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Abstract.

The production of Δ in nuclei through charge exchange reactions induced by medium energy light projectiles has been undertaken at Laboratoire National Saturne. The possible existence of a pionic collective mode built on Δ-hole correlations has been proposed to explain medium effects which appeared in inclusive experiments. Using the Diogene 4π apparatus to detect the charged particles, the decay pattern of the Δ-hole states has been separated into its different modes. 3 of them deserve particular attention: the quasi free Δ production, the two nucleon absorption channel and the coherent mode.

Introduction

The Δ(1232) resonance is the simplest excitation of the nucleon. It is strongly connected to the pion since it corresponds to the P_{33} pion nucleon resonance, which is the dominant channel in a very broad energy region. The understanding of the Δ-nucleus dynamics is then one of the most challenging issue in intermediate energy physics. This domain is strongly linked to the heavy ions physics programm which are being pursued at GSI. It is clear that a lot of Δ's are created in the interaction region when two heavy ions collide at GeV per nucleon energies. But before being able to fully describe the collision in all its complexity, we have to understand on a quantitative level how Δ's and pions behave in nuclei. To reach this goal, one should start by the most simple case, that is to put one single Δ at a time in a nucleus and to follow its history.

Δ's can be excited via strong or electromagnetic interactions. The response of the nucleus to these two probes is quite different. While real photon absorption shows a universal response for all nuclei [1], inclusive (e,e') experiments do show a large structure centered at the free Δ peak whose position depends slightly on the momentum transfer [2]. This dependance could be partly explained by the presence of other processes (tail of the quasi elastic peak, contribution of higher mass resonances or non resonant channels). The first (e,e') exclusive data with a nearly 4π detector have just been carried out at MAMI[3]. A extensive program will be done at CEBAF with CLAS.

On the strongly interacting particles side, the real pion play an important role, and the response of the nucleus to the real pion probe has been investigated in great details at pion factories. Exclusive experiments in the pion absorption channel with 4π detector are relatively recent [4]. The total absorption cross section on ^{12}C displays a resonance type stucture which is shifted 35 MeV down in energy and appreciably damped [1]. These effects increase with target mass. This behavior is in sharp contrast with the observations made with charge exchange reactions [5] (CER), which I am going to discuss in detail in this paper. In intermediate energy CER, the spin isospin channel is the dominant one. The exchanged quantum in these reactions is either a virtual π or a virtual ρ. Both of them contribute to the inclusive cross section. They are different in their spin structure. The pion exchange has a longitudinal (L) structure which corresponds to $\vec{S}\cdot\vec{q}$ whereas the ρ exchange is transverse (T) and associated to $\vec{S}\times\vec{q}$. According to theoreticians, attractive correlations would appear in the L channel resulting in a downward shift of the Δ resonance in nuclei, but not in the T channel. The effect of the correlations is a depletion of strength along the real pion dispersion line [6,7]. Such correlations would then not be seen with real pions. The strength is found in two different regions of the ($\vec{q}$,ω) plane, one below the pion dispersion line, the so-called pionic branch and the other above, dominated by Δ-hole states. Because CER probe a region in the ($\vec{q}$,ω) plane below the photon line, they are able to explore the low energy part of the response. Calculations including these correlations and a consistent description of the reaction mechanism and of distortions have been carried out for the (p,n) and the (^{3}He,t) reactions [7,8,9]. They show that about 40 % of the observed shift, i.e. $\sim$ 30 MeV, is due to correlations in the spin longitudinal channel. Projectile excitation has been considered as an alternative explanation for the observed shift [10]. I will first recall the main results of the inclusive experiments. Then I will present in more detail the exclusive measurements which have been set up to separate the different parts of the response and in particular to obtain a clean signature of the pionic mode.

Inclusive reactions

In figure 1 is shown spectra for the (^{3}He,t) reaction at a lab angle of 0 degree. Both spectra exhibit a strong excitation in the region of the Δ resonance. The peak on ^{12}C is shifted 70 MeV down in energy with respect to the free Δ^{++}. This behavior has been observed in all charge exchange reactions, and even more pronouced in reactions induced by ^{40}Ar ions (see figure 2). Complete sets of data ranging from the lightest target to heavy ones (^{208}Pb) exist for (p,n) and (^{3}He,t), but also for polarized projectiles ($\vec{d}$ and $^6\vec{Li}$) and heavy ions (^{12}C, ^{20}Ne and ^{40}Ar) [5]. If one excepts the (p,n) case, the form factor leads to an apparent shift on all targets. Nevertheless, the shift we are talking about is the shift observed when comparing different targets using the same projectile ejectile couple.

