Pion induced reactions on $^4$He in the $\Delta$ resonance energy region

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Abstract. Measurement of the in-medium modifications of the $\Delta$ 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 $T_\pi =106$ MeV at PAINUC experiment.

1. Introduction

The PAINUC experiment has collected new data on elastic and inelastic $\pi^\pm$ $^4$He interaction, at $T_\pi =106$ MeV where the measured maximum excitation of the $\Delta$ resonance on $^4$He has been observed. The events have been collected using a triggerable self shunted streamer chamber filled with helium at atmospheric pressure, installed in a magnetic field and exposed to the pion beam of the Joint Institute for Nuclear Research (JINR) in Dubna (Russia). The apparatus allows the measurement of all the charged secondaries, down to 1 MeV protons and helium fragments; the particle and the event identification efficiency is improved by the use of track brightness [1].

The study of low and intermediate energy pion-induced reactions is of great interest. At low energies, where other detectors start to show their limitations, the used technique has allowed to collect information on different fields of research: from the physics of nuclei and pion-nucleus interactions, with interesting observations of nuclear collective states, to the physics of phase transitions, with evidences for thermal emission of photons from the so called nuclear matter.
2. Experimental findings in $\pi^{\pm}^4$He interactions at $T_\pi = 106$ MeV

2.1. 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 $\gamma$ emission mechanism, namely the initial or final state radiation (external bremsstrahlung), the internal radiation (internal bremsstrahlung), the $\Delta^{++}$ magnetic dipole radiation, the $\Delta$ 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 $\pi^+$ and $\pi^-$. The internal radiation shows a good agreement in the high energy $\gamma$ region, but is totally in disagreement with the experimental spectra at low $\gamma$ energies. However, the main evidence against the bremsstrahlung radiation as the mechanism responsible for the observed $\gamma$ emission, is the high branching ratio of the channel, $\sim 0.1$ w.r.t. elastic scattering, which is a factor from 10 to 20 higher than the expected.

The hypothesis of the emission of the $\gamma$ via an intermediate $\Delta^{++}$ magnetic dipole radiation has also been considered. This mechanism is expected to occur only in $\pi^+$-proton and $\pi^+$-nucleus interactions, producing a clear bump at 80-100 MeV in the energy distribution of the emitted gammas; with the current statistic the presence of the peak cannot be excluded nor confirmed. It has also to be stressed that the presence of the $\Delta$ magnetic dipole radiation has not been confirmed even on proton target and at higher pion energies. ([4]). The free $\Delta$ radiative decay ($\Delta \rightarrow N\gamma$) has a too low branching ratio and it cannot be observed with the present statistics. In addition, one has also to bear in mind that modifications can be expected in both $\Delta^{++}$ magnetic dipole radiation and radiative $\Delta$ decay when occurring on a nucleus, if compared with a free nucleon, which would make their identification more difficult.

Finally, the $\gamma$ 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.

Should this hypothesis be confirmed by further measurements, it would be an evidence that even a light nucleus at low temperature can behave as a system of oscillators, thus opening new issues in the description of the cold nuclear matter.

Figure 1. Photon energy distributions from $\pi^{\pm}^4$He$\rightarrow\pi^{\pm}^4$He$\gamma$ reactions. The green curves are fits with Planck black-body radiation distributions. The extracted temperature of the corresponding black-bodies is 16 MeV.
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 [5] while the first experimental observations of modifications in the various resonant elastic \(\pi\)-nucleus cross sections were collected by F. Balestra et al. during the 80's [6].

From our analysis of \(\pi^{-4}\text{He}\rightarrow \pi^{-3}\text{He}\ n\) reaction at \(T_\pi=106\ \text{MeV}\), the first experimental observation of the excitation of the \(\Delta^-\) resonance has been obtained in an inelastic channel and below the pion production threshold. The mass of the resonance turns out to be \(M_\Delta=(1157\pm14)\ \text{MeV}/c^2\) and the measured width is \(\Gamma=(38\pm2)\ \text{MeV}/c^2\), thus respectively smaller and narrower with respect to the values of the \(\Delta\) excitation on the free-nucleon (see fig. 2).

