angle between nucleon-pion pair in the CM were applied based on Monte Carlo simulations. These cuts are presented in Fig. 8.

The excitation functions for both reactions were determined for a "signal rich" region corresponding to momenta of the ^{3}He in the CM system with $p^{cm}_{^3He} \in (0.1, 0.2)$GeV/c and for a "signal poor" region with $p^{cm}_{^3He} \in (0.2, 0.23)$GeV/c which are marked with (A) and (B) in the left upper panel in Fig. 8, respectively.

The excitation functions for the $dd \rightarrow$ ^{3}He$n\pi^0$ and $dd \rightarrow$ ^{3}He$p\pi^-$ reactions are presented in Fig. 9.

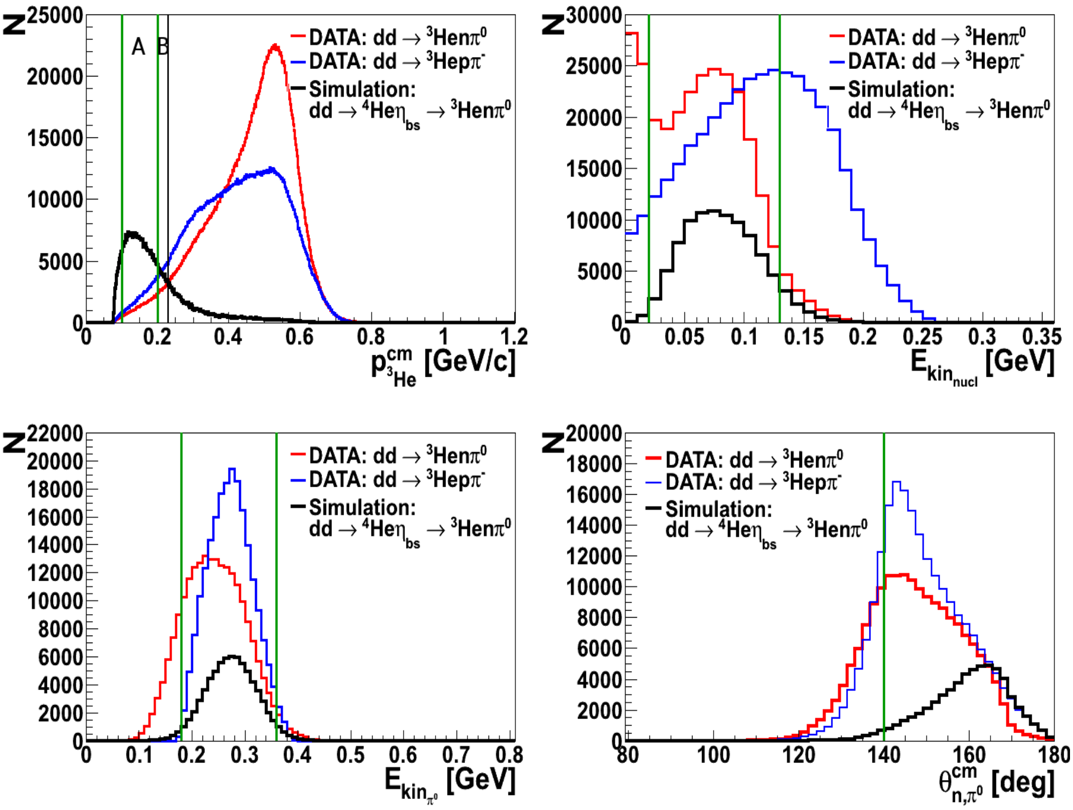

Figure 8: Spectrum of p^{cm}_{3He} (left upper panel), $E^{cm}_{kin_{nucl}}$ (right upper panel), $E^{cm}_{kin_{\pi}}$ (left lower panel) and $\theta^{cm}_{nucl,\pi}$ (right lower panel). Data are shown in red and blue for $dd \to {}^3\text{He}n\pi^0$ and $dd \to {}^3\text{He}p\pi^-$ reaction, respectively. Monte Carlo simulations of signal are shown in black, while the applied cuts are marked with the green lines.

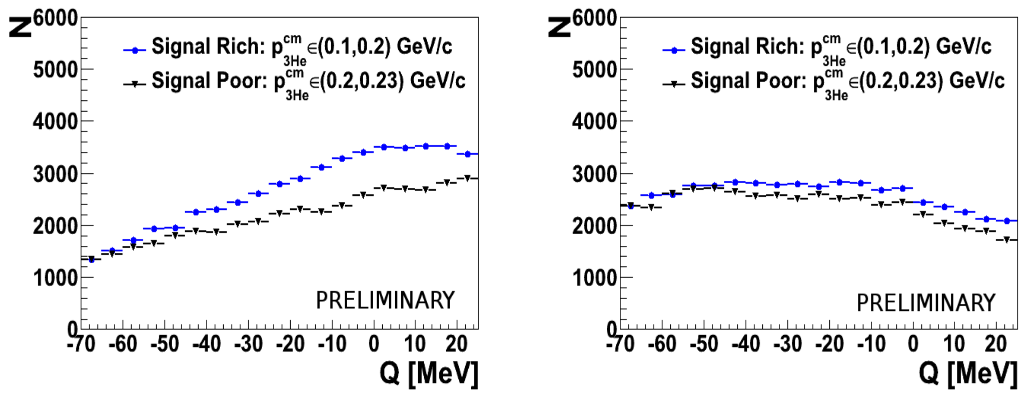

Figure 9: Excitation function for the $dd \to {}^3\text{He}n\pi^0$ reaction (left panel) and the $dd \to {}^3\text{He}p\pi^-$ reaction (right panel). The "signal rich" region is shown in blue while the "signal poor" region normalized to the first bin of the "signal rich" region is shown in black. The analysis is based on the whole data sample.

