Δ RESONANCE DECAY AND ABSORPTION 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 bombarding energy. The quasi-free decay of the Δ resonance and the absorption process on a (p,n) pair are clearly observed. We also find evidence for coherent pion production.

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1. Introduction

In the frame of the charge exchange program at LABORATOIRE NATIONAL SATURNE, (^{3}He, t) coincidence experiments at 2 GeV incident energy have been performed on ^{1}H, ^{2}H, ^{12}C, ^{208}Pb targets and recently on ^{4}He target in order to analyse the decay modes of the Δ-hole states in nuclei. Three decay channels are investigated : the quasi-free decay, the absorption process, and the coherent pion production.

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The goal is to find out which processes contribute to the 70 MeV shift in energy transfer of the peak position of the Δ resonance excited in nuclei in comparison with the free Δ's measured on the proton target.

2. Inclusive charge exchange experiments

Charge exchange is a suitable probe to investigate spin-isospin correlations. In the spin-isospin channel, the interaction can be described by π exchange at rather long distances, by ρ exchange at shorter distances and by a short repulsive term. π exchange excites the spin longitudinal response ($\vec{S}\cdot\vec{q}$ T), whereas ρ exchange excites the spin transverse one ($\vec{S}\times\vec{q}$ T).

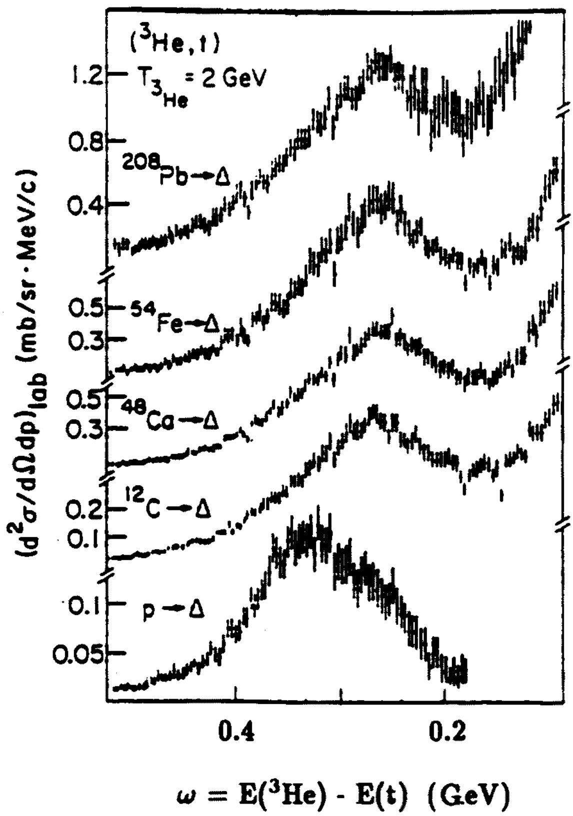

Fig. 1. Energy transfer spectra in (^{3}He, t) reaction at 2 GeV on hydrogen and other nuclei.

At SATURNE, inclusive (^{3}He, t), ($\vec{d}$, 2p[$^1S_0$]), ($^6\vec{Li}$, ^{6}He) and heavy ion charge exchange reactions have been performed using the SPES4 spectrometer. Energy transfer spectra recorded up to 600 MeV in (^{3}He, t) at

2 GeV show a strong excitation of the Δ resonance in nuclei around 300 MeV [1]. Furthermore, the Δ peak position in nuclei (from ^{12}C to ^{208}Pb) is found to be shifted by about 70 MeV towards lower energy transfer as compared to the proton target, and the Δ width to be independent of the target from ^{12}C to ^{208}Pb (Fig. 1). These features are common to all charge exchange reactions around 1 GeV per nucleon whether induced by proton, light or heavy ion beams [2, 3].

Theoretical calculations lead to the conclusion that about one half of the shift is due to Δ-hole correlations in the spin longitudinal response where the Δ-hole interaction is attractive [4–6]. On the contrary, no shift is expected in the spin transverse response since the effective interaction in this channel is weakly repulsive. The remaining half comes from mean field effects (Δ binding), Fermi broadening combined with the steep (^{3}He, t) form factor. Another contribution to the shift may come from Δ excitation in the projectile [7].

In order to elaborate further on these effects, the decay modes of the Δ-hole states have to be investigated and separately analysed. Coincidence experiments using "4π" detectors make this analysis possible.