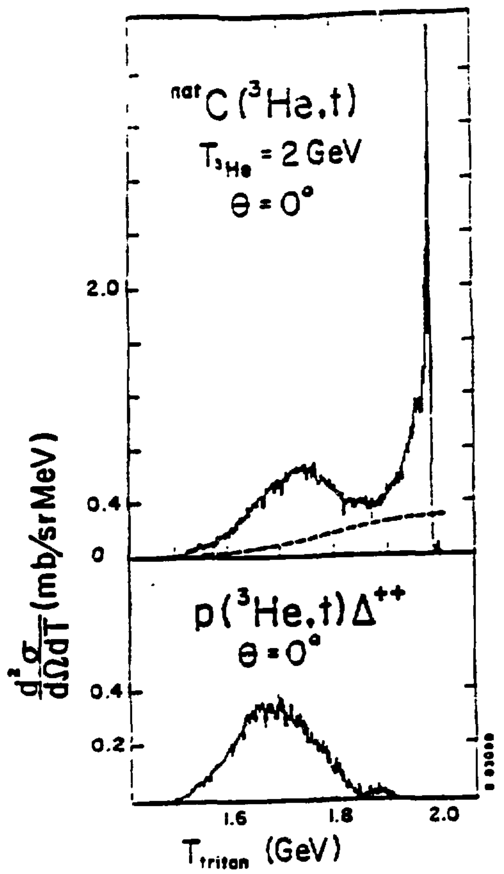


Fig 1. Energy transfer spectra of the (^{3}He,t) reaction taken at 0° on ^{1}H and ^{12}C.

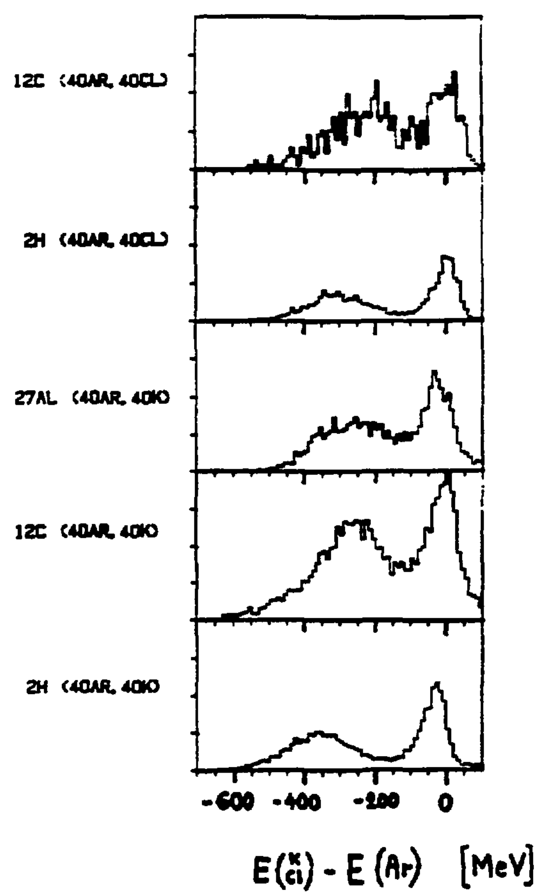


Fig 2. Energy transfer spectra of the (^{40}Ar,^{40}K) and (^{40}Ar,^{40}Cl) reactions taken at 0° and 780 MeV per nucleon on different nuclear targets.

Decay of Δ-hole states

A recent experiment Saturne [12] on the decay of the Δ-hole states in nuclei has helped clarifying the situation. In such an experiment charged particles are detected in the 4π detector Diogene in coincidence with a forward triton emerging from the (^{3}He,t) reaction. I will first present the experimental aspect before discussing three specific processes that we have so far carefully analysed.

The experimental set-up.

The forward triton was taken as the trigger. Then the charged pions and/or protons were detected in a large acceptance detector (85% of 4π). The detecting triton arm consisted of a flat field dipole magnet of about 2 Tesla.meter bending power, two scintillation hodoscopes for triggering purposes and on-line background deuterons rejection and two drift chambers 1.5 m apart for precise momentum and angular measurements. The covered ranges were respectively 1.4 to 2.0 GeV in energy and -1.0 to 4.0 degrees in horizontal angle in a single exposure. Two helium bags were used to reduce the multiple scaterring , leading to a typical energy resolution on the triton energy of about 15 MeV and a angular resolution on the scattering angle of 0.5 mrd. The cylindrical Diogene dectector consists of ten trapeze-shaped drift chambers operating with a 4 bar Argon Ethane mixture in a 1 Tesla solenoidal field. Using the time and amplitude informations of the hit wires, particle identification and momentum vector measurements are made for particles with polar angles between 20 and 132 degrees over the full azimuthal angular range. The FWHM momentum resolution is 18 % for protons and 10 % for pions, whereas polar and azimuthal angles are measured with a precision of a few degrees. Another important parameter is the energy threshold, 15 MeV for pions and 35 MeV for protons slightly angle dependent. The experiment were performed on liquid hydrogen (1.3 g/cm^2), liquid deuterium (3.1 g/cm^2) liquid helium 4 (1.25 g/cm^2), carbon (0.36 g/cm^2) and lead (1.15 g/cm^2) with typical beam intensities of 10^5 to 10^6 particles per spill. The energy calibration was carefully examined. On light targets the check on different type of event, using missing mass and total kinetic energy balance, was made to keep the absolute energy calibration uncertainty down to 5 MeV. On heavy targets, the Gamow Teller transition was used to do the calibration.