The excitation functions for data of $dd \to ({}^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$ reaction is presented in the upper panel in Fig. 10 while for WMC simulations of background $dd \to {}^3\text{He}n\pi^0$ and $dd \to {}^3\text{He}N^* \to {}^3\text{He}n\pi^0$ reactions are presented in the left and right lower panel in Fig 10,

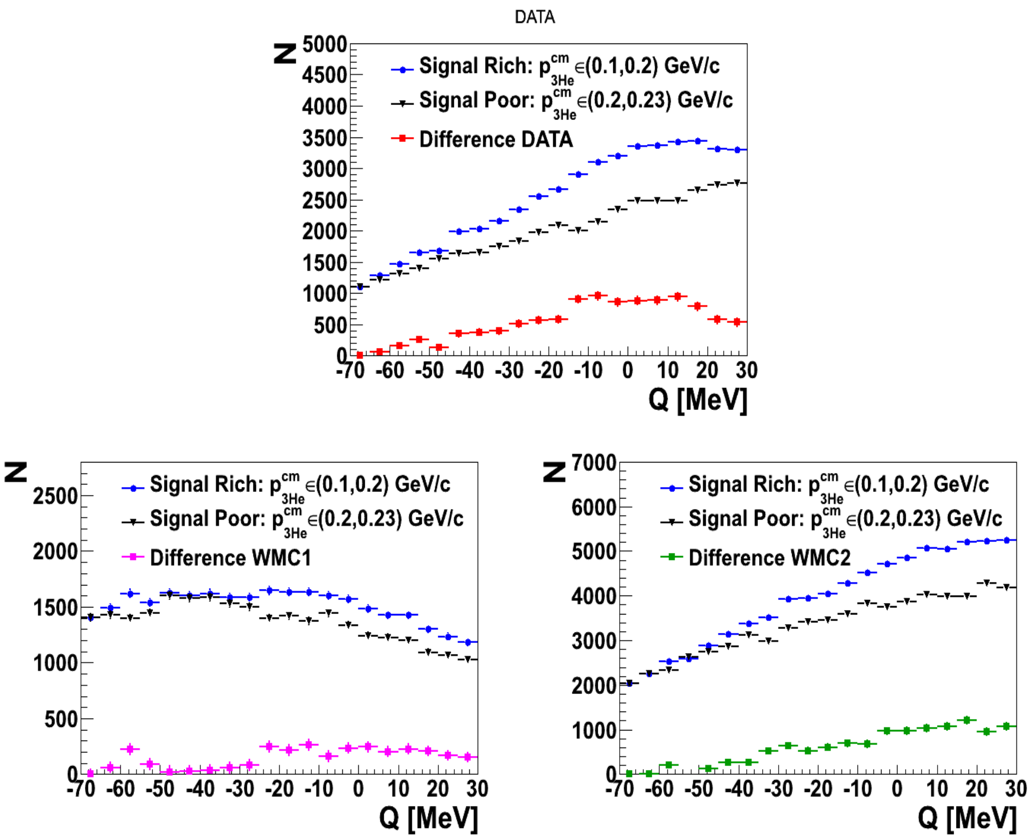

Figure 10: Excitation functions for Signal Rich, Signal Poor Regions and the difference between them for DATA (upper panel), for $dd \rightarrow {}^3\mathrm{He}n\pi^0$ (left lower panel) and for $dd \rightarrow {}^3\mathrm{He}N^* \rightarrow {}^3\mathrm{He}n\pi^0$ reactions (right lower panel). The "Signal Poor" region (black) is normalized to the first bin of "Signal Rich" region (blue). The difference between the excitation functions is marked with red, magenta and green lines, respectively. The analysis is based on WMC simulations for 10 million of generated events.

respectively.

The analysis is still in progress. However, already now we can conclude that a collected data are of a very good quality and that we have achieved a promised sensitivity of the cross section of the order of few nb for the bound state production in $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$ and $dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ reactions.

