Studies of eta-mesic nuclei at the LPI electron synchrotron

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CONTENTS

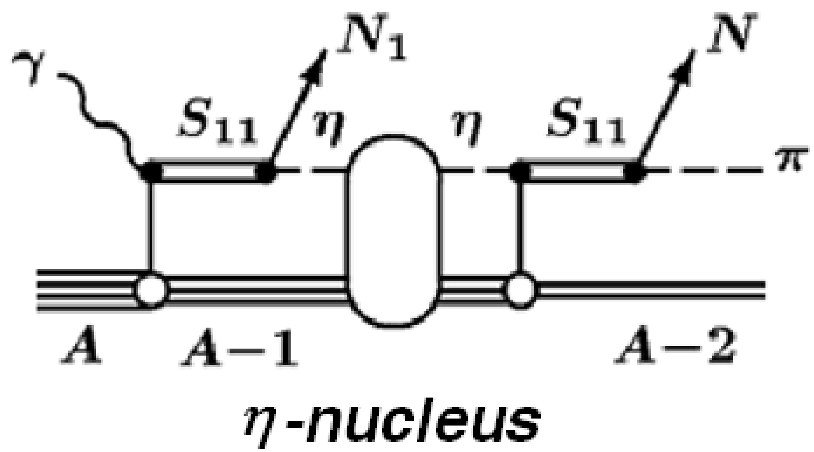
η-mesic nuclei :

Systems with η-meson bound by strong ηN-interaction with other nucleons in the nucleus. This interaction is attractive at low energies (Bhalerao, Liu, 1985), so that nuclei with sufficiently large *A* can bind the η-meson in the *s*-wave (or higher) state (Haider, Liu, 1986).

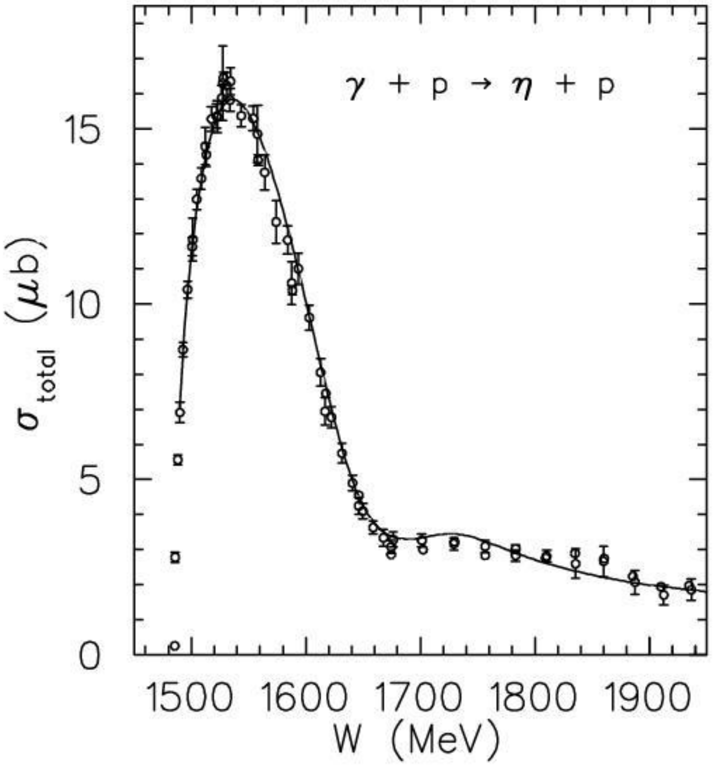
Photoproduction of η-nuclei is mainly caused by the subprocess

$$\gamma + N_{in} \rightarrow S_{11}(1535) \rightarrow \eta + N_1$$

where η has a low (even subthreshold) energy and the nucleon N_1 is fast and escapes the nucleus. Decaying through the channel πN, the η-nucleus is seen as an intermediate state in the chain



The attractive low-energy ηN interaction is related with the nucleon $S_{11}(1535)$ resonance that has the mass only slightly above the channel threshold $m_\eta + m_N = 1486$ MeV and a very large coupling to ηN (branching ratio of $S_{11}(1535) \rightarrow \eta N$ is >50%).



See example: the total cross section of
$\gamma + p \rightarrow S_{11}(1535) \rightarrow \eta + p$.