3. Δ decay modes

Before presenting the (^{3}He, t) coincidence experiment at SATURNE, let us present the three expected Δ decay modes :

- the quasi-free decay : $\boldsymbol{\Delta} \to \boldsymbol{\pi} + \boldsymbol{N}$.

In this process, Δ's do not interact with other nucleons of the target.

- the absorption process : $\boldsymbol{\Delta} + \boldsymbol{N} \to \boldsymbol{N} + \boldsymbol{N}$.

The final state consists of two nucleons without a pion.

- the coherent pion production : $\boldsymbol{A}_{gs}\ \boldsymbol{\pi}_{virtual} \to \boldsymbol{A}_{gs}\ \boldsymbol{\pi}_{real}$ (A_{gs} = target nucleus in the ground state).

The exchanged virtual pion propagates through the nucleus coherently until it escapes as a real pion, leaving the recoiling nucleus in its ground state. The angular distribution of the real pion is expected to be strongly peaked around the momentum transfer direction.

4. Exclusive (^{3}He, t) experiment

In the (^{3}He, t) experiment at 2 GeV bombarding energy (Fig. 2), the Δ decay products are detected in a large acceptance detector DIOGENE in coincidence with the forward scattered triton [8]. A (p,n) experiment has also been performed at KEK [9]. Only charged particles (pions and/or protons) are detected in DIOGENE.

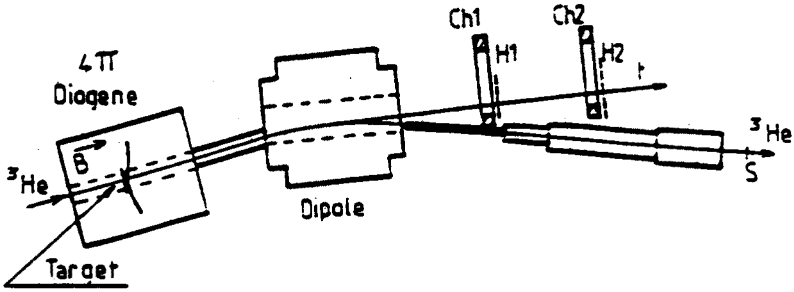

Fig. 2. Experimental set-up

The detecting arm for the tritons consists of a dipole magnet (L_{magn}=1.33 m) operating at 1.9 T and two sets of drift chambers [10] allowing energy and angle measurements in the range 1.4 - 2 GeV and 0 - 4 deg respectively. The angular opening is 20 to 70 mrad in the horizontal plane and $\pm$ 14 mrad in the vertical plane. Two helium bags are used to reduce the multiple scattering of the triton in order to keep its energy and angle resolutions below 20 MeV and 0.5 mrad respectively (FWHM).

Originally built for nucleus-nucleus collision studies, the cylindrical "4π" detector DIOGENE consists of 10 trapezoidal drift chambers in a longitudinal magnetic field of 1 Tesla [11]. Combination of track reconstruction and pulse height analysis allows for particle identification and momentum vector measurements for particles with polar angle between 20 and 132 deg without azimuthal angular cuts. The momentum resolution (FWHM) is typically 18% for protons and 10% for pions, and angles are measured with a precision of a few degrees. As the detection energy threshold depends on the particle angle and the target thicknesses, only typical values can be given : about 15 MeV for pions and 35 MeV for protons.

Liquid hydrogen, liquid deuterium, liquid helium, carbon and lead targets have been used for the following reasons. On the ^{1}H target, the only possible decay channel is the free decay ($\Delta^{++} \rightarrow \pi^+ + p$), and the measurement of both energy and angle of the two decay products gives an overdetermination which allows to check the calibration of DIOGENE. ^{2}H is the lightest nucleus where the absorption process is possible. A comparative analysis on ^{4}He, ^{12}C and ^{208}Pb targets gives information about the Δ decay dependence on the nuclear density. The helium target is interesting as it is a dense nucleus with only four nucleons. The data have not been fully analysed yet, especially helium and lead.

Events are classified according to different types. The rates of the different event types measured in DIOGENE in the Δ peak, *i.e.*

140 MeV $< \omega = E(^3\text{He}) - E(t) <$ 600 MeV, are shown in Table I.

TABLE I

Percentage of the different types of events measured in DIOGENE in coincidence with the forward scattered triton for the ^{1}H, ^{4}He and ^{12}C targets. A gate is put on energy transfer (140 MeV $< \omega <$600 MeV) to select events in the Δ peak.