3 Estimation of the signal and background for the search of the ^{3}He-η bound state in the proton-deuteron reaction with WASA-at-COSY

3.1 Estimation of the signal

It is a priori impossible to predict in a model independent way a cross section for the creation of the η-mesic nucleus. This depends strongly on the strength of the relatively poorly known η-Nucleon interaction below threshold, and involves computations of the behaviour of the many-body system. However, recently for the first time total cross sections for the dd and pd reaction at the η-mesic pole was estimated [9, 17]: It amount to about 80 nb for the $pd \rightarrow ({}^3\mathrm{He} - \eta)_{bound} \rightarrow Xp\pi^-$ [9] and is in the range from 4.5 nb [17] to

30nb for the $dd \rightarrow (4He - eta)_{bound} \rightarrow Xp\pi^-$ reaction [9]. These values are in the range of expectations presented by us in the original proposal. These estimates based on the assumption that the real and imaginary part of the helium-η scattering length are almost the same and 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 connected with the absorption of the η meson on the helium nucleus) is to first order the same as the close to threshold cross section for the η meson production. This leads to the assumption, that the cross section at the maximum of the distribution for the $pd \rightarrow (^3\text{He-}\eta)_{bound}$ production is about 400 nb. The dominant decay channels of the $(^3\text{He-}\eta)_{bound}$ state are due to the absorption of the eta meson by a nucleon, its excitation to the N*(1535) resonance, and a subsequent decay of the N* into $\pi - N$ pair:
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$,
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppn\pi^0$,
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow pnn\pi^+$,
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$,
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dn\pi^+$,
Thus the cross sections expected for the above listed channels on the average amounts to about 80 nb per channel (as an order of magnitude estimate).

The possibility of non-$N\pi$ decays of the mesic-helium was pointed out by Wycech [17] and Wilkin [9]. In this case the reaction may proceed e.g. as follows:
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppn$,
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow pd$.
Such processes could be due to the absorption of η-meson via e.g. $\eta d \rightarrow pn$ reaction. However, Wilkin [9] estimated in the first approximation that the two-nucleon absorption constitutes at most 5% of the total decay rate [9], and in addition these channels are buried in a large background.

The decay of the eta meson when it is still orbiting around the nucleus seems to be more promising experimentally due to the very low background. Gal et al. pointed out, as a model independent feature, that "in-medium subthreshold amplitudes encountered in eta-nuclear bound-state calculations are substantially weaker both in their real part as well as in their imaginary part than the $\eta - N$ scattering length"[11]. This decreases the rate for the process through the N* and its decay into $N - \pi$ but it increases the rate for the decay of the η when still orbiting around the nucleus. As a very rough approximation we may estimate the cross sections for the processes: $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\,2\gamma$, and $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\,6\gamma$ to be about 0.4 nb
This value can be estimated taking into account that the total width of the eta meson is about 1.3 keV, the width of the $(^3\text{He-}\eta)$ is less than about 500 keV, and the 2γ and 6γ branching ratios amounts to about 39% and 33%, respectively [9].

3.1.1 Estimation of the background

From the measurements with COSY-11 performed with a deuteron beam and a proton target [36] and the measurements performed with WASA we estimate a background for the $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$, reactions to about 2500 nb. At the COSY-11 experiment the observed background correspond to about 5000 nb. This was however measured for the case that only protons were registered and pions were identified via missing mass. In the WASA experiment we can register all ejectiles and can decrease the background by at least a factor of two by the condition that the center-of-mass relative angle between proton and pion registered in the Central Detector should be around 180 degree.

As regards reactions with ^{3}He ions in the final state, their identification works very well at the WASA detector as it was proven in many previous experiments and we expect the same or even better conditions without the FRH detectors but with the possibility of the time-of-flight application. In this case a coincident measurement of the ^{3}He ions in the Forward Detector and gamma quanta in the Central Detector will allow for an identification of the $pd \to {}^3\mathrm{He}\,2\gamma$ and $pd \to {}^3\mathrm{He}\,6\gamma$ reactions. We expect that in this case physical background below threshold for ^{3}He-η production will be much smaller than the experimental background with main contribution originating from the splitting and merging of clusters in the electromagnetic calorimeter.

The reactions which can have dominant contribution to the background are presented in Tables 1 and 2 in Appendix 1. The results are based on the WASA-Monte-Carlo simulations carried out for each of the reaction separately. As can be inferred from the result of simulations the main background e.g. for the $pd \to {}^3\mathrm{He}\,6\gamma$ will originate from the direct production of $3\pi^0$ and $2\pi^0$ via reactions $pd \to {}^3\mathrm{He}\,3\pi^0$ and $pd \to {}^3\mathrm{He}\,2\pi^0$. The background from other reaction can be suppressed to a negligible level by the identification of ^{3}He ion in Forward Detector and at least six clusters in Central detector. In addition the values given in the last column of table 2 can be reduced by using missing mass distribution for further suppression of the background. Altogether for this reaction below the threshold we expect a background in the order of 1nb in the case if ^{3}He ion is registered in the Forward Detector and 64nb if the ^{3}He escapes detection in the beam-pipe. In the latter case the main expected background originates from the $pn \to pn2\pi^0$ reactions and this may be further significantly reduce (we assume to 16 nb) by the kinematical fitting with the requirement that the no observed ion has a mass of ^{3}He, and that the registered clusters would combine into 3 pairs of gamma quanta from the π^0 meson decay and additional further reduction of the splittings by optimization of requirements on minimal cluster energy and on minimal distance between clusters.

