Δ PRODUCTION AND PROPAGATION IN NUCLEI*

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We present data on the decay of the Δ resonance excited in ^{1}H, ^{2}H, ^{4}He , ^{12}C and ^{208}Pb by the (^{3}He, t) reaction at 2 GeV incident energy. The quasi-free decay of the Δ resonance and the absorption process are investigated. We find indication for a coherent process where a pion is emitted and the target nucleus is left in its ground state. This process is now being studied with the dedicated set-up Spes4π. The first data with this new detection system have just been taken.

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1. Introduction

As the Δ isobar is a resonance in the π+N system, the study of the Δ resonance in nuclei is closely related to the in medium behaviour of the pion and to the coexistence of pions, nucleons and Δ-hole states in the nucleus. It has been stressed for many years that Δ-hole correlations can build collective pionic modes (or pionic branch)[1, 2]. Unlike the real pion induced reactions, charge exchange reactions at around 1 GeV/nucleon probe the nucleus in the good kinematical region to look for these collective effects. However, in these

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reactions both the spin-transverse and the spin-longitudinal responses of the nucleus are excited and only the longitudinal response (*i.e.* the "pionic" one) is expected to be significantly modified by medium effects. These reactions are very peripheral which also is expected to reduce the effects of these collective modes.

However, a first indication of this pionic branch has probably been obtained in the inclusive charge exchange reactions on nuclei where a shift of the resonance excited in nuclei is observed with respect to the free one [3–7]. This effect is illustrated on Fig. 1 in the case of the (^{3}He,t) reaction studied at Saturne [5]. The energy transfer spectra have same position and same width, whichever the target from ^{12}C to ^{208}Pb and are shifted by 70 MeV towards low energy transfers with respect to the spectrum obtained on the proton target. Calculations of Ref. [8, 9] performed for the (^{3}He,t) and (p, n) reactions are able to reproduce the experimental spectra and explain half of this shift by simple effects like Fermi motion or mean field effects combined with the steep (^{3}He, t) form-factor. The other half comes from effects of Δ-hole correlations on the spin-longitudinal response function. However, Oset *et al.* [10] stress that these approaches do not take into account processes such as projectile excitation or quasielastic processes which contribute in the low energy side of the energy transfer spectrum.

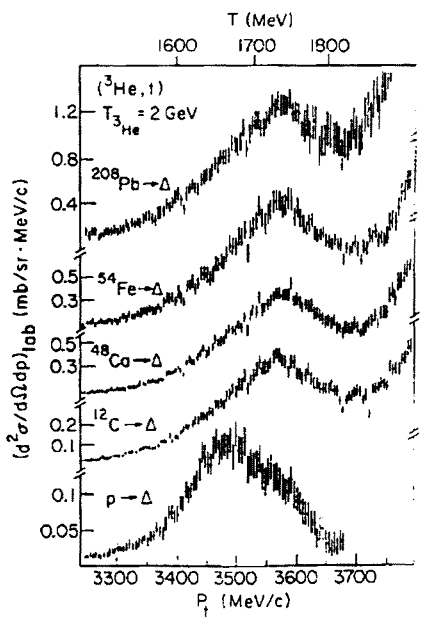

Fig. 1. Energy transfer spectra for (^{3}He, t) reaction on nuclei at 2 GeV from Ref. [5]

The study of the Δ decay channels in the nuclear medium gives more information about the origin of this shift and therefore put more constraints on these models.

Three different decay processes are studied: the quasifree process $\Delta \to \pi + N$, where the Δ decays without interacting with other target nucleons, the absorption process $\Delta N \to NN$, and the coherent process $A_\Delta \to \pi + A_{gs}$, where one pion is emitted and the nucleus is left in its ground state.

Some exclusive experiments have been carried out to study these different processes. At KEK, the exclusive (p,n) reaction has been studied at 800 MeV with the Fancy detector [11]. At Dubna, the (t,^{3}He) reaction has been performed at 2.24 GeV/nucleon with a streamer chamber [12, 13]. At Laboratoire National Saturne, we have performed an exclusive (^{3}He,t) experiment at 2 GeV with the large acceptance Diogene detector. We have obtained a complete set of data on ^{1}H,^{2}H, ^{12}C, ^{4}He and ^{208}Pb targets[14, 15].