Binding ηA potential is roughly given by the sum of separate ηN potentials, although several effects decrease ηA attraction (nucleon Fermi motion, broadening of the $S_{11}(1535)$, etc.).
According to many theoretical evaluations and depending on the assumed ηN-potential strength the bound ηA states may exist for $A \geq 3$.

Energy and widths of the bound η : theory (examples)

Very different predictions (dependent on assumed properties of the ηN interaction):

1. Q. Haider, L.C. Liu, Phys. Rev. C 66, 045208 (2002)

^{12}C(1s state): E = −1.19 MeV, Γ = 7.4 MeV.

No bound states for A<12 !

2. C. Garcia-Recio et al., Phys. Lett. B 550 (2002) 47

^{12}C(1s state): E = −9.71 MeV, Γ = 35 MeV (energy-dependent potential)

E = −17.71 MeV, Γ = 51 MeV (energy-independent potential)

So, information on E and Γ is valuable both for testing theories and for establishing main properties of η and S_{11}(1535) in nuclear medium.

Signature of η-mesic nucleus

η-mesic nuclei can be observed as peaks in the distribution of the energy transfer ($E_\gamma - E_{N1}$ in our case) or the energy of the decay products (like $E_\pi + E_N$). Both the quantities indicate the energy of η in the nuclear medium.

According to Chiang, Oset, Liu, Phys. Rev. C 44, 738 (1991) and Kulpa, Wycech, Green, Acta Phys. Pol. B29, 3077 (1998)
the main decay modes of η-mesic nuclei are:

πN ~ 70–85% [single-nucleon annihilation of η]

NN ~ 15–30% [two-nucleon annihilation of η in the nucleus]

Emerging particles in these pairs have approximately equal but opposite 3-momenta (back-to-back pairs).

Sokol and Tryasuchev (1991) suggested to explore the πN decay mode for searching for η-mesic nuclei.

Isotopic contents of decay products

For not very light nuclei fractions of various πN and NN pairs are:

$\pi^+ n$ **<u>1/3</u>** of πN
$\pi^0 p$ 1/6 of πN
$\pi^0 n$ 1/6 of πN
$\pi^- p$ 1/3 of πN (due to isospin 1⁄2)

pp ~5% of NN
nn ~5% of NN
pn **<u>~90%</u>** of NN (!)
(because the cross section of pn $\to$ ηpn (or ηd) near threshold is ~10 times bigger than the cross section of pp $\to$ ηpp)

As a result, the yields of $\pi^+ n$ and pn pairs (our experiment!) are compatible.

Kinematic properties of the decay products

Threshold of η photoproduction on the free nucleon = 707 MeV.

1. **Decays of bound η to the πN channel:**

$$\eta + N_0 \rightarrow S_{11}(1535) \rightarrow \pi + N \qquad (\pi^+ n \text{ in our exp.})$$

$E_\pi + E_N \approx m_\eta + m_N = 1486$ MeV (up to binding)
$T_\pi \approx 313$ MeV, $T_N \approx 94$ MeV, $T_\pi + T_N \approx m_\eta - m_\pi = 407$ MeV
$\boldsymbol{\beta_\pi \approx 0.95}$, $\beta_N \approx 0.42$

2. **Decays of bound η to the NN channel:**

$$\eta + NN \rightarrow N + S_{11}(1535) \rightarrow N_1 + N_2 \qquad (pn \text{ in our exp.})$$

$T(N_1) \approx T(N_2) \approx m_\eta /2 = 273$ MeV
$\boldsymbol{\beta_1} \approx \beta_2 \approx \mathbf{0.63}$