Event type	^{1}H	^{4}He	^{12}C
none	20.5	24.0	30.0
$1\pi^+ + 1p$	36.0	7.5	6.0
$1\pi^+$	31.0	27.5	18.0
$1p$	5.0	19.0	24.0
$2p$	2.0	15.0	13.0
$3p$	0.0	1.2	1.4
others	5.5	5.8	7.6
total	100.0	100.0	100.0

As previously said, the only possible decay on ^{1}H target is $\Delta^{++} \rightarrow \pi^+ + p$. The occurrence of incomplete events is due to the detector acceptance - forward and backward particles as well as particles with energy below threshold are lost - or ray-tracing inefficiency. An additional 6% inefficiency due to in flight pion decay has been estimated by using Monte-Carlo simulations. The 2p events come from the liquid hydrogen target windows. On ^{4}He, the $1\pi^+ + 1p$ event rate drops as compared to the ^{1}H target : in addition to the quasi-free decay, the absorption process and the coherent pion production can contribute. Even a significant fraction of 3p events appears as the absorption process is likely to involve several nucleons. The same trends are found on carbon as compared to helium except that the $1\pi^+$ event rate is a little lower.

In the remaining, we focus on three event types with low missing energy : $1\pi^+ + 1p$ events to investigate the quasi-free Δ^{++} decay, 2p events for the study of the absorption process on a (p,n) pair, and $1\pi^+$ events to look for the production of coherent pions which have to be experimentally confirmed.

5. $\pi^+ + p$ events

For $\pi^+ + p$ events, the Δ bump in the energy transfer spectra on the ^{1}H, ^{2}H and ^{12}C targets is peaked at the same position with the same width within 15 MeV (Fig. 3). Moreover, invariant mass spectra on ^{1}H and ^{12}C display two main features. On one hand, the peak for the ^{1}H spectrum is 40 MeV lower than the free mass value, and on the other hand the invariant mass for ^{12}C is shifted by 25 MeV towards lower values as compared to the hydrogen target. The former feature is explained by the (^{3}He, t) form

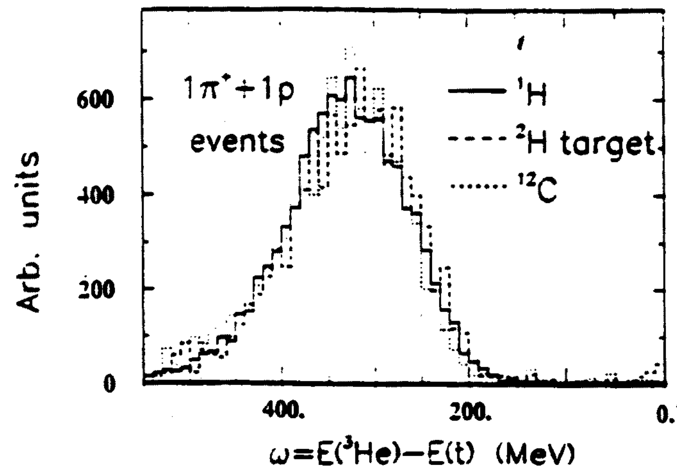

Fig. 3. Energy transfer spectra for $\pi^+ + p$ events on ^{1}H (full line), ^{2}H (dashed line) and ^{12}C (dotted line) targets.

factor effect [12], and the latter one is only due to binding energy effects. The missing mass and missing momentum spectra show indeed that the energy transfer to other target nucleons is less than a few MeV.

The Δ decay channel in $1\pi^+ + 1p$ really selects a quasi-free process where a Δ^{++} created in the nucleus is excited with the same energy transfer and width as on a free nucleon. These events do not contribute to the shift observed in the inclusive spectra.

6. 2p events

For 2p events, a clear Δ bump in the energy transfer spectrum shows up on carbon. This bump is shifted by 100 MeV downwards relatively to $\pi^+ + p$ events (Fig. 4). Contrary to the quasi-free channel, the 2p channel can stretch far below the pion threshold. This phase space effect accounts for part of the shift as shown by cascade calculations [13]. The remaining shift is interpreted as strength concentration in pionic collective states at lower energy transfer, which decay in 2 particle - 2 hole states at lower energy transfer too.

The missing energy spectra on ^{12}C and ^{208}Pb suggest that the contribution of 3 and 4 nucleon processes in the 2p events is small, in contrast with what is observed in real pion absorption where multinucleon processes dominate [14, 15]. This difference is clearly shown in Fig. 5.