2. Experimental set-up

Triggered by the triton, the charged pions and/or protons emitted by the excited nucleus are detected in DIOGENE (Fig. 2). The detecting arm for the tritons consists of a dipole magnet and two sets of drift chambers allowing for energy and angle measurement in the range 1.4 to 2 GeV and 0° to 4°. The energy (respectively angle) resolution (FWHM) for tritons range from 25 to 45 MeV (respectively 1 to 4 mrd) depending on target geometry. 99% of the deuterons produced by the ^{3}He break-up are hardware rejected by the trigger made by a coincidence between two scintillator hodoscopes located behind the drift chambers.

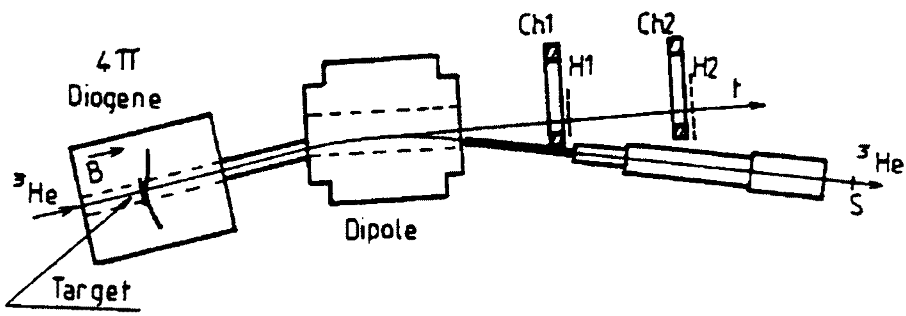

Fig. 2. Experimental set-up

The cylindrical "4π" detector, Diogène, originally built for nucleus-nucleus collision studies, consists of 10 trapezoidal drift chambers in a 1 T longitudinal magnetic field [16]. Combining track reconstruction and pulse height analysis, it allows particle identification and momentum vector measurement for particles with polar angle between 20° and 132° over the full azimuthal angular range.

The momentum resolution (FWHM) is typically 18% for protons and 10% for pions; angles are measured with a precision of a few degrees. Typical values for the detection energy threshold obtained in our experiment were 15 MeV for pions and 35 MeV for protons.

The experiment has been performed on liquid hydrogen ($1.3\,g/cm^2$) liquid deuterium ($3.1 g/cm^2$), liquid helium 4 ($1.125 g/cm^2$), carbon ($0.36 g/cm^2$) and lead ($1.135\,g/cm^2$) targets.

We focus in the following on events for which the particles detected in Diogene carry an important fraction of the energy transferred to the target and try to extract from these events information on the different Δ resonance decay channels.

3. $\pi^+ + 1p$ events

When $1\pi^+$ and 1p are detected in Diogene in coïncidence with the triton, the residual undetected nucleus is left with an excitation energy less than a few MeV.

Moreover, the energy transfer spectrum has same position and width within 15 MeV on all the targets studied in our experiment.

Both results show that these events select a quasi-free decay of the Δ resonance and do not contribute to the shift observed in inclusive data. Cascade calculations [17] show that these $\pi^+ + p$ events correspond to Δ's produced at the nucleus surface.

4. $2p$ events

The energy transfer spectrum obtained for $\pi^+ + p$, $2p$ and $3p$ events are compared to the inclusive spectra in Fig. 3. On ^2H , there is no apparent Δ bump for 2p events. This shows that the absorption of the Δ resonance in deuterium is weak.

On helium 4, a very clear structure is observed in the $2p$ spectrum, with an impressive 130 MeV shift with respect to the one observed in the $\pi^+ + p$ events. This trend is also found for the ^{12}C and ^{208}Pb targets , but the maximum of the $2p$ spectrum is shifted towards higher ω values, as the mass of the target increases, whereas the $\pi^+ + p$ spectrum stays at the same position. Cascade simulations performed in the case of ^{12}C target show that an important part of the shift between $\pi^+ + p$ and 2p energy transfer spectra is due to phase space effects [17]. However, these calculations fail to explain the low energy side of the $2p$ spectrum. Calculations by Osterfeld *et al.* [18]

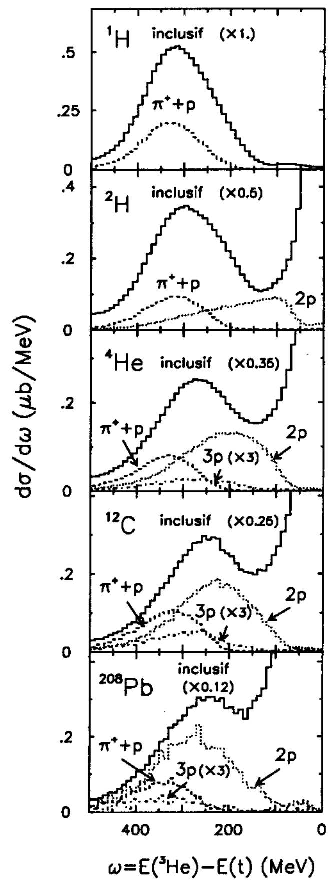

Fig. 3. Energy transfer spectra for all events (full line), $1\pi^+ + 1p$ events (dashed line), 2p events (dotted line) and 3p events (dashed-dotted line) for ^{1}H, ^{2}H, ^{4}He, ^{12}C and ^{208}Pb targets.

show that some strength in the $2p$ spectrum is produced in this region by the correlations.