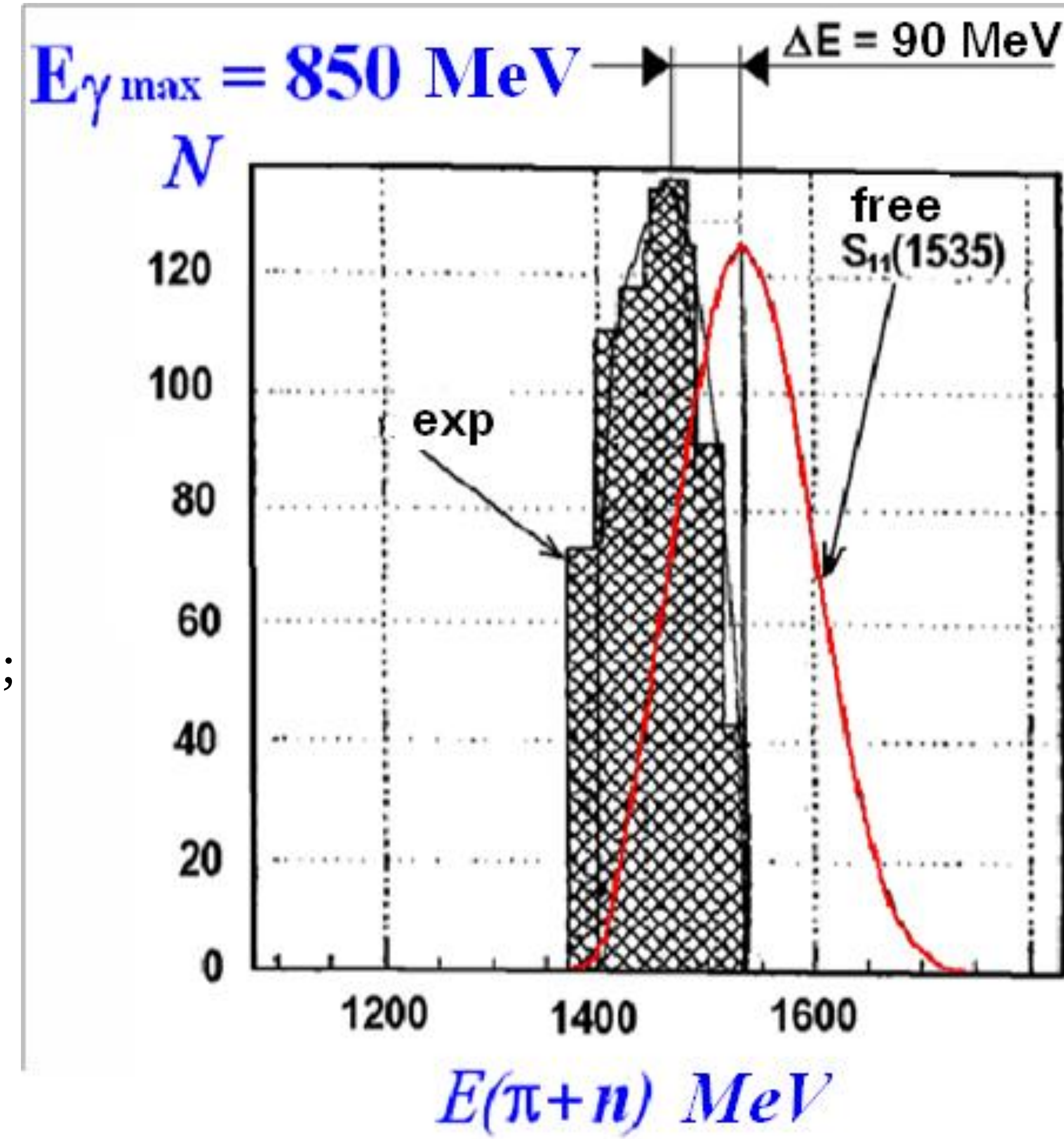
Some previous experimental results

1. LPI, Moscow.

$\gamma + {}^{12}C \rightarrow \pi^{+} + n + X$

Bremsshtralung photons

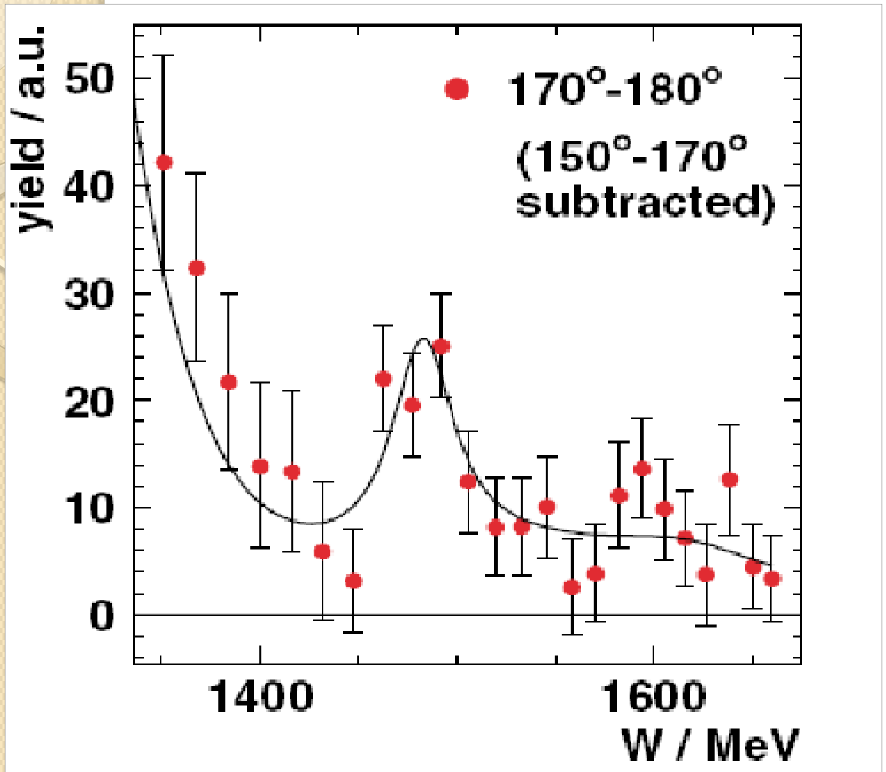
up to 850 MeV



G. Sokol et al. Fizika B8, 85 (1999);