As the 2p event yield is large in ^{12}C, these events largely contribute to the low energy part of the Δ resonance. The cascade calculations show

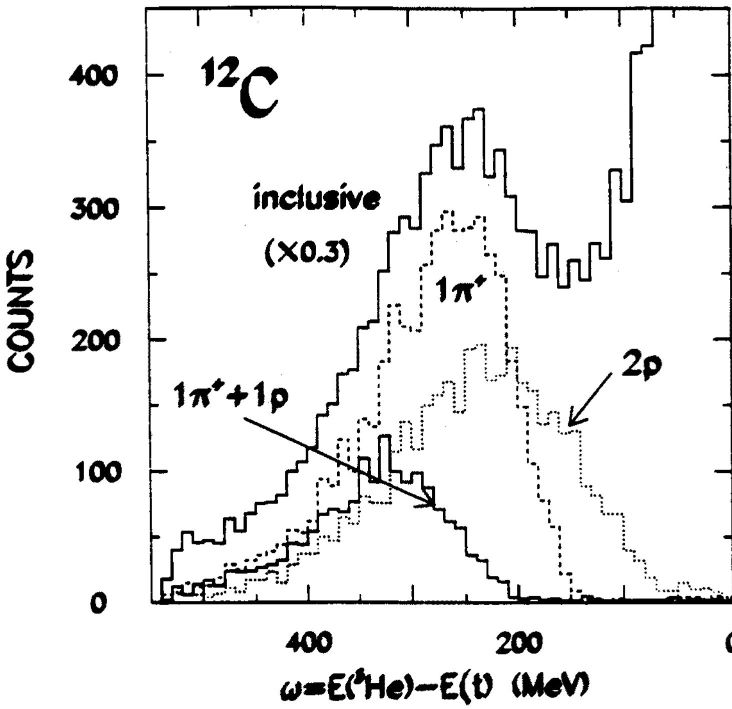

Fig. 4. Energy transfer spectra on ^{12}Ctarget for all events (full line), $\pi^+ + p$ events (lower full line), $2p$ events (dotted line) and π^+ events (dashed line).

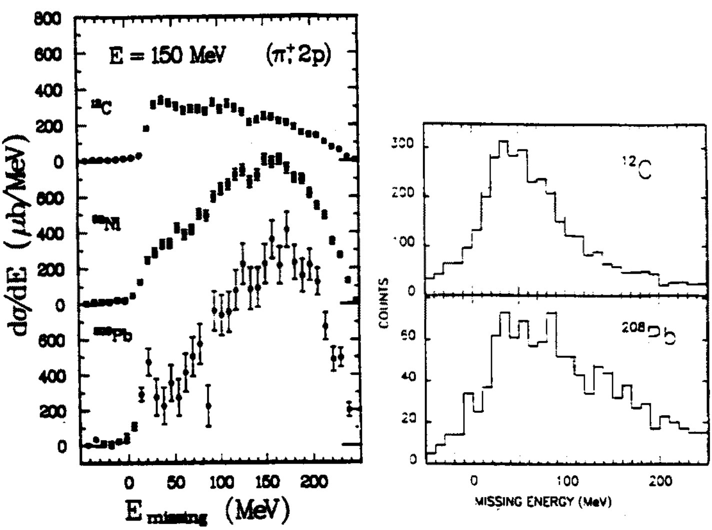

Fig. 5. Missing energy for the $2p$ events in pion absorption (left) at 150 MeV and in (^{3}He, t) at 2 GeV (right).

that the $\Delta N \to NN$ process takes place deeper inside the nucleus than the quasi-free decay : 2p events are thus sensitive to medium effects.

7. π^+ events

Among π^+ events, some correspond to incoherent pion production with one or more undetected knocked out nucleons, but others are expected to come from the coherent pion production.