In summary: In the case of the mechanism when the η meson is absorbed by one of the nucleons which subsequently decays into $N-\pi$ final state for most favourable channels: $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to ppp\pi^-$, $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to ppn\pi^0$ we expect cross section for the bound state formation in the order of 80 nb, and from the previous experiments we estimate a background to about 2500 nb. In the case of the second considered mechanism, when the η meson decays while orbiting around the ^3He nucleus we expect a cross section for the $pd \to {}^3\mathrm{He}\,6\gamma$ reactions in the order 0.4nb and background in the order of 16nb.

3.2 Counting rate estimate

For the reactions $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to ppp\pi^-$, $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to ppn\pi^0$ and $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to pd\pi^0$, we will set the trigger condition based on the detection of one or more charged particles in the Forward Detector combined with conditions on the particles going into the Central Detector. In case of the reaction $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to ppp\pi^-$: at least 2 charged particles, and in case of the reaction $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to ppn\pi^0$ at least two neutral particles will be required in the Central Detector. The neutron will be reconstructed offline using standard missing mass techniques. In case of the reaction $pd \to ({}^3\mathrm{He}\text{-}\eta)_{bound} \to pd\pi^0$, at least two neutral particles in Central Detector and at least one charged in the Forward Detector will be required.

For the reactions with $pd \to {}^3\mathrm{He}\text{–}\eta$ the most effective trigger will contain the conditions on the detection of one charged particle with optimized thresholds (^{3}He) in the Forward Detector. However, in case of the pd to ^{3}He η in the low excess energy region close or below the threshold the geometrical acceptance of ^{3}He ions detection is very limited. Most of the ^{3}He will go into a beampipe. In order to cover also this region we will use an additional trigger which will match the η decay registered in the Central Detector. We focus on the $\eta \to \pi^0\pi^0\pi^0 \to 6\gamma$ decay, imposing the condition of at least 6 neutral clusters in the Calorimeter combined with the veto on the Forward part, which corresponds to the ^{3}He going into the beampipe. The more loose condition, at least 2 neutral clusters in the Calorimeter would cover also the $\eta \to \gamma\gamma$ reaction, however it would be impossible to use without a very high trigger prescaling due to the high expected trigger rate.

In order to estimate the expected counting rate we checked the similar trigger setting from available data from 2008 for two triggers:

1. trigger 22: At least four neutral clusters in the calorimeter with the veto in the forward part. The prescaling factor was set to 10.

2. trigger 26: At least two neutral clusters in the calorimeter with the veto in the forward part. The prescaling factor was set to 200.

In Fig. 11 we show the multiplicity of neutral clusters reconstructed for both triggers (red line and blue lines). One needs to keep in mind that the prescaling factors were different for each trigger.

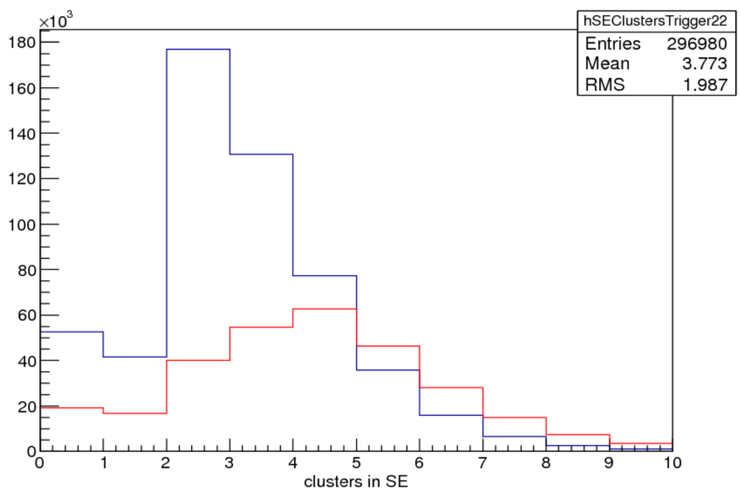

Figure 11: Cluster multiplicity in the Calorimeter for two triggers. Trigger 26 (blue, trigger prescaling 200) and trigger 22 (red, trigger prescaling 10). The plot is based on the sample of about 8% from 2008 data set.

From the obtained cluster multiplicities (see Fig 11) we can estimate that if we apply the condition at least 6 neutral clusters, then the number of registered events would correspond to about 18% of events registered by the trigger 22 and to about 5 % of events registered by the trigger 26. This corresponds to the counting rate of at most 1200 events/s with the averaged luminosity of $2{\cdot}10^{30} s^{-1} cm^{-2}$. This result should scale roughly linearly with the luminosity, therefore for the expected $5{\cdot}10^{30} s^{-1} cm^{-2}$, we can assume about 3000 events/s. This rate can be handled by the WASA DAQ.

4 Beam Time estimate

From the recent articles in which η-mesic states widths and binding energies were calculated for various models [4, 11] we can learn that, independent of the model, the binding energy of the possible η-mesic helium is small. This is in line with estimates of Wilkin [9]. Therefore, we assume that the pole is very close to threshold, in the range of few MeV. However, the predicted width of the mesic-nucleus depends strongly on the model and it varies from MeV to about 20 MeV. Therefore we intend to scan the excess energy range around the ^{3}He-η threshold from -50 to 20 MeV. In order to decrease the systematic uncertainties we want to ramp the beam momentum for each measurement cycle. In order to be prepared for a small width in the order of MeV we need to collect statistics large enough for the binning into 1 MeV intervals.