Part. Nucl. Lett. 5[102], 71 (2000);

Yad Fiz 71, 532 (2008)



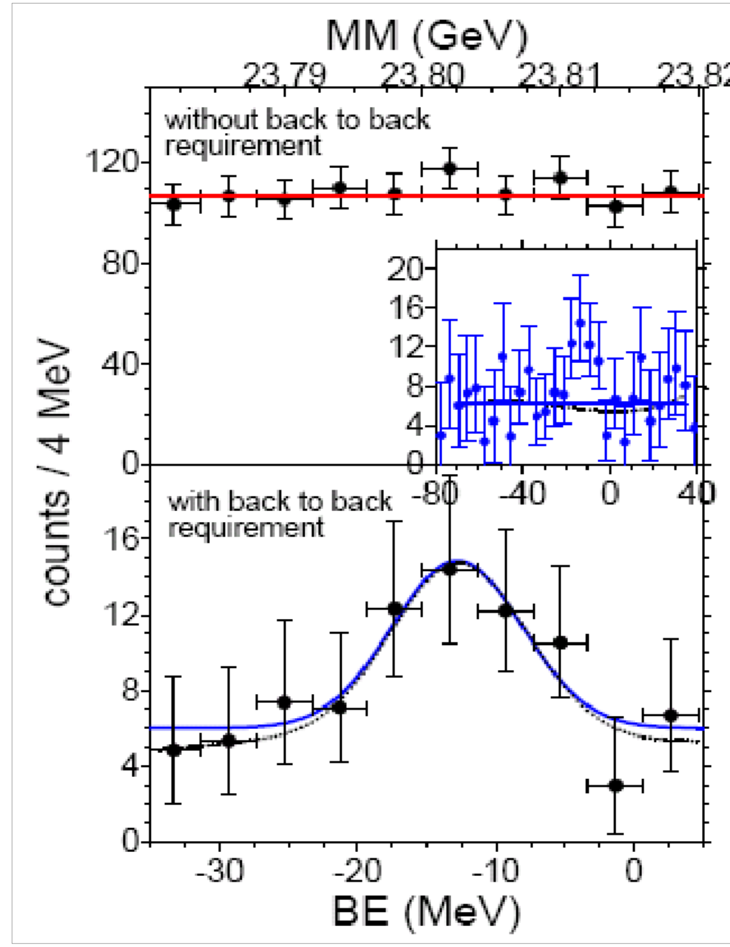
2. <u>MAMI-B, Mainz</u>, tagged photon beam up to 850 MeV

$\gamma + {}^{3}He \rightarrow \pi^{0} + p + X$

without N_1 detecting !