For the ^{4}He target, the mean excitation energy of the residual deuterium is less than 5 MeV, which means that the 2 protons carry most of the energy transferred to the target. On ^{12}C and ^{208}Pb targets, the residual nucleus is found with increasing excitation energies. The energy transferred to the target is thus shared among more and more nucleons. In the low energy transfer region, the 2 protons may then have too small an energy to be detected as $2p$ events and may then appear as 1p or empty events. This might explain the shift of the observed $2p$ spectrum towards higher values. As stressed by Oset [19], some $2p$ events in heavy targets may also come from absorption of the real pion emitted in the decay of the Δ resonance, which process should appear at energy transfers around the position of the $\pi^+ + p$ events and should then contribute to shift the 2p spectrum towards higher ω values. This process has been identified in photoabsorption reactions on ^{3}He [20].

A Δ bump is also present in the 3p spectrum (dashed-dotted line on Fig. 3) and is located at higher energy transfers, as expected, due to the energy threshold for one more proton to be detected in DIOGENE.

In the case of the ^{208}Pb target, the large excess of neutrons and the high number of rescatterings inside the nucleus might explain the overall decrease of the $2p$ and $3p$ events rate for the benefit of $1p$ or empty types of events.

In the cases of the ^{12}C target and especially of the ^{208}Pb targets, the analysis of the 2 proton correlations is difficult because the energy of the undetected particles is large. Therefore, we focused on the study of the ^{2}H and ^{4}He . On the deuterium target, the missing mass spectra allow to select the 1p and 2p events for which no pion has been emitted.

The excitation energy spectra of the 2 proton system are displayed on Fig. 4 for these events for different four-momentum bins. For large four-momenta, 2 processes distinguish themselves clearly: on the one hand a quasi-elastic process at small invariant masses, which dominates at small four-momentum transfers, on the other hand at large invariant masses of the 2 protons a resonant process corresponding to excitation of the Δ resonance. A similar result had been obtained in the reaction pd→npp at 1 GeV studied at Dubna and the cross-section in the region of the Δ resonance was well reproduced by the calculations by Wilkin in the one pion exchange model

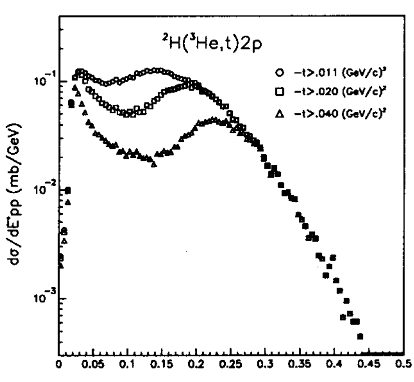

Fig. 4. Excitation energy of the 2 protons on the ^{2}H target for $1p$ and $2p$ events with no emitted pion for different bins in four momentum transfer.

[21]. For the (^{3}He,t) reaction, similar calculations performed recently by Wilkin overestimate the cross-section by a factor 1.7 and the contribution is located at an excitation energy too high by about 30 MeV. Calculations based on OPE for the quasi-elastic process are also being performed by Zupranski and Deloff.

By analogy with the γd$\to$pp and πd$\to$pp, we studied the angular distributions of the 2 protons in the frame of the excited target. We selected the events with excitation energy greater than 150 MeV to eliminate the quasi-elastic process. These angular distributions are compared on Fig. 5 to the results of a simulation including acceptance and resolution effects and assuming isotropic angular distributions (dashed lines) or $1+3\cos^2\theta$ (points) of the protons in the frame of the excited target. This latter distribution is the one obtained in real pion absorption where the interaction is longitudinal ($\vec{S}\cdot\vec{q}$ where $\vec{S}$ is the spin transition operator $N\to\Delta$ and $\vec{q}$ the momentum transfer [22]. At low four-momentum transfers, the data are in agreement with an isotropic angular distribution or a distribution with