For the first discussed mechanism with the emission of the $N - \pi$ pair we estimate the cross section of 80 nb at the excess energy corresponding to the pole and the cross section for the background of 2500 nb. Since 80 nb is an order of magnitude of the estimated cross section we would like to reach a sensitivity of 10 nb. To estimate the time of the measurement (based on the experience of the ^{4}He-η state search) we assume that number of events from the 'signal' region and from the 'background' region are approximately equal. This leads to an approximate formula for the time of the measurement needed for each bin:

$$t = \sigma_{bcg}/(L \cdot \epsilon \cdot \delta^2(\sigma)) \quad (1)$$

where: σ_{bcg} - background cross section,
L - luminosity,
ϵ - efficiency,
$\delta(\sigma)$ - cross section sensitivity,

Thus in order to achieve the sensitivity of 10nb for 70 bins in the range from -50MeV to 20MeV we need two weeks of measurement with an average luminosity of $5 \cdot 10^{30}\ cm^{-2}s^{-1}$. At the same time such measurement would allow to achieve a sensitivity of about 0.5 nb for the mechanism with the decay of the eta meson while orbiting around the nucleus.

In order to realize the proposed studies we would like to ask for two weeks of the proton beamtime in the slow ramping mode.

The profile of the excitation curves will allow, in the case of an observation of the peak, to determine the binding energy and the width of the $\eta - {}^3$He bound state. Otherwise the measurement will permit to lower the upper bound for the cross section in the case of the $pd \rightarrow (^3\text{He}\eta)_{bound} \rightarrow ppp\pi^-$ reaction from the present limit of 270nb [36] **down to the value of 10nb**. It is important to stress that such sensitivity will permit to reach the range of values of the cross section predicted for the creation of the η-mesic ^3He.

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5 APPENDIX 1

As an example for the most promising channel in Fig. 12 we present the acceptance of the WASA-at-COSY setup for the simultaneous registration of all ejectiles. It amounts to about 45% for the registration of the $pd \rightarrow (^3\mathrm{He}\eta)_{bound} \rightarrow ppp\pi^-$ reaction. It is worth noting that the acceptance is large and even more importantly it is flat in the whole range of the excess energies interesting for the proposed studies.

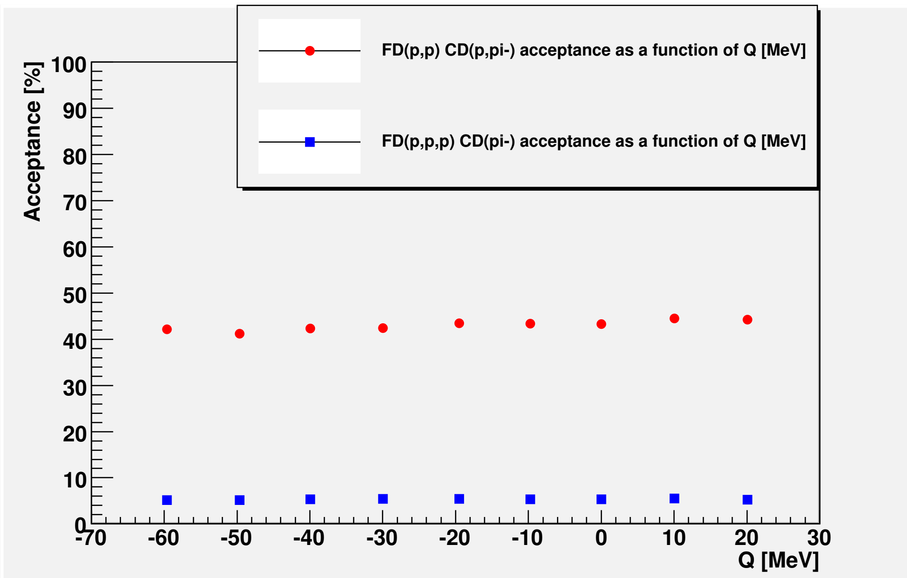

Figure 12: Acceptance of the WASA-at-COSY detector for the $pd \rightarrow (^3\mathrm{He}\eta)_{bound} \rightarrow ppp\pi^-$ reactions shown as a function of excess energy.

Below we present results of simulations performed in order to estimate an experimental background for the studies of the reactions: $pd \rightarrow (^3\mathrm{He} - \eta)_{bound} \rightarrow^3 \mathrm{He}2\gamma$ and $pd \rightarrow (^3\mathrm{He} - \eta)_{bound} \rightarrow^3 \mathrm{He}6\gamma$.

The detailed explanation of used abbreviations is given in the text below the tables.