Pfeiffer et al. Phys Rev Lett 92, 252001(2004)

[See, however, revision in Pheron et al. Phys. Lett. B709, 21 (2012)]



3. <u>COSY-GEM Collab</u>

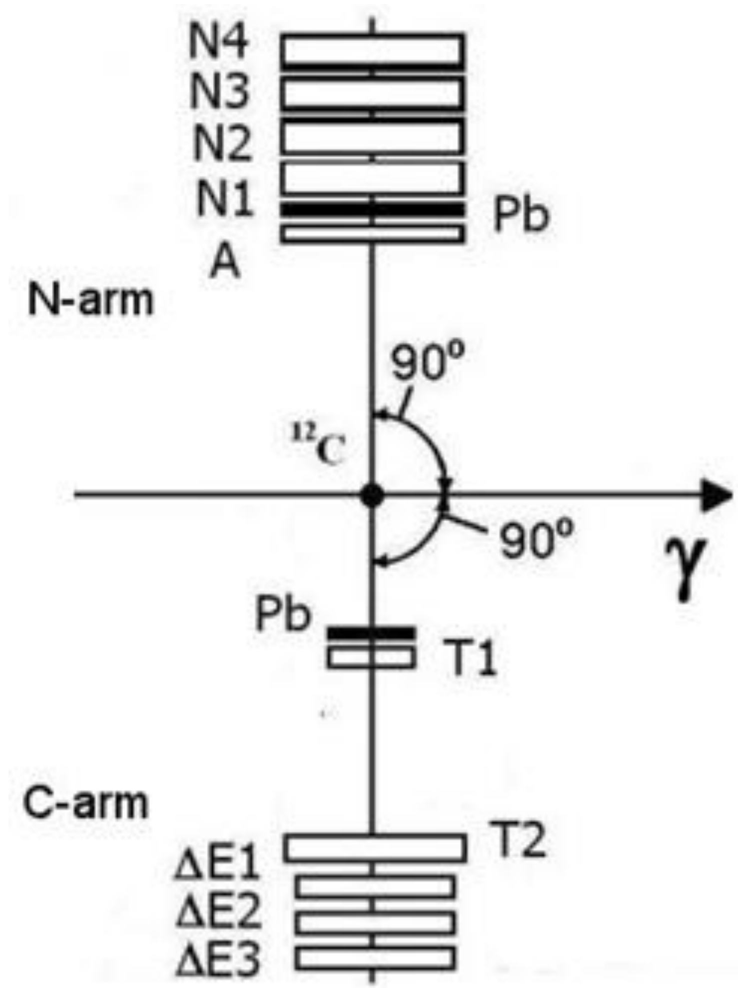
Phys Rev C 79, 12201(R)(2009)

$p + {}^{27}Al \rightarrow {}^{3}He + \pi^{-} + p + X$

The strongest evidence!

Experimental setup at LPI

Two time-of-flight arms (scintillation telescopes) for detection in coincidence of charged and neutral particles of back-to-back pairs are both positioned to 90° to the beam in order to minimize background.



C-arm (for charged particles)

(TOF spectrometer for pions/protons):

- start of TOF (T1) (25x25x2 cm^3),
- stop of TOF (T2) (50x50x5 cm^3),
- ΔE1, ΔE2, ΔE3 detectors (40x40x2 cm^3)
- Pb plate is used for TOF calibrations with produced relativistic electrons/positrons

N-arm (for neutral particles)

(TOF spectrometer for neutrons):

- veto counter A (50x50x2 cm^3),
- plastic blocks N1, N2, N3, N4 (50x50x10 cm^3)

  (neuteron detection efficiency ε_n ~ 30%),
- Pb plate is used for TOF calibrations

Each scintillator counter/block volume is viewed with 4 phototubes.

Parameters of the TOF spectrometers:

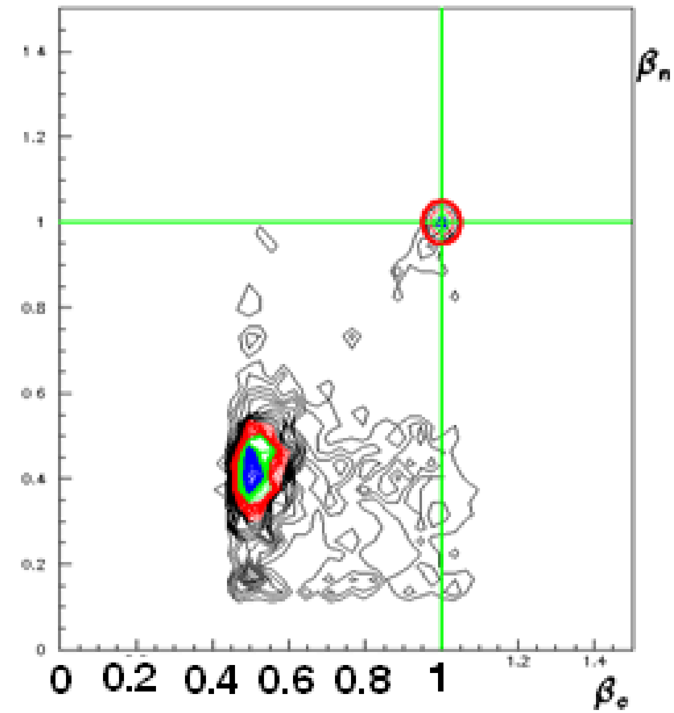
- time resolution $\Delta t \approx 200$ ps (sigma),
- TOF base ≈ 1.3 m.