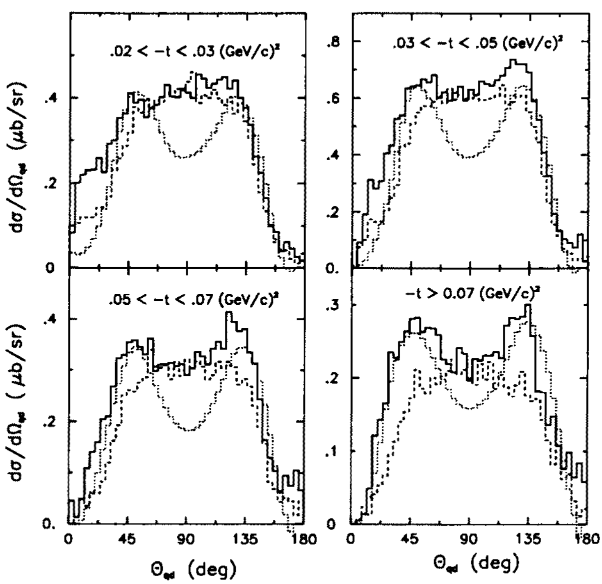

Fig. 5. Angular distributions of the protons in the frame of the excited deuterium target (full line). All 1p and 2p events with no emitted pion and excitation energy of the 2 protons greater than 150 MeV are taken into account. The dashed lines (respectively dotted lines) are the results of a simulation with an isotropic angular distribution (respectively in $1+3\cos^2\theta$) in the frame of the excited target (see text).

a flat maximum, as the one observed in reactions induced by real photons where the interaction is transverse ($\vec{S} \times \vec{q}$) [23]. When the four-momentum increases, the angular distributions grow hollow and their shape becomes near to being in $1 + 3\cos^2\theta$, which is characteristic of the dominance of the Δ in the pion absorption process. This analysis suggests that, for this absorption process, the contribution of the longitudinal component of the interaction increases with respect to the transverse one when the four momentum transfer increases.

For the ^{4}He target, the contribution of quasi-elastic processes is less important in the 2p events than for the ^{2}H target. We selected the events which were consistent with the quasi-deuteron model which assumes that the energy-momentum quantum (q,ω) exchanged between the projectile and the target is absorbed on a (p, n) pair moving in the ^{4}He nucleus [24]. For these events, the angular distributions in the frame of the excited (p, n) pair show the same evolution as for the deuterium target. At large four-momentum transfers, they present however a deeper minimum and are then in agreement with the $1 + 3\cos^2\theta$ obtained in real pions.

5. $1\pi^+$ events

The $1\pi^+$ events are expected to be due on the one hand to incoherent processes, such as quasi-free decay of the Δ resonance where the nucleon emitted is not detected, either because it is neutral or because of the Diogene acceptance cuts or inelastic processes where the target nucleus is left in an excited state. On the other hand, pions may be produced in a coherent process where the nucleus is left in its ground state.

The excitation energies of the target nucleus obtained for $1\pi^+$ events on ^{4}He , ^{12}C and ^{208}Pb are shown on Fig. 6. A clear enhancement is found around zero excitation energies in the case of ^{4}He and ^{12}C targets, about 30 MeV [17] lower than the maximum expected for the quasi-free process. Although the resolution is not good enough to isolate the ground state, this result gives strong indication for coherent pion production.

The pions corresponding to the lowest target excitation energies are found to be strongly peaked around the direction of the momentum transfer. For small triton angles, a very big fraction of them is thus emitted in the acceptance hole of the Diogene detector. Their angular distribution is shown on Fig. 7 for tritons emitted at laboratory angles greater than 2.5° for which the momentum transfer points at angles larger than 27° in the laboratory (for $\omega = 250$ MeV) and therefore the acceptance cuts are smaller.

After corrections for acceptance cuts, the width of these distributions are 24° for ^{4}He and 20° for ^{12}C. These events also correspond to lower energy transfers, as shown on Fig. 8.

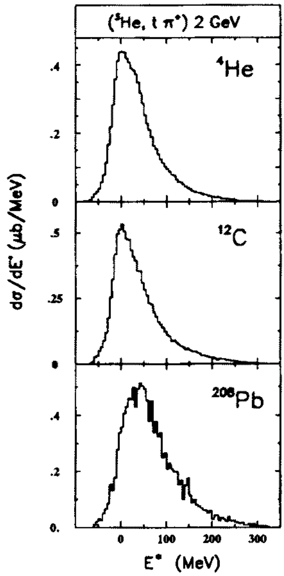

Fig. 6. Excitation energies of the residual nucleus for $1\pi^+$ events for ^{4}He, ^{12}C and ^{208}Pb targets.