No.	Reaction	$p^{thr}_{beam}[GeV/c]$	$E^{thr}_{beam}[GeV]$	$A^{thr}_{(0,3)}[\%]$	$A^{thr}_{(3,18)}[\%]$
1	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}3\pi^0$	1.573	0.893	60	0
2	$pd \to pd\eta \to pd3\pi^0$	1.583	0.902	0 (5)	0 (30)
3	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}2\gamma$	1.573	0.893	85	0
4	$pd \to pd\eta \to pd2\gamma$	1.583	0.902	0 (12)	0 (42)
5	$pd \to {}^3\mathrm{He}3\pi^0$	1.273	0.643	8	53
6	$pd \to {}^3\mathrm{He}2\pi^0$	0.977	0.416	3	68
7	$pd \to pd3\pi^0$	1.283	0.651	0.07	23
8	$pd \to pd2\pi^0$	0.988	0.424	0.01	9
9	$pp \to pp3\pi^0$	1.578	0.898	0 (25)	0 (9)
10	$pp \to pp2\pi^0$	1.192	0.579	0.08	30
11	$pn \to pn3\pi^0$	1.577	0.897	0 (28)	0 (15)
12	$pn \to pn2\pi^0$	1.1915	0.578	2	42

Table 1: Main background reactions, their threshold beam momenta, kinetic energies, geometrical acceptances. The detailed explanation of abbreviations is in text below the tables.

No.	Reaction	$\epsilon_{(0,3)}[\%]$	$\epsilon_{(3,18)}[\%]$	$\sigma[\mu b]$	$\epsilon_{(0,3)} \cdot \sigma[\mu b]$	$\epsilon_{(3,18)} \cdot \sigma[\mu b]$
1	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}3\pi^0$	5.3	16	0.13	0.007	0.021
2	$pd \to pd\eta \to pd3\pi^0$	0.9	13	0.05	0.0004	0.006
3	$pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}2\gamma$	1.8	5.4	0.157	0.003	0.008
4	$pd \to pd\eta \to pd2\gamma$	0.9	13	0.05	0.0004	0.006
5	$pd \to {}^3\mathrm{He}3\pi^0$	3	18	0.027	0.0008	0.005
6	$pd \to {}^3\mathrm{He}2\pi^0$	0.0007	0.08	2.8	$2{\cdot}10^{-5}$	0.002
7	$pd \to pd3\pi^0$	0.02	7.2	0.068	$1.4{\cdot}10^{-5}$	0.005
8	$pd \to pd2\pi^0$	0.0001	0.003	1.26	$1.3{\cdot}10^{-6}$	$4{\cdot}10^{-5}$
9	$pp \to pp3\pi^0$	4.3	8.4	$2.8{\cdot}10^{-8}$	$1.2{\cdot}10^{-9}$	$2.4{\cdot}10^{-9}$
10	$pp \to pp2\pi^0$	0.0001	0.021	0.849	$8.5{\cdot}10^{-7}$	$1.8{\cdot}10^{-4}$
11	$pn \to pn3\pi^0$	5.4	9	$8.4{\cdot}10^{-8}$	$4.5{\cdot}10^{-9}$	$7.5{\cdot}10^{-9}$
12	$pn \to pn2\pi^0$	2.5	21.8	2.55	0.064	0.56

Table 2: Main background reactions, their relative excess energies, reconstruction efficiencies and cross sections. The detailed explanation of abbreviations is in text below.

The description of abbreviations used in Table 1 and 2:

p^{thr}_{beam} - threshold beam momentum,

E^{thr}_{beam} - threshold beam kinetic energy,

$A^{thr}_{(0,3)}$ - geometrical acceptance for conditions: all charged ejectiles (^{3}He,d,p) going into beam-pipe - $\theta \in (0,3)^\circ$ and all gamma quanta registered in Central Detector (SEC) for reconstructed excess energy Q=0 (Q=$\sqrt{s_{pd\to^3He\eta}} - \sqrt{s^{thr}_{pd\to^3He\eta}}$), in case of reactions (2), (4), (9) and (11) two values for Q=0 MeV and in paranthesis for Q=10 MeV are given.

$A^{thr}_{(3,18)}$ - geometrical acceptance for registration of charged ejectiles (^{3}He,d,p) in Forward Detector - $\theta \in (3,18)^\circ$ and all gamma quanta in Central Detector (SEC) for reconstructed excess energy Q=0, in case of reactions (2), (4), (9) and (11) two values are included for

Q=0 MeV and in paranthesis for Q=10 MeV,
Geometrical acceptances $A^{thr}_{(0,3)}$ and $A^{thr}_{(3,18)}$ are presented in left and right panel of Fig. 13, respectively.

$\epsilon_{(0,3)}$ - reconstruction efficiency for detection of at least 6 neutral clusters in CD (SEC) and charged ejectiles (^{3}He,d,p) in pipe.

$\epsilon_{(3,18)}$ - reconstruction efficiency for detection of at least 6 neutral clusters in CD (SEC) and charged ejectiles (^{3}He,d,p) in Forward Detector.
Distributions of number of neutral clusters for each of studied reaction are presented in Fig. 14.

σ - cross section.

The Monte Carlo Simulations for each of reactions are carried out varying excess energy Q in the range between 0 and 50 MeV. In the analysis the minimal energy of neutral cluster was set to 20 MeV.