Bremsstrahlung photon beam:

- $I_e \sim 10^{12}\ s^{-1}$,
- $E_{\gamma max}$ = 850 MeV (650 MeV in test runs),
- duty factor ~ 10%

Time calibration

Time calibration in arms was done using the reaction $\gamma p \rightarrow \pi^+ n$ (off the carbon target) with the arm's angles $\theta_C = 50°$, $\theta_N = 50°$.



Pb convertors were used in some runs to convert photons from π^0 decays into electrons/positrons and to have a reliable relativistic ($\beta \approx 1$) reference point for particle's velocity.

The calibration provided a linear scale of velocities in the range of $\beta = 0.6 - 1$ with the relative error of about 3% (1σ). The linearity was checked using cosmic rays and different distances between detectors.

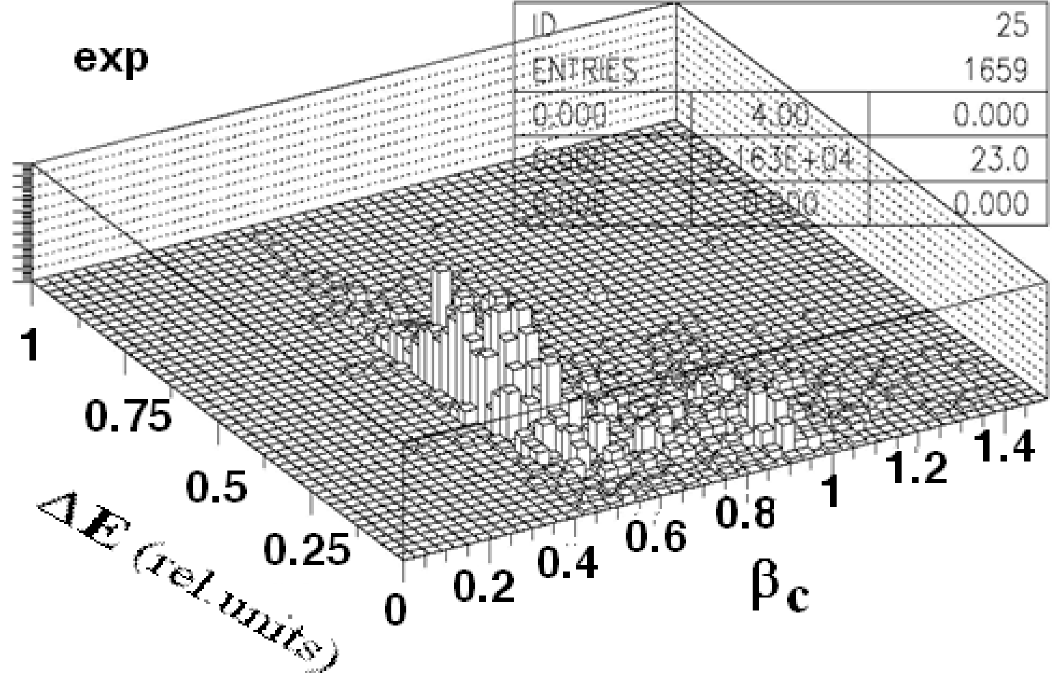
Measurements

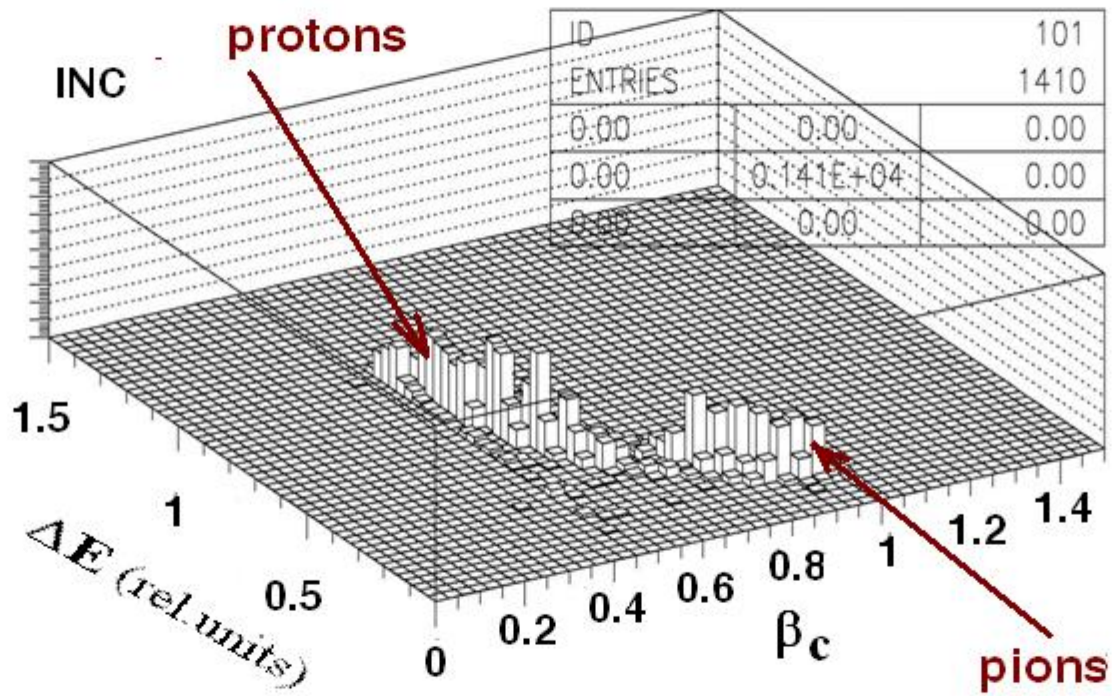
Measurements have been done at two energies: $E_{\gamma max}$ = 650 MeV and 850 MeV (below and above the η photoproduction threshold).