The observed parameter modifications are similar to those observed in ref. [6] on the \(\Delta\) excitation in the elastic scattering of pions on several nuclei. The peaks of the \(\Delta\) 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 \((>120^\circ)\).

The modifications of the observed \(\Delta^-\) mass and width could be produced by the activation of an isobaric collective resonance, involving more than one nucleon in the excitation of the resonant state, as it was proposed for explaining the effects observed in [6]. Both in elastic ([6]) and inelastic (this work) \(\pi\)-nucleus interactions, the modified \(\Delta\) 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 \(Q^2\) means 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]).

![Figure 2. \(\pi^{-}\)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 \(\Delta\) excited on a free nucleon.](image.png)
The results of the fit describe the collective state as a cluster of nucleons and a $\Delta$, 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 oxygen). The size of the uniform central part turns out to be 1.15 nucleon radii and the p.d.f. exponentially decreasing peripheral part turns out to fall in 0.3-0.4 fm. The contribution to the binding per additional 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 loosely interacting with the remaining nucleons in the nucleus (see [3, 8]).

With the present model the Fermi momentum contribution to the lowering of the excitation energy cannot be evaluated, however its presence cannot be excluded. At the same time multiple scattering effects, producing slight broadening of the resonance, can also be present. As it has been demonstrated by several works ([7, 9]) both Fermi momentum of nucleons and multiple scattering effects are not able to explain the width narrowing, which can be only explained by the excitation of a collective resonant state.

Finally, the contribution coming from the $\Delta$ excitation on peripheral single nucleons to the total $\Delta$ width and amplitude has also to be taken into account. However, in the present data at $T_\pi =106$ MeV, this contribution has to be small, since the excitation on a peripheral, thus quasi-free, nucleon occurs at higher pion energies (180 MeV).

It clearly turns out that the excitation of resonances in nuclear matter at intermediate energies is far from being understood and hides important information for the description of the nuclear potential at intermediate energies and in the $\Delta$ energy region, where peculiar effects can occur. The extracted parameters, together with other experimental observations obtained from the analyzed sample at 106 MeV, can be used to develope models in order to describe the observed collective states and their complete physical features (density, allowed energy levels and spin state etc.) Moreover, the observations clearly state that there exist strong motivations to deepen the study of the cold nuclear matter, both on the experimental and on the theoretical side.

2.3. 3-body correlation in pion absorption reactions

The pion absorption channel in the region of excitation of the $\Delta$ 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 \( \pi^+ + ^4\text{He} \rightarrow 3\text{pn} \) absorption reactions at \( T_\pi \sim 106 \text{ MeV} \) 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 two-nucleon correlations has been studied by comparing the opening angle, the relative momentum and the invariant mass of the two-nucleon systems with phase space MC expectations. The analysis of the two-nucleon kinematical correlations, for all the six possible nucleon pairs in the final state, 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 three-nucleon correlations has been studied via the bidimensional distributions of the two opening angles \( \theta_{N1N2} - \theta_{N2N3} \), the distribution of three-nucleon plane angle \( \xi \) (see [3]) and the three-nucleon system kinetic energy. The analysis reveals that a fraction of \( \sim 14\% \) 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 spectator. The result is in agreement with that obtained at PSI [10], even if, in that case, protons with energy below 20 MeV were not measured and the observations showed agreement with a true three-nucleon absorption mechanism. According to our analysis, another \( \sim 42\% \) cannot be unambiguously identified as a 2NA + (H)SFSI/ISI or 3NA process; the result is again in agreement with the findings of Matheos [11], which gives \( \sim 37\% \) for the same uncertainty. In addition, from the analysis of the three-nucleon kinetic energy distributions, the excitation of a dibaryonic d' in the pion absorption, via the channel \( (\pi^+ mn)p \rightarrow d'N \rightarrow 3\text{N} + 190 \text{ MeV} \), cannot be excluded.