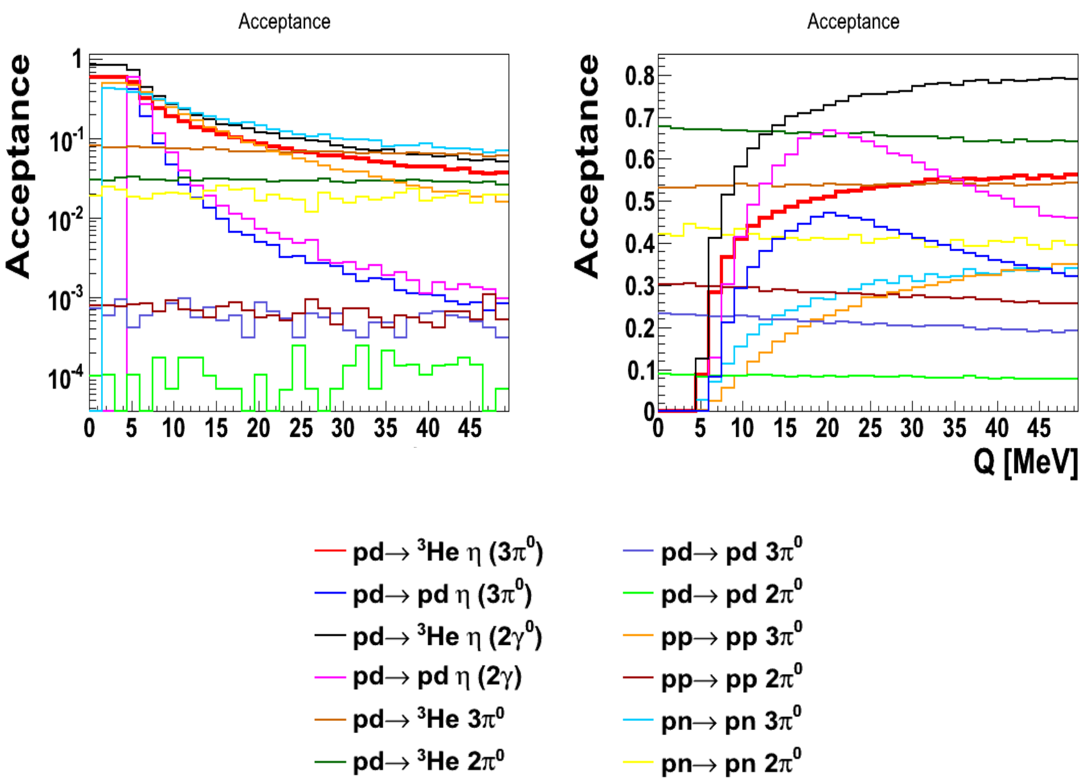

Figure 13: Acceptance as a function of reconstructed excess energy (Q=$\sqrt{s} - \sqrt{s^{thr}_{pd \to ^3He\eta}}$) for charged ejectiles (^{3}He,d,p) going to beam-pipe (left) and for charged ejectiles registered in Forward Detector (right). The simulations were carried out for condition: all neutral particles registered in Central Detector (SEC). The legend for both histograms is presented in the lower panel.

The cross section for $pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}3\pi^0$ and $pd \to {}^3\mathrm{He}\eta \to {}^3\mathrm{He}2\gamma$ reactions were