Events were selected with all $\Delta E_i > 0$ (i=1,2,3).

Experimental data at $E_{\gamma max}$ = 850 MeV are shown together with results of simulation using the INC model.

Here $\Delta E = \sum \Delta E_i$.





Simulations with INC

INC = Intra Nuclear Cascade model + GEANT3

[Ilijinov, Pshenichnov et al., Nucl. Phys. A616, 575 (1997)]

This model includes production of various mesons and baryon resonances, their free propagation in the nuclear matter and then various collisional reactions $2 \rightarrow 2$, including $\eta N \rightarrow \pi N$. Binding effects and reactions like $\eta NN \rightarrow NN$ are omitted.

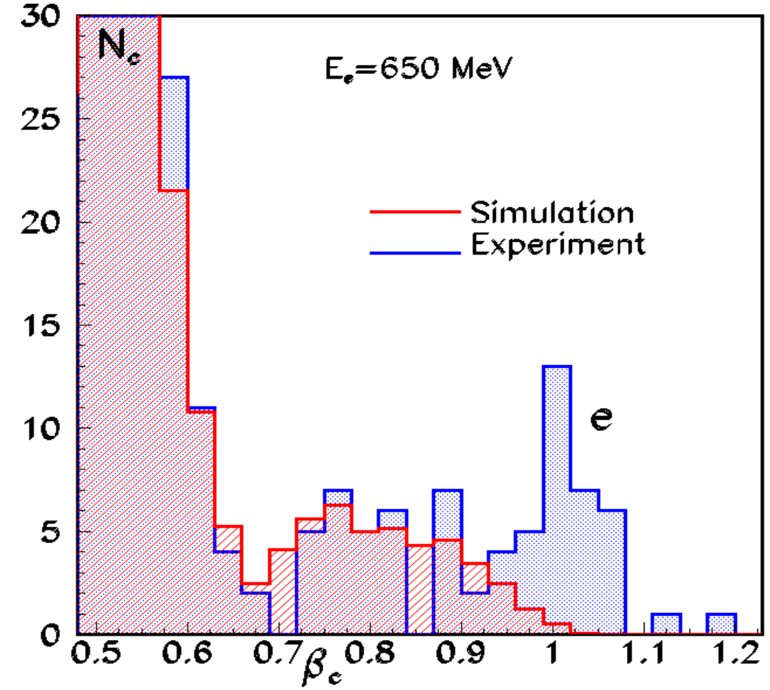
The simulation shows that the rule $\Delta E_i > 0$ (i=1,2,3) separates very well protons (as particles with $\beta_C \leq 0.7$) and pions (as particles with $\beta_C \geq 0.7$): overlap is less than 1%.

