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Nuclear matter and ν properties from π induced reactions and decays

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Abstract. 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 with the PAINUC experiment at JINR. 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.

1 Introduction

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). Below 10 MeV, 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.

2 Experimental findings in $\pi^{\pm 4}$He interactions at T_π =106 MeV

2.1 The thermal emission of photons

The analysis of $\pi^{\pm 4}$He scattering events at T_π ~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 poor 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 π^+ ^{4}He and π^- ^{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 (~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.

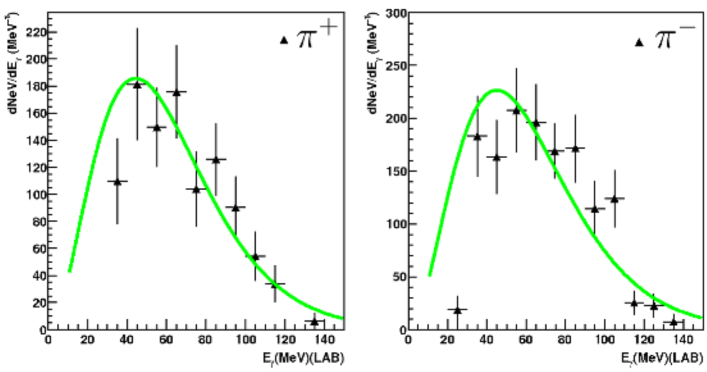

Figure 1. Photon energy distributions from $\pi^{\pm}$-^{4}He$\rightarrow$ $\pi^{\pm}$-^{4}Heγ reactions. The green curves are fits with Planck black-body radiation distributions. The extracted temperature of the corresponding black-bodies is 16 MeV. Points below 30 MeV were not taken into account because of the high probability of wrong identification for elastic and radiative events.

2.2 Signatures of Collective Resonances

The hypothesis of the existence of a giant (I,S)=(3/2,3/2) nuclear resonance was presented by Dillig and Huber in 1974 [4] while the first experimental observations of modifications in the various resonant elastic π-nucleus cross sections were collected by F. Balestra et al. during 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±14) MeV/c^2 and the measured width is Γ =(38±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). The observed parameter modifications are similar to those observed in ref. [5] on the Δ excitation in the elastic scattering of pions on several nuclei. The peaks of the Δ excitation functions show a shift towards lower pion energies, while their widths undergo a narrowing: the phenomenon is more pronounced in the case of pion scattered at high angle (>120^o). Both in elastic ([5]) and inelastic (this work) π-nucleus interactions, the modified Δ resonance seems to be produced at high momentum transfer and low Q^2, in support of the hypothesis that several nucleons are involved in the energy transfer (low Q^2 corresponds to large probing wavelength).

The observed excitation energy shift and the width shrink seem to be mainly related with the increase of binding energy coming from the participating nucleons to the resonance (see [3]). In order to explain both these observations, a semi-empirical model has been developed, which 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 central part of the p.d.f. turns out to be 1.15 nucleon radii while the exponentially decreasing peripheral part turns out to fall

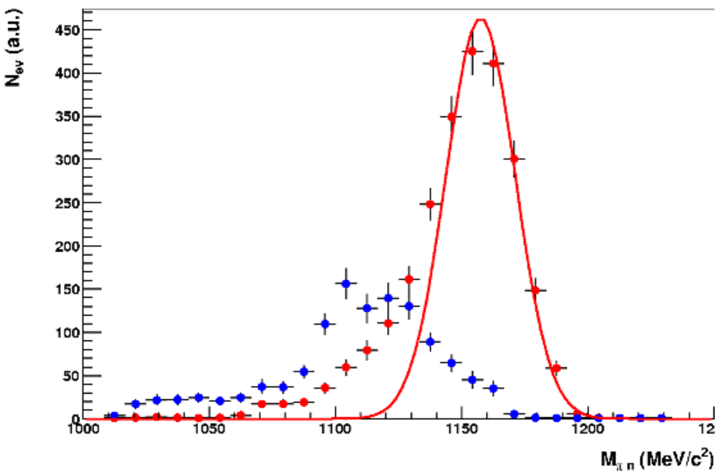

Figure 2. π^-n invariant mass distribution in neutron knock-out reaction for high (red points) and low (blue points) transferred momentum. The resonant (red) distribution reveals a mass lowering and width narrowing w.r.t. the values for a Δ excited on a free nucleon.

in 0.3-0.4 fm. The contribution to the binding per additional nucleon is E_B ~50 MeV (see fig. 3). Therefore, the described collective resonance seems to be a strongly bound state, with binding energies per nucleon about 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]).

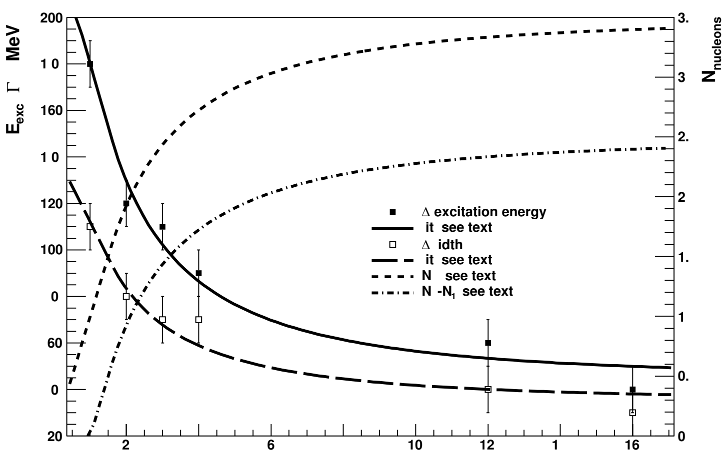

Figure 3. Full and empty squares: peaks and widths of Δ excitation functions for several nuclei, respectively; solid and dashed curves are fits with the semi-empirical model (see text). Fine-dashed and dotted-dashed curves: number of all and of additional nucleons (out of the one destroyed by Δ excitation)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

2.3 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→3p+n absorption reactions at T_π ~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.

The study of the two-nucleon correlations reveals that none of the observed absorption events, in the region where strong correlations have been observed, can be unambiguously identified as a pure two-nucleon absorption (2NA); feeble signatures of Hard and Soft Final State Interactions ((H)SFSI) or Initial state Interactions (ISI) as well as signatures of three-nucleon absorption are present.

The study of three-nucleon correlation reveals that a fraction of ~14% of the absorption events occurs on the three final state protons, in agreement with an absorption on a pd cluster in the initial state: the absence of strong (H)SFSI suggests the absorption occurs on a pd cluster rather than on the deuteron with a proton as a mere spectator. According to our analysis, another ~42% cannot be unambiguously identified as a 2NA + (H)SFSI/ISI or 3NA process. The behavior of the differential cross section reveals the presence of a P wave contribution to all the final state three-nucleon systems. These results are in agreement with the observations obtained at PSI [7, 8].
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.

3 Limits on the extraction of the ν_μ mass

The muon neutrino mass is a fundamental constant in particle physics, having a deep impact in neutrino oscillation physics, electroweak theory and providing constraints on several unsolved problems in astrophysics.

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 as a function of the pion and muon momentum resolution and of the 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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