Search for η-mesic nuclei in the SRC/BM@N experiment at the Nuclotron

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Abstract. The SRC/BM@N experiment was carried out in the 55th run of the Nuclotron using a liquid hydrogen target and a carbon beam with a kinetic energy of about 3.1 GeV/n. We propose to analyze the experimental data to search for a quasi-bound state of η-meson and nucleons in the reaction ^{12}C+p $\rightarrow$ $_{\eta}$(A-1)+X $\rightarrow$ π+p+(A-2). To achieve this goal, it is necessary to identify the residual nucleus (A-2) and the proton-pion pair formed from η-nuclei decay.

1 Introduction

A bound system of strongly interacting particles in a nucleus has provided variable information about some aspects of hadron-nucleon interaction in the nucleon environment. The intensive studies of the η-meson led to the prediction of the existence of a bound state of η-meson in a nucleus. This phenomenon has been termed as η-mesic nucleus [1]. At the present moment, some measurements give a positive indication of the existence of these bound states [2–5].

In 2006-2010 a set of experimental data at two arms time-of-flight setup and an internal d-beam of the Nuclotron was obtained. The JINR collaboration performed the search for back-to-back πp pairs related to the η-mesic bound states in $d +^{12} C \rightarrow \pi + p + X$ process [6]. An observation of the πp back-to-back correlation as well as the resonance like structure below η production threshold could be associated with the two-body N* resonance decay related with an η-mesic nucleus formation [7].

In the 55th run of the Nuclotron, the "Short Range Correlations" (SRC) group carried out its first research using the extracted ^{12}C beam and the BM@N beam line. They intended to study SRC by means of the proton knockout reaction, p(^{12}C,2p)X, which is performed at large momentum transfer and a center-of-mass scattering angle around 90^o [8]. By triggering on the coincidence detection of the two protons from the p(^{12}C,2p)X reaction, they also proposed to detect in coincidence the recoil partner nucleon emitted in the hard breakup of the SRC pair, as well as the spectator (A-2) system. The knockout protons and spectator nuclear fragments are planned to detect by using the existing BM@N detectors. Recoil nucleons will be detected using the LAND neutron detector. In general, the SRC experiment is aimed at measuring simultaneously the following triple and fourfold coincidence reactions: $^{12}C + p \rightarrow^{11} B + pp;^{12} C + p \rightarrow^{10} B + pp + X;^{12} C + p \rightarrow^{10} Be + pp + X;^{12} C + p \rightarrow^{10} B + pp + n;^{12} C + p \rightarrow^{10} Be + pp + p$.

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2 Experimental setup for the SRC program

A schematic view of the experimental setup for the SRC program is shown in Fig. 1. The setup is based on the original BM@N layout with some important modifications accounting for the kinematics of the quasi-elastic scattering reaction ^{12}C(p,2p(A-2)p(n)).

In order to reconstruct the beam direction and monitor the beam position, multiwire proportional chambers (MWPCs) located right after the last quadrupole lens were used. The 30 cm long liquid hydrogen target and the trigger detectors were placed inside the gap of the steering magnet SP-57, which was turned off during the SRC run. The scintillator-based beam counters BC1, BC2, veto counter (VC), BC3, and BC4 were manufactured and tested at JINR. The BC2, read out by a MCP-PMT, was located right before the target and served as a start detector. The BC3 was used offline to separate the residual systems with different charges. Two pairs of scintillator counters (X1, Y1 and X2, Y2) were complementing the BC1, BC2 and VC in the SRC trigger.

There are two arms of the setup, which are used to register the leading protons. The arms include scintillator trigger detectors (X1–Y1 and X2–Y2), coordinate detectors GEM (gas electron multiplier stations), and time-of-light detectors TOF-400 (MRPC walls) located on both sides of the analyzing magnet SP-41.

The three silicone planes and two MWPCs downstream the target tracked the recoil nucleon and the residual nucleus. The trajectory after the analyzing magnet SP-41 was measured by drift chambers (DCh) stations. SRC were aimed at distinguishing between ^{10}B, ^{11}B, and ^{10}Be by measuring the turning angle and the time-of-flight using ToF-700. The forward-going recoil neutrons were measured by the LAND (Large Area Neutron Detector) [9].