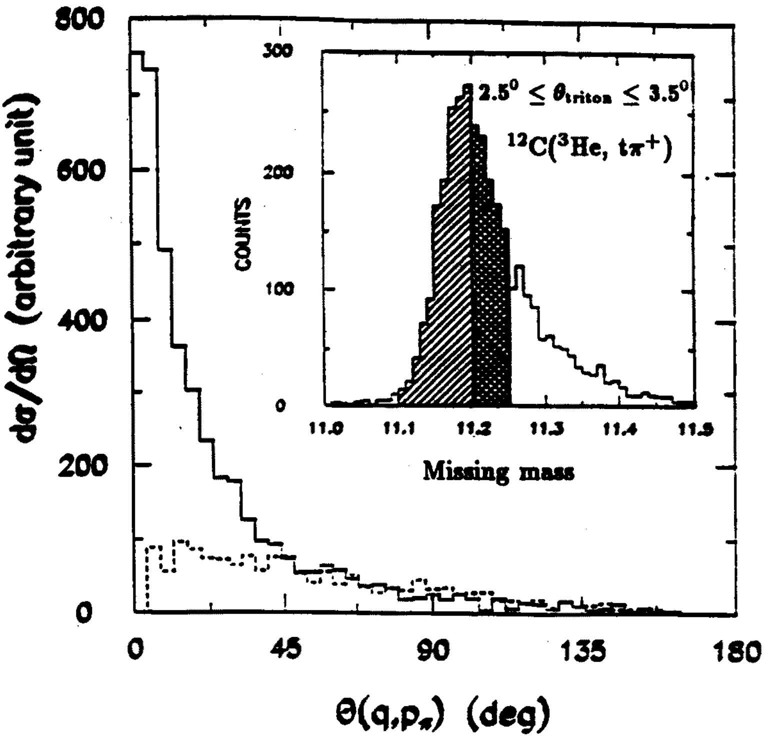

Fig. 6. Angular correlation between the momentum transfer $\vec{q}$ and the pion momentum for $1\pi^+$ events on carbon target with triton angles ranging from 2.5° to 3.5°. Full curve: $1\pi^+$ events with ^{12}C excitation energy below 25 MeV. Dashed curve: $1\pi^+$ events with ^{12}C excitation energy between 25 MeV and 75 MeV. The gates in ^{12}C excitation energy are indicated in the insert figure.

The missing mass spectrum on ^{12}C (Fig. 6, insert) is peaked at lower masses than expected (about 35 MeV lower than expected from cascade calculations for incoherent pion production) [16]. Unfortunately, the g.s.

can not be separated due to the experimental resolution of about 30 MeV. For events with triton angles ranging from 2.5 to 3.5 deg, we can examine the angular correlation between $\vec{q}$ and the momentum of the detected pion, $\vec{p}_\pi$, and specifically cover the small relative angles. Without this gate on triton angles, the angular correlation would be extremely biased as DIOGENE is blind at small triton angles with the result that many coherent pions are lost.

Fig. 6 shows a striking difference between the angular correlation spectrum corresponding to events with carbon excitation energies below 25 MeV and the one corresponding to excitation energies ranging from 25 to 75 MeV. For pions where the ^{12}C nucleus is left in its g.s. or low lying states, the angular correlation between $\vec{q}$ and $\vec{p}_\pi$ is sharply peaked at small relative angles (15^0 FWHM) whereas the latter spectrum is completely flat. Theoretical calculations [17, 18] performed in the last few months reproduce the experimental angular distribution of pions in the target nucleus g.s. region.

The same features appear for the ^4He target but with a broader angular distribution of pions in the g.s. region. This makes the scenario of elastic scattering of the pion in coherent production a more plausible one.

Finally, the energy transfer spectrum on ^{12}C peaks at 230 MeV for pions selected in the carbon nucleus g.s. region, which is about 100 MeV lower than for $\pi^+ + p$ events (Fig. 4). According to Ref. [17], the peak position of the coherent pion component is significantly shifted towards lower excitation energies by the Δ-hole correlations, and coherent pion production is an excellent tool to investigate the longitudinal response in the Δ resonance region.

8. Conclusion

The (^3He, t) coincidence experiment at 2 GeV performed on hydrogen, deuterium, helium, carbon and lead targets has already given some answers to the 70 MeV shift of the Δ peak previously observed in inclusive energy transfer spectra, and the data analysis is still in progress. The present results can be summarized in the following way :

- $1\pi^+ + 1p$ events, detected in DIOGENE in coincidence with the forward emitted triton, select a quasi-free decay of the Δ resonance with the same energy transfer as charge exchange on the free nucleon. They contribute to the high energy part of the resonance.

- 2p events on the carbon target are direct evidence of the coupling of Δ-h states to 2p-2h states. Since created deeper inside the nucleus than $1\pi^+ + 1p$ events, they are affected by medium effects. As shown for the carbon target, their yield is large and they contribute to the low energy part of the resonance. An additional interesting feature is that the missing energy is found to be much smaller on carbon and lead targets than in real pion absorption.

- In $1\pi^+$ events, we find evidence for coherent pions formed in the following way : virtual pions produced in the (^{3}He, t) reaction scatter elastically from the target nucleus and subsequently emerged as real. As expected, the experimental angular distribution of the detected pion is found to be sharply peaked in the direction of the momentum transfer. Theoretical calculations show that coherent pion production is a unique signature of the nuclear pionic mode [17].

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