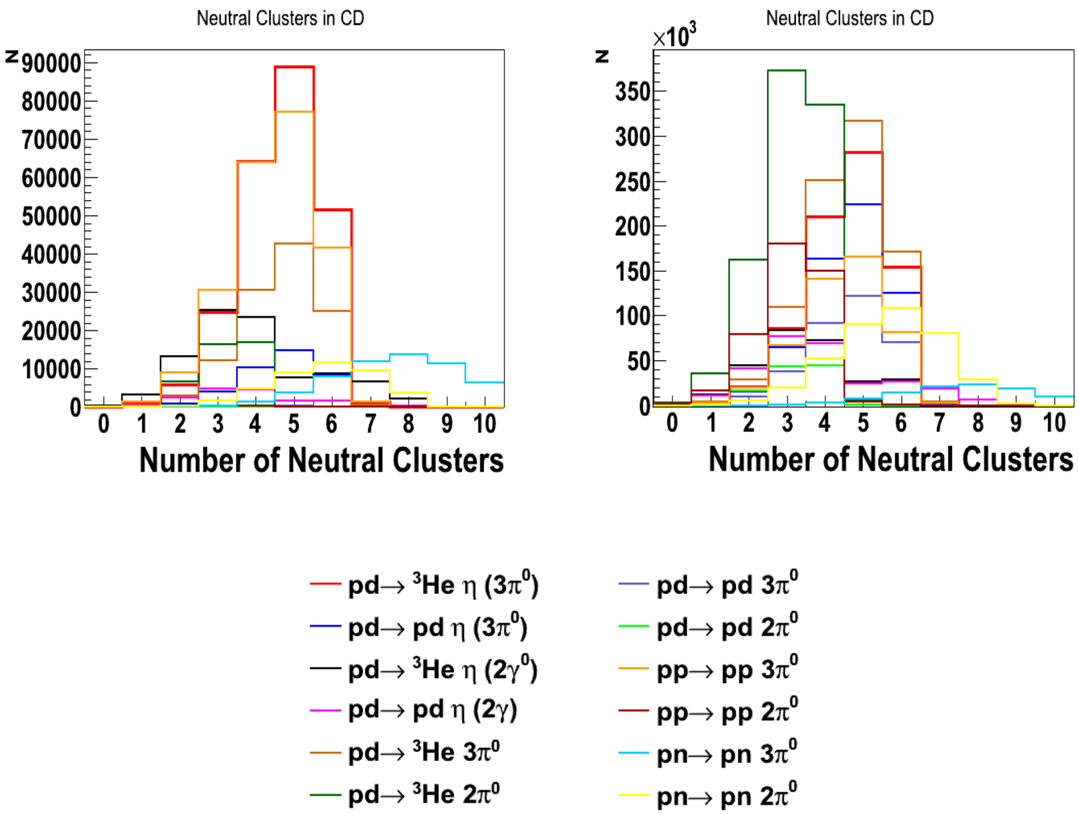

Figure 14: Number of neutral clusters for charged ejectiles (^{3}He,d,p) going into beam-pipe (left) and for charged ejectiles registered in Forward Detector (right). The legend for both histograms is presented in lower panel.

determined based on the measurements carried out with COSY-11 and COSY-ANKE collaborations (Fig. 1). We take the cross section just above η production threshold - σ=400nb and BR($\eta \to 3\pi^0$)=32.57% and BR($\eta \to 2\gamma$)=39.31%, respectively.

In case of $pd \to pd\eta \to pd3\pi^0$ and $pd \to pd\eta \to pd2\gamma$ cross sections were calculated based on results presented in Fig. 15 adopted from Ref. [37]. We take into account value σ=0.15μb as well as Branching Ratios equal to 32.57% and 39.31%, respectively.

The cross section for $pd \to^3$ He$3\pi^0$ was calculated based on Ref. [38] and formula (4.4) included in Ref. [40]. $pd \to^3$ He$2\pi^0$ reactions was adopted from Ref. [39] while for $pd \to^3$ He2γ reaction the cross section estimated $\frac{\sigma(pd \to ^3He\eta \to ^3He2\gamma)}{\sigma(pd \to ^3He\eta)}$.

For $pd \to pd3\pi^0$ and $pd \to pd2\pi^0$ reactions cross section value was calculated as $\sigma(pd \to pd2(3)\pi^0)$=$\frac{\sigma(pd \to ^3He2(3)\pi^0)\sigma(pd \to pd\eta)}{\sigma(pd \to ^3He\eta)}$.

The cross section values at η production threshold for $pp \to pp2\pi^0$ and $pp \to pp3\pi^0$ reactions were determined based on Fig. 15(right) adopted from Ref. [40]. For the first reaction the cross section was calculated for p_{beam}=1.573 GeV/c corresponding to the threshold beam momentum for reaction $pd \to {}^3$Heη while for second reaction calculations were performed for p_{beam}=1.594 GeV/c corresponding to Q=10 MeV of $pd \to {}^3$Heη reaction.

In case of $pn \to pn2\pi^0$ and $pn \to pn3\pi^0$ reactions based on the [41] we assume that the cross sections are 3 times higher that in case for $pp \to pp2\pi^0$ and $pp \to pp3\pi^0$ reactions.

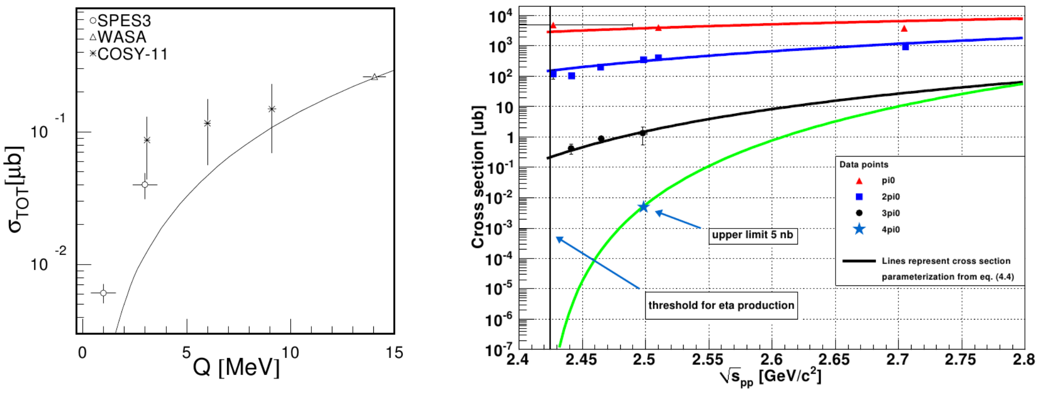

Figure 15: (left) Dependence of total cross-section on the excess energy. The line indicates three body phase-space volume normalised to the PROMICE/WASA point [42]. Open circles show data from reference [43], and stars denote results determined by the COSY-11 group [37]. (right) Experimental cross section for direct pions production in proton-proton collision (points). Superimposed lines denotes result of the fit to the experimental points [44]. The figure is adopted from [40].