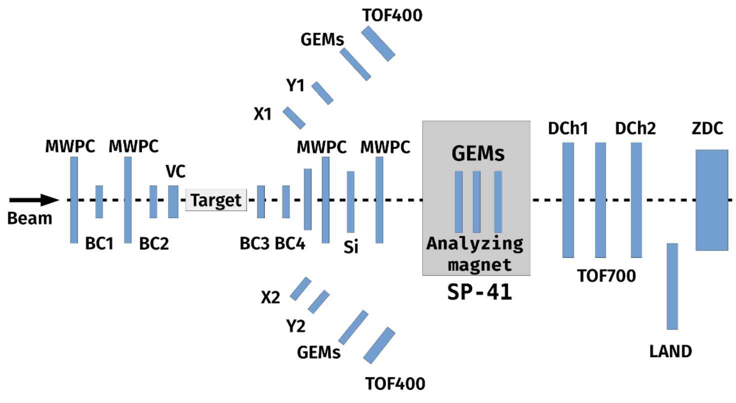

Figure 1. Schematic presentation of the experimental setup for SRC at BM@N experiment (not to scale). MWPC is multiwire proportional chamber; target is a 30 cm long vessel with liquid hydrogen; BC1, BC2, veto counter (VC), BC3, BC4 are scintillator-based beam counters; X1, X2, Y1, Y2 are scintillator trigger detectors of proton-proton arms; GEM is a gas electron multiplier station; TOF is a time-of-light detector; DCh is a drift chamber station; LAND is a large area neutron detector; ZDC is a hadron zero degree calorimeter

3 What are we planning to look for?

Important prerequisite for a successful experiment is a right choice of reaction participants and optimization of initial parameters. Colliding nucleons give rise to η-mesons in the processes of single-pion exchange. In these collisions (taking into account the isotopic contributions and antisymmetrization) η is mainly produced in pn (not in pp) charge-exchange reaction with emission of a proton and neutron forward.

Theoretical predictions for the s-wave η-N scattering amplitude demonstrate an attraction between η and N at the kinetic energy of the η-meson less than 70 MeV. The interaction of the η-meson with a nucleon near the threshold is mainly determined by the S_{11}, $J^P=\frac{1}{2}^-$ resonance N*(1535), which is just 49 MeV above the ηN threshold (1486 MeV) and has a width Γ=150 MeV, thus covering the whole low energy region of the ηN interaction. The S_{11} resonance also decays to πN (32-52 %), ηN(30-55%) and $\pi\pi$N(3-14%) channels. In the final stage the η-mesic nuclei decay mainly through a resonant state S_{11} and the products of this decay are analyzed. The random walk inside the nucleus allows the η-meson to have independent multiple scatterings on different nucleons $\eta + N_1 \rightarrow \eta + N_1$, $\eta + N_2 \rightarrow \eta + N_2$, $\eta + N_3 + N_4 \rightarrow \eta + N_3 + N_4$. This chain of rescattering completes conversion of η-meson-nucleon (η-meson-nucleon-nucleon) to energetic π N or NN-pair which escapes from the nucleus.

It is important to recognize that if we register πN pair with approximately equal but opposite momentum components (in c.m.s.), even with some suitable total energy $E_\pi + E_p \approx m_\eta + m_N$ = 1486 MeV, it does not necessarily mean that we have registered the decay products of the η-mesic nucleus. The pair with a small total momentum can be produced from the annihilation of a slow unbound η-meson and slow intranuclear nucleon.

Generally [5], observation of a relatively narrow resonance peak in the spectrum of E_η in the subthreshold region $E_\eta < m_\eta$ is mandatory for claiming an observation of η-mesic nuclei at all.The energy and width of πN distribution will give information about the energy level of the meson bound in a nucleus.

Possible pairs of final particles in the decay of η-nuclei are $\eta N \rightarrow S_{11} \rightarrow \pi N$ (the probability of 80 - 90 %) and $\eta NN \rightarrow S_{11}N \rightarrow NN$ (the probability of 10 - 20 %). In more detail: $(\eta p) \rightarrow \pi^0 p$; $(\eta p) \rightarrow \pi^+ n$; $(\eta n) \rightarrow \pi^0 n$; $(\eta n) \rightarrow \pi^- p$; $(\eta pp) \rightarrow pp$; $(\eta pn) \rightarrow pn$; $(\eta nn) \rightarrow nn$. Since the two arms of the SRC spectrometer cannot yet register neutrons and π^0, we suggest using reactions $(\eta n) \rightarrow \pi^- p$ and $(\eta pp) \rightarrow pp$.

The information from BC1 and BC2 detectors located up to the target showed that nitrogen and oxygen nuclei were also present in the carbon beam of the Nuclotron (Fig. 2). Thus, the process of η-mesic nuclei formation can be considered using reactions (proton and neutron fly forward): ${}^{12}C \rightarrow {}^{11}C + p + n + \eta$, ${}^{14}N \rightarrow {}^{13}N + p + n + \eta$, ${}^{16}O \rightarrow {}^{15}O + p + n + \eta$.