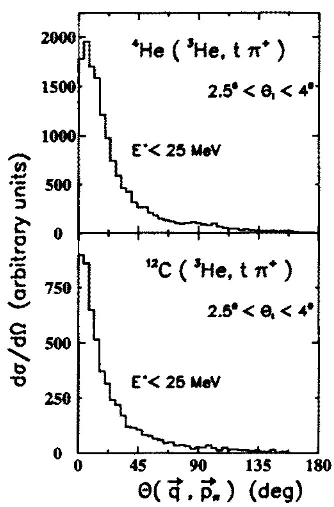

Fig. 7. Distributions of the angle with respect to the momentum transfer direction of $1\pi^+$ events with residual excitation energy less than 25 MeV for ^{4}He (top), and ^{12}C (bottom) targets. Only events with triton angles between 2.5° and 4° are selected.

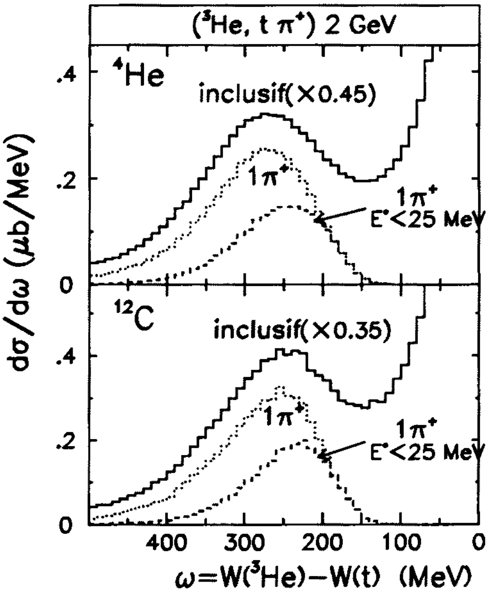

Fig. 8. Energy transfer spectra are displayed for ^{4}He (top) and ^{12}C targets (bottom). Full lines correspond to all events, dotted lines to $1\pi^+$ events and dashed lines to $1\pi^+$ events with excitation energy less than 25 MeV.

We have estimated to respectively $10.6\% \pm 1.0\%$ and $5.4\% \pm .6\%$ the proportion of coherent process with respect to the inclusive. For the lead target, this ratio is lower than 1%. These results are in agreement with theoretical predictions [25–27] for coherent pion production. However, they are only valid for triton angle ranging from 2.5 to 4°, where the cross-section is small but where the acceptance effects can be accounted for.

According to these models, coherent pions are mainly produced by the longitudinal component of the interaction and are therefore very sensitive to Δ-hole correlations. This motivates the specific study of this process which is being carried out at Saturne with the Spes4π detector.

6. SpesIV π experiment

The new SpesIV π detector consists in adding around the target point of the SpesIV spectrometer a detection consisting in a large gap magnet a scintillator hodoscope and large wire chambers, well suited to coherent pion detection[28, 29]. The missing mass resolution expected with such a set-up is of the order of 3 MeV/c^2 and allows to sign unambiguously the process. The full acceptance at forward angles and the high counting rate that the detectors can stand allow a study of the process as a function of momentum and energy transfers and for different projectile-ejectile combinations as (^{3}He,t), ($\vec{d}$,2p), (^{12}C,^{12}N). Farhi has presented at this conference the first preliminary results obtained with this experimental set-up. Although the nominal resolution is not yet achieved, the coherent process shows up very clearly and seems to be the dominant pion production process at low energy transfers.

7. Conclusion

In conclusion, the study of the exclusive (^{3}He,t) reaction at 2 GeV on ^{1}H, ^{2}H , ^{4}He ^{12}C and ^{208}Pb allows to isolate three different decay channels.

- Events where one pion and one proton are detected in coincidence with the forward emitted triton select a quasi-free excitation of the Δ resonance with the same energy transfer on nuclei and on the free nucleon.
- The 2p events are related to the absorption process of the Δ resonance. This process dominates in a region of lower energy transfers where the correlations play an important role. The analysis of the angular distribution of the protons in the frame of an excited (p,n) pair give interesting indications on the ratio of longitudinal and transverse components of the interaction. This decay channel involves an increasing number of nucleons as the mass of the target increases.
- We find indications for the coherent process leading to emission of a pion and leaving the target nucleus in its ground state. This process is directly related to the spin longitudinal channel of the interaction. A specific study of this process is being carried out at Saturne with the experimental set-up Spes IV π.

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