The behavior of the differential cross section in the three-nucleon plane angle \( \xi \), for all four possible three-nucleon systems in the final state, has been fitted with Legendre polynomials, revealing the presence of a P wave contribution to all the final state three-nucleon systems. This is again in agreement with the observations obtained at PSI [10].

Further statistics is needed in order to perform a global fit with a weighted sum of models (3NA, 2NA, 2NA+(H)SFSI, 3NA(d')), that would allow to simultaneously extract the different contributions of different absorption processes to the whole population of pion absorption events. However it is clear from several pion absorption studies ([10, 11, 3]) that new theoretical models, taking into account a real 3-4NA process, have to be developed in order to reliably explain the absorption interactions in the \( \Delta \) resonance energy region.

Finally, for the first time, the invariant mass spectra of all the four possible final state three-nucleon systems have been studied. The spectra reveal the presence of structures. The structures are clearly visible also in the 3pn invariant mass spectrum, shown as an example in fig. 4. The broadening of the mass spectrum above \( 4 \text{ GeV}/c^2 \) is due to the propagation of the measurement uncertainties on incident pion and on final state protons momenta: the phase space MCs - that take into account all the experimental uncertainties - show the same behaviours, but with no peaks. The different contributions - continuum and mass peaks - to the total invariant mass spectra of all the three-nucleon systems have been extracted. Notwithstanding the broadening effects, common values of mass peaks are present in the different three-nucleon system invariant mass spectra, at \( M_{3\text{N}} \sim 3030, 3300, 3650 \) and \( 4150 \text{ MeV}/c^2 \); with the present momentum resolution they can only be taken as a qualitative evidence. Finally, the system with the lowest energy shows levels at lower energies (for more information see [3]).

In order to correctly understand the meaning of the measured peaks, some comments are needed at this point. First, the analyzed pion absorption events are measured at \( T_\pi = 106 \text{ MeV} \), where the maximum of pion-induced excitation of the \( \Delta \) resonance on \( ^4\text{He} \) is expected.
the excitation of a collective resonance, involving up to 3-4 nucleons on $^4\text{He}$, have been obtained. Second, the well known change of the slope of the pion absorption cross section as a function of the target nucleus mass number, from a fast $\sigma_{\text{abs}} \propto A^3$ if $A < 4$ to a slow $\sigma_{\text{abs}} \propto A^{2/3}$ if $A > 4$ (see [11] and references therein), is again in support of a collective excitation; the change occurs precisely on the nucleus (the $^4\text{He}$) with a number of nucleons equal to the maximum involved in the collective resonance activation, according to the semi-empirical model. In this view, the observation of common peaks in the three-nucleon invariant mass spectra in the analyzed pion absorption interactions, together with signatures of 3NA processes, strongly suggest that the collective resonance takes a fundamental role also in the pion absorption channel in the $\Delta$ energy region. The whole set of experimental evidences would suggest a set of measurements at higher momentum resolution in order to confirm the observations and to provide precise values for the measured mass spectra structures. Together with the physical parameters of the collective resonance extracted (number of nucleons involved, binding energy per additional nucleon, $\Delta N$ potential size and fall, contribution to the mean life), they could be useful physical quantities to improve our knowledge on the collective resonant states and develope static and dynamical models to be compared with future measurements.

Figure 4. Invariant mass distribution of the four-nucleon 3pn observed in the absorption reactions final states. Legend: full circles, experimental data; blue solid line, phase-space simulations; dotted black line, contribution of the continuum; dotted colored lines, contributions to the total spectrum from the different mass peaks; solid black line, sum of all the contributions. The last two structures are not taken into account in the fit.

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