It follows that we can try to consider the following particles from the η-mesic nuclei decay:

$$ {}^{12}C + p: \quad {}^{11}C_\eta \rightarrow {}^{10}C + \pi^- + p, \quad {}^{11}C_\eta \rightarrow {}^{9}Be + p + p; \tag{1} $$

$$ {}^{14}N + p: \quad {}^{13}N_\eta \rightarrow {}^{12}N + \pi^- + p, \quad {}^{13}N_\eta \rightarrow {}^{11}B + p + p; \tag{2} $$

$$ {}^{16}O + p: \quad {}^{15}O_\eta \rightarrow {}^{14}O + \pi^- + p, \quad {}^{15}O_\eta \rightarrow {}^{13}C + p + p; \tag{3} $$

The information from BC3 and BC4 scintillation detectors located after the target shows us a set of nuclei that have been formed after the beam-target interaction (Fig. 3). It is possible to allocate a set of nuclei after beam-target interaction for each type of initial beam nucleus with help of BC1, BC2, BC3 and BC4 detectors (Fig. 4). To distinguish isotopes in offline analysis, we need to use information from coordinate and TOF detectors to determine the turning angle in the magnetic field of SP-41 and the time of flight of a particle.

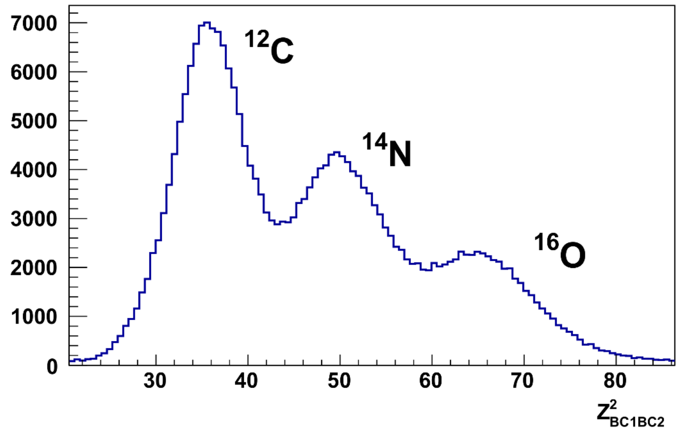

Figure 2. The square of the beam particle charge before the beam-target interaction

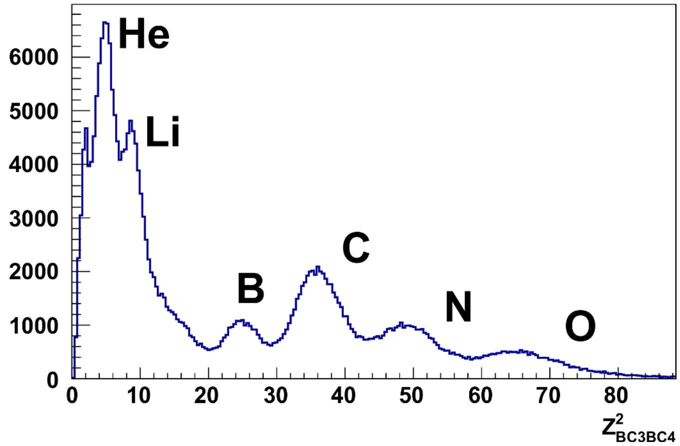

Figure 3. The square of the particle charge after the beam-target interaction

4 Conclusions

We propose to use the experimental data obtained by the SRC/BM@N setup to search for and study η-mesic nuclei. For this purpose, we need to identify particles (back-to-back π^-p or pp pairs and the residue nucleus flying forward) from η-mesic nuclei decay and determine their energy. Adding neutron detectors to the two arms of the SRC spectrometer will allow us to consider additional channels of η-mesic nuclei decay.

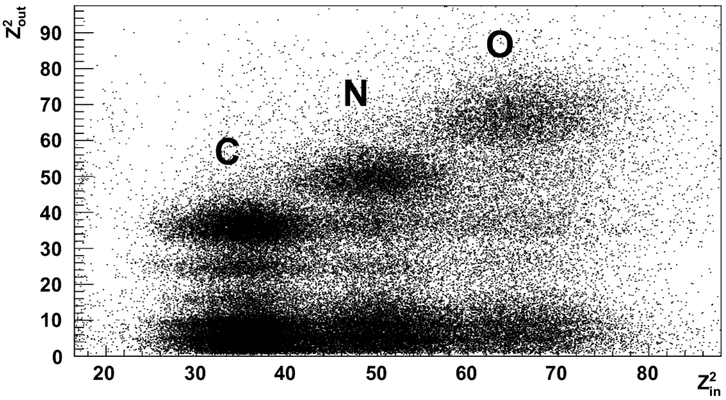

Figure 4. The dependence of the square of the particles charge after the beam-target interaction on the one before the interaction

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