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Nuclear matter and ν properties from π induced reactions and decay

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The PAINUC experiment has collected new data on elastic and inelastic $\pi^{\pm}$ ^{4}He interaction, at T_π =106 MeV where the measured maximum excitation of the Δ resonance on ^{4}He has been observed. The events have been collected using a triggerable self shunted streamer chamber [1] filled with helium at atmospheric pressure, installed at the Joint Institute for Nuclear Research (JINR) in Dubna (Russia). At low energies, where other detectors start to show their limitations, the used technique has allowed to collect information on nuclear collective states and on the physics of phase transitions.

Measurement of the in-medium modifications of the Δ resonance, signatures of the excitation of nuclear collective states and the first experimental evidence for a thermal emission of photons have been obtained from the analysis of new $\pi^{\pm}$ ^{4}He data at T_π =106 MeV at PAINUC experiment. Experimental limits on the direct measurement of the muon neutrino mass is also being studied: the pion mass resolution, at present 350 eV, heavily constrains the accessible m_ν sector above 419 keV/c^2.

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1. The thermal emission of photons

The analysis of $\pi^{\pm 4}$He scattering events at $T_\pi \sim$106 MeV revealed the existence of a channel with the emission of a high energy photon in the final state (see [2, 3]).
Several hypotheses have been tested in order to identify the γ emission mechanism, namely the initial or final state radiation (external bremsstrahlung), the internal radiation (internal bremsstrahlung), the Δ^{++} magnetic dipole radiation, the Δ radiative decay and, finally, the thermal emission.
The energy spectra of the external radiation has shown a low agreement with experimental data, both in the cases of π^+ and π^-. The internal radiation shows a good agreement in the high energy γ region, but is totally in disagreement with the experimental spectra at low γ energies.
Finally, the γ energy distributions have been found in good agreement with a Planck black body radiation distribution (see fig. 1), at a temperature of about 16 MeV for both $\pi^{+\,4}$He and $\pi^{-\,4}$He interactions. The hypothesis of a thermal radiation is also in agreement with other physical features of the observed radiative events: a) the high energy tail of the gamma energy distributions, which exceeds 100 MeV, is compatible with the low energy available per nucleon (20 MeV) and with the extracted nucleus temperature ($\sim$16 MeV); b) the thermal emission is consistent with the isotropic differential cross section in the pion scattering angle and c) with the high branching ratio observed, unlike the bremsstrahlung radiation mechanism.

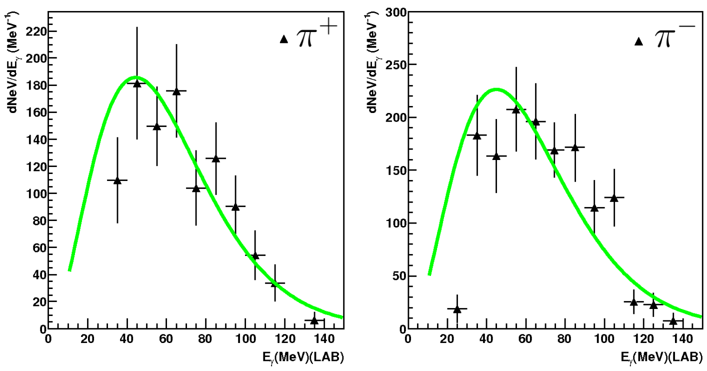

Figure 1: Photon energy distributions from $\pi^\pm$-^{4}He$\rightarrow$ $\pi^\pm$-^{4}Heγ reactions. The green curves are fits with Planck black-body radiation distributions. The extracted temperature of the corresponding black-bodies is 16 MeV.

2. Signatures of Collective Resonances

The hypothesis of the existence of a giant (I,S)=(3/2,3/2) nuclear resonance is by Dillig and Huber in 1974 [4] while the first experimental observations of modifications in resonant elastic π-nucleus cross sections were collected by Balestra et al. in the 80's [5].
From our analysis of π^{-4}He$\rightarrow$ π^{-3}He n reaction at T_π =106 MeV, the first experimental observation of the excitation of the Δ^- resonance has been obtained in an inelastic channel and below the pion production threshold. The mass of the resonance turns out to be M_Δ =(1157$\pm$14) MeV/c^2 and the measured width is Γ =(38$\pm$2) MeV/c^2, thus respectively smaller and narrower with respect to the values of the Δ excitation on the free-nucleon (see fig. 2). Similar modifications were observed in ref. [5] on the Δ excitation in the elastic scattering of pions on nuclei. The peaks of excitation functions are shifted towards lower energies, while the widths undergo a narrowing: the effect is stronger at high scattering angle (>120^o). Both in elastic ([5]) and inelastic (this work) π-nucleus interactions, the modified Δ resonance is produced at high momentum transfer and low Q^2, in support of the hypothesis that several nucleons are involved (low Q^2 means large probing

wavelength). These modifications could be related to the additional binding energy from the additional nucleons in the resonance (see [3]). A semi-empirical model has been developed, which

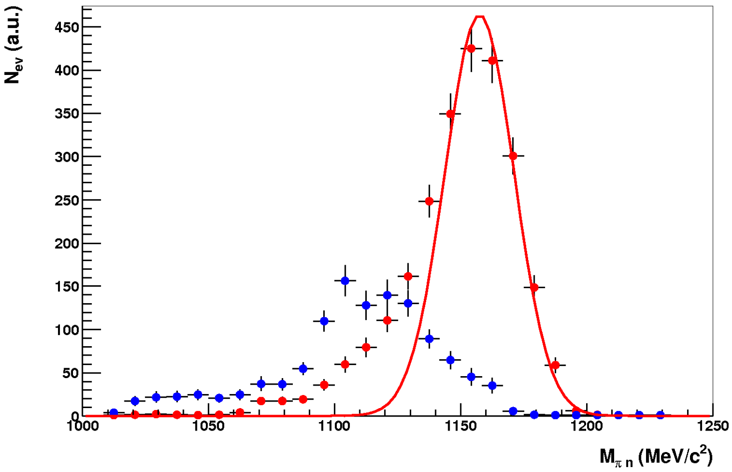

Figure 2: π^{-}n invariant mass distribution in neutron knock-out reaction for high (red points) and low (blue points) transferred momentum. The resonant (red) distribution reveals a mass lowering and width narrowing w.r.t. the values for a Δ excited on a free nucleon.