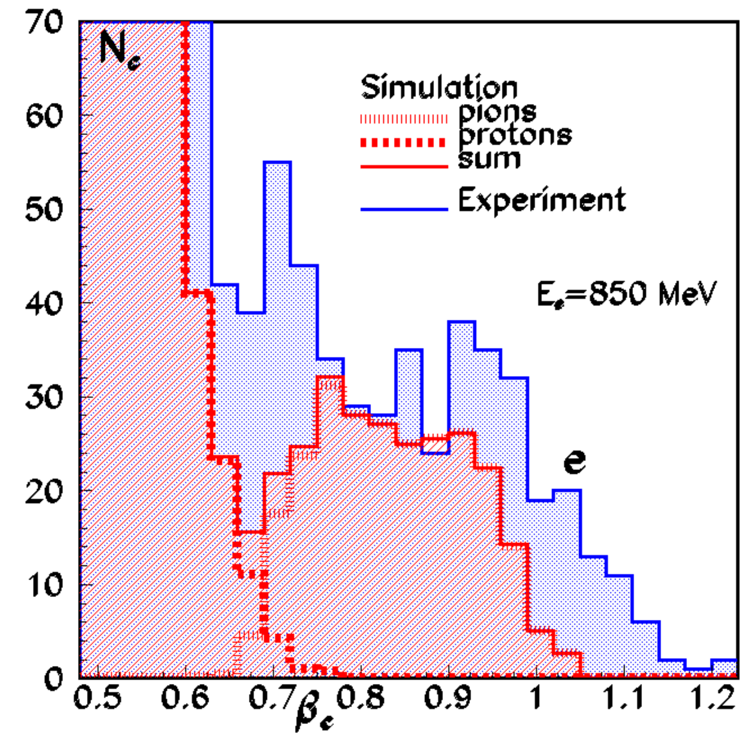
Exp data vs simulation

INC predictions (pink hatched area and red curves) are normalized to exp data.
Shown are yields of protons and pions.

In contrast to the INC results, at $E_{\gamma max}$ = 850 MeV an excess of events (shown in blue) is clearly seen at $\beta_C \approx 0.7$ and $\beta_C \approx 0.95$.

Given a very low count rate of pions with $\beta_C < 0.7$, we conclude that there is a strong evidence for production of correlated pn pairs with energies typical for decay products of η-mesic nuclei.





Cross section estimates

Assuming that the observed access events are related with formation and isotropic decays of η-mesic nuclei, we can estimate their photoproduction cross section.

The number photons of E_γ = 650–850 MeV in exp runs was found using the total yield of charged pions detected by the setup and predictions of INC for that yield: $N_\gamma = 1.36 \cdot 10^{11}$.

Taking into account the solid angle of the C-arm telescope (Ω_C = 0.027 sr), efficiencies of detectors, a geometric efficiency of the setup (~ 18%) that was estimated using an expected distribution of particles in the correlated pairs over the opening angle, we arrived at the cross section of η-mesic nucleus formation

$$\boldsymbol{\sigma(\gamma\, ^{12}C \rightarrow \eta\text{-nucleus}) \sim 10\ \mu b}$$

that is consistent with available theoretical estimates.

Conclusions

The obtained data confirm the main features of the πN signal of formation and decay of η-mesic nuclei off carbon in photoreactions seen in the previous work.

A new signature for formation and decay of η-mesic nuclei, the back-to-back *pn* pairs, was explored. It is found that the yield of such pairs in the region of $\beta \sim 0.6 \div 0.7$ is quite visible and therefore is also suitable for a search for η-mesic nuclei .

Assuming that the observed excess of events is related with η-mesic nuclei , estimates of the total cross section of formation and decay of η-mesic nuclei in a photoreaction with carbon have been obtained: $\sigma(\gamma\ ^{12}C \rightarrow \eta\text{-nucleus}) \sim 10\ \mu b$.

We have plans to carry out a more precise experiment, with a much better energy resolution, at the deuteron beam of the JINR nuclotron.