Collective and thermal signatures in $\pi^4\text{He}$ interaction in the $\Delta$ excitation energy region

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Abstract. Measurement of the in-medium modifications of the $\Delta$ resonance has been performed at a PAINUC experiment. Signatures of the excitation of nuclear collective states and the first experimental evidence for thermal emission of photons have been obtained from the analysis of the $\pi^4\text{He}$ data taken at $T_\pi=106$ MeV.

1. Introduction

The study of low and intermediate energy pion-induced reactions is of great interest. The PAINUC experiment has collected new data on elastic and inelastic $\pi^4\text{He}$ interaction at $T_\pi=106$ MeV where the maximum of the $\Delta$ resonance production on $^4\text{He}$ 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 makes possible the observation of all the charged secondaries, down to 1 MeV protons and other helium fragments. The particle identification efficiency has been improved by the use of the track brightness method [1]. At low energies, where other detectors start to show their limitations, by use of this technique the PAINUC collaboration was able to collect information in different fields starting 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 $\pi^4\text{He}$ interactions at $T_\pi=106$ MeV

2.1. The thermal emission of photons

The analysis of the $\pi^4\text{He}$ scattering events at $T_\pi \sim 106$ MeV revealed the existence of a channel with 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 bad agreement with the experimental data, both in the $\pi^+$ and $\pi^-$ cases. The internal radiation spectrum shows a good agreement in the high energy $\gamma$ region, but is totally in disagreement with the experimental spectra at low $\gamma$-ray
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, \( \sim 0.1 \) relative to the elastic scattering, which is a factor of 10 to 20 higher than expected.

The hypothesis of the emission of a $\gamma$ via an intermediate $\Delta^{++}$ magnetic dipole radiation has also been considered. This mechanism is expected to occur only in $\pi^+\text{-proton}$ and $\pi^+\text{-nucleus}$ interactions, producing a clear bump at 80-100 MeV in the energy distribution of the emitted $\gamma$-rays. With the current statistics the presence of the peak can neither 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 a 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 are expected both in $\Delta^{++}$ magnetic dipole radiation and in radiative $\Delta$ decay taking place in a nucleus, compared to the free nucleon case, 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), assuming about 16 MeV temperature for both $\pi^+\text{-}^4\text{He}$ and $\pi^-\text{-}^4\text{He}$ 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 nuclear temperature ($\sim16$ 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 $\pi^\pm\text{-}^4\text{He} \rightarrow \pi^\pm\text{-}^4\text{He}\gamma$ reactions. The green curves are fits with Planck black-body radiation distributions. The extracted temperature of the corresponding black-bodies is 16 MeV.](image)

### 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 done by F. Balestra et al. during the 80’s [6].

From our analysis of the $\pi^-\text{-}^4\text{He} \rightarrow \pi^-\text{-}^3\text{He}\gamma$ reaction at $T_\pi=106$ MeV, the first experimental evidence on 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 $M_\Delta=(1157\pm14)$ MeV/$c^2$ and the measured width is $\Gamma=(38\pm2)$ MeV/$c^2$, thus smaller and narrower with respect to the corresponding values of the $\Delta$ excitation on a free-nucleon (see fig. 2).

The observed parameter modifications are similar to those observed in ref. [6] on the $\Delta$ excitation in 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°). The modifications of the observed Δ− mass and width could be caused 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 the explanation of the effects observed in Ref. [6]. Both in elastic ([6]) and inelastic (this work) π-nucleus interactions, the modified Δ resonance seems to be produced at high momentum transfer and low Q², in support of the hypothesis that several nucleons are involved in the energy transfer (low Q² means large probing wavelength). The observed excitation energy shift and the width shrink seem to be mainly related to the increase of the binding energy coming from the nucleons participating in the resonance (see [3]). In order

![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 with respect to the values for a Δ excited on a free nucleon.](image)

to explain both the observations of the present work and those of [6], 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; the parton density function (p.d.f) of the collective state has been formulated as a composition of a spherical symmetric and uniform central part and of an exponentially decreasing peripheral part. The semi-empirical model has been used to fit data on several nuclei in Ref. [6]; the fit is based on the simple idea that each additional nucleon involved in the collective resonance gives a contribution in terms of binding energy, thus, narrowing the width and increasing the life time of the resonance.

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 for deuteron and 4He, respectively. 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 radius and the exponentially decreasing peripheral part of the p.d.f. turns out to fall in 0.3-0.4 fm. The contribution to the binding energy 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 7 times the standard binding energy of a nucleon in a nucleus. The fast drop of the p.d.f. suggests that 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]) neither Fermi momentum of nucleons nor multiple scattering effects are able to explain the width narrowing, which can only
be explained by the excitation of a collective resonant state. Finally, the contribution coming from the Δ excitation on peripheral single nucleons to the total Δ 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 well understood and the present experimental observations clearly show that there are strong motivations to deepen the study of the cold nuclear matter, both on experimental and theoretical sides.

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 the $\pi^+^4$He$\rightarrow$3pn absorption reactions at $T_\pi$ $\sim$106 MeV allowed the observation 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 has been performed by using a set of two-nucleon kinematical variables, namely: the opening angle, the relative momentum and the invariant mass of the two-nucleon systems. The bidimensional distributions of these variables have been compared with those obtained from the Monte Carlo simulation of the phase space. 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 unambiguously be 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 has been performed by using a set of variables in order to identify the three-nucleon system under study, namely: the bidimensional distributions of the two opening angles $\theta_{N1N2}$-$\theta_{N2N3}$, the distribution of three-nucleon plane angle $\xi$ (see [3]) and the kinetic energy of the three-nucleon system. 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 mere 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 dibarionic \(d'\) in the pion absorption, via the channel \((\pi^+nn)p\rightarrow d'N\rightarrow 3N+190\ MeV\), 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 ([3, 10, 11]) 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.

In order to correctly understand the meaning of these experimental findings, some comments are needed. First, the analyzed pion absorption events are measured at \(T_{\pi} = 106\ MeV\), where the maximum cross section of pion-induced excitation of the \(\Delta\) resonance on \(^4\)He is expected. Signatures of the excitation of a collective resonance, involving up to 3-4 nucleons, on \(^4\)He have been obtained. Second, the well known change of the slope of the pion absorption cross section as a function of the mass number of the target nucleus, from a fast \(\sigma_{abs} \propto A^3\) if \(A < 4\) to a slow \(\sigma_{abs} \propto A^{2/3}\) if \(A > 4\) change (see [11] and references therein), is again in support of a collective excitation; the change occurs precisely on the nucleus (the \(^4\)He) with the 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 signatures of 3NA processes strongly suggests that the collective resonance takes a fundamental role also in the pion absorption channel in the \(\Delta\) energy region.

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 time), can be useful physical quantities to improve our knowledge on the collective resonant states and to develop static and dynamic models to be compared with future measurements.

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