assumes that a Δ resonance excited in a nucleus interacts with the remaining nucleons, giving rise to a collective state [6]. The semi-empirical model has been used to fit data on several nuclei from [5]. The results of the fit describe the collective state as a cluster of nucleons and a Δ, where the total number of nucleons goes from 1 for H to 1.7 and 2.7 on deuteron and ^{4}He, respectively; then the number saturates at 3.5 for nuclei with A>12-16 (carbon and oxigen). The size of the uniform core turns out to be 1.15 nucleon radii while the peripheral decrease turns out to fall in 0.3-0.4 fm. The binding energy per nucleon is $E_B \sim$50 MeV (see fig. 3). Therefore, the described collective resonance seems to be a strongly bound state, with binding energies per nucleon 7 times the standard binding energy of a nucleon in a nucleus. The fast drop of the p.d.f. suggests the state is well confined within the uniform central part, thus losely interacting with the remaining nucleons in the nucleus (see [3, 6]).

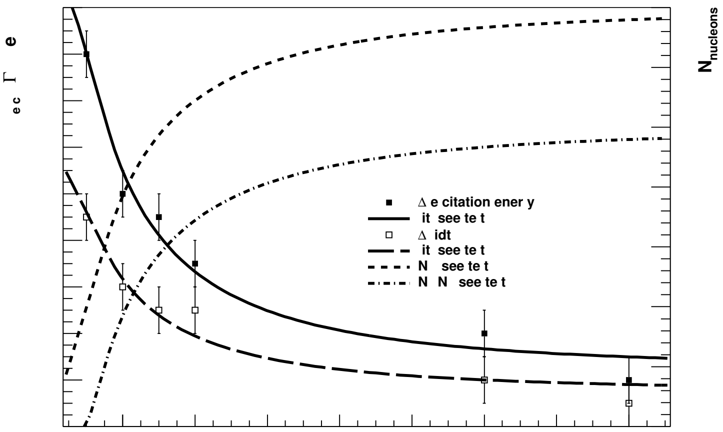

Figure 3: Full and empty squares: peaks and widths of Δ excitation functions for several nuclei, respectively; solid and dashed curves are fits with the semi-empirical model (see text). Fine-dashed and dotted-dashed curves: number of all and of additional nucleons (out of the one destroyed by Δ excitation) participating to the formation of the collective state.

3. 3-body correlation in pion absorption reactions

The pion absorption channel in the region of excitation of the Δ resonance in nuclei is of interest because it can give information on the multinucleon pion absorption mechanisms and on the

role of the in-medium excitation of the resonance.
The analysis of π^{+4}He$\rightarrow$3pn absorption reactions at $T_\pi \sim$106 MeV allowed the identification of 2-3 nucleon absorption signatures as well as signals of the formation of a collective state. It has to be mentioned that the complete phase space has been measured, down to 1 MeV protons. Two-nucleon correlations shows that none of the absorptions can be clearly identified as a pure 2-nucleon abs (2NA); feeble signatures of Hard and Soft Final State Interactions ((H)SFSI) or Initial State Interactions (ISI) as well as signatures of 3-nucleon abs are present. Three-nucleon correlation reveals that $\sim$14% of the absorptions occur on the 3-proton final state, in agreement with an absorption on a pd cluster in the initial state. Another $\sim$42% cannot be unambiguously identified as a 2NA + (H)SFSI/ISI or 3NA processes. The behavior of the differential cross section reveals a strong P wave contribution.
Further statistics is needed in order to extract the contributions from the various abs channels (3NA, 2NA, 2NA+(H)SFSI, 3NA(d')), while new theoretical models, taking into account a 3-4NA process, have to be developed for understanding the π absorption in the Δ resonance energy region. The observation of signatures of 3NA processes strongly suggest that the collective resonance takes a fundamental role also in the pion absorption channel in the Δ energy region.

4. Limits on the extraction of the ν_μ mass

The direct measurement of the muon neutrino mass is a fundamental physical quantity to be obtained in order to complete the standard model, for opening scenarios for new physics and finally as fundamental value for many open questions in astrophysics could find an answer.
The most accessible channel for the study of the muon neutrino mass is, at present, the pion decay. A high precision simulation has been performed, in order to study the limits on the reconstructed neutrino mass vs pion and muon momentum resolution and vs pion mass resolution.
However, with present magnetic spectrometers momentum resolution, the direct measurement is not allowed. On the other side the extraction of an upper limit has strong limitations, due to the mass difference between pion and muon, that makes the necessary momentum resolution, for the measurement of a 1 keV neutrino, to be about 1 meV/c. This value is not far from being possible in a near future. An additional constrain comes out from the pion mass resolution, which is at present 350 eV; the situation for the muon is better, since with measurements on μ-atoms, the muon mass resolution is 4 eV. The pion mass resolution fixes the minimum measurable neutrino mass at 419 keV.
It is clear that a new approach to the data analysis and a new statistical estimator for the muon neutrino mass has to be studied; on the other side, the study of the pion mass has to be pursued in order to efficiently address the fundamental topic of the smallness of the leptons masses.

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