I will mostly discuss in this paper results on ^{1}H, ^{2}H and ^{12}C. Data on ^{4}He and ^{208}Pb are more recent and so far not fully analysed. The first informations which come out of the analysis is the ratio of the different types of events. 6 types of events were recorded in these experiments, nothing in the 4π detector, one single pion, one single proton, one pion and one proton, two protons and three protons. I will discuss in this paper only three of them. I will neither discuss one proton which corresponds clearly to incomplete events nor present the three protons contribution because it represents only a small fraction ($\sim 1\%$) of the inclusive cross section and is subject to important acceptance corrections.

The quasi-free process

This process corresponds to events where both the proton and the positive pion from the Δ^{++} decay are detected in Diogene. The energy transfer spectra on all targets is quite similar in shape and position (see figure 3).

A look at the missing energy spectra tells us that the recoiling nucleus is in its ground state or in a very low energy state (less than a few MeV). The $(\pi^+ + p)$ invariant mass spectrum on ^{12}C is shifted to lower mass by approximately 20 MeV (see figure 4) and can be attributed to trivial mean field effects. This contribution is the quasi free process. It corresponds , as shown by cascade calculations [14], to Δ's formed in the surface of the nucleus which are then not sensitive to correlations.

The two nucleon absorption process

An other important channel is the absorption channel, i. e. the channel in which the exchange quantum is absorbed and gives its momentum $\vec{q}=\vec{k}(^3\text{He})-\vec{k}(\text{t})$ and energy $\omega=E(^3\text{He})-E(\text{t})$ to several nucleons. A particularly interesting one is the two nucleon absorption channel which leads to the emission of two energetic protons which are easily detected in the 4π detectors. It represents a sizeable fraction of the events and is clearly seen on all targets, from ^{2}H to ^{208}Pb (see figure 5), although rather weakly on ^{2}H. In the ^{12}C(^{3}He,t2p) reaction, it appears as a broad bump, whose position is shifted 100 MeV down in ω with respect to the quasi-free peak position. Its widths is also larger, $\sim$ 200 MeV, compared to the other processes discussed here. The importance of this shifted contribution is a natural explanation for the shift observed in the inclusive spectrum.

On deuterium, the spectrum does not show any peak. This is probably due to the low density of the deuterium nucleus. The probabilty for the Δ to interact with the other nucleon is small and it mainly decays as π+N. In the real pion induced reaction π^++d$\rightarrow$pp , a clear resonance is observed for pion absorption; however, it represents only 5% of the total cross section, The relative contribution of this resonant absorption is also probably cut down by the form factor effect, which does not exist in the case of the real pion absorption process.

The 2p events for ^{12}C exhibit a clear Δ. The energy balance and missing mass spectra indicate that the mean residual kinetic energy is less than a few MeV. This suggests that the contribution of three and four nucleon processes in the 2p events is small. For ^{12}C, the decay into the 2p channel is thus direct evidence for the coupling of Δ-hole states to 2p-2h states. We interpret the shift in ^{12}C between the two types of events, quasi-free and 2p, as a result of a competition between the two decay channels. At low ω, the Δ cannot decay into $\pi^+ + p$, because of the strong threshold effect for pion emission. The Δ resonance is a P-state for the pion-proton relative motion, and this gives a $(p_\pi)^3$ dependance on the pion center of mass momentum. The 2p channel does not have such a threshold effect and this channel will therefore be sensitive to the part of the Δ-hole states that is shifted down in energy. This interpretation is supported by

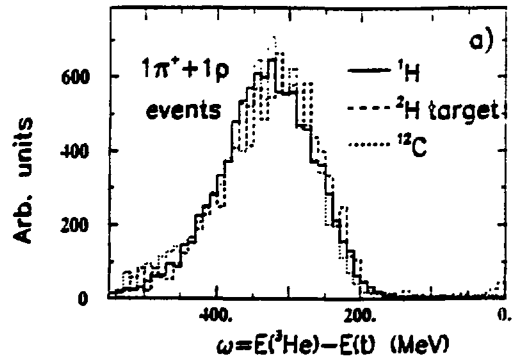


Fig 3. Energy transfer spectra obtained for π^++p events are shown for ^{1}H (full line), ^{2}H (dashed line) and ^{12}C (dotted line) targets. The spectra have been arbitrarily normalized in order to be compared.

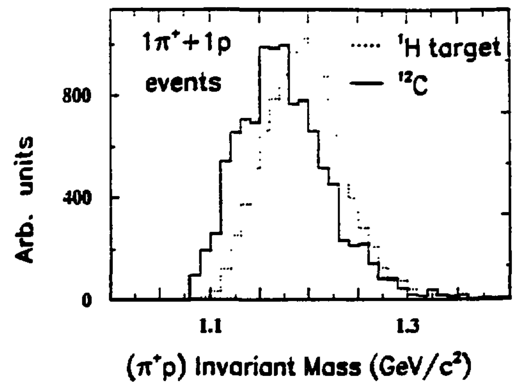


Fig 4. (π^++p) invariant mass spectra for the reaction (^{3}He,tπ^+p) on hydrogen and carbon nuclei. Note the modification of the free Δ position due to the (^{3}He,t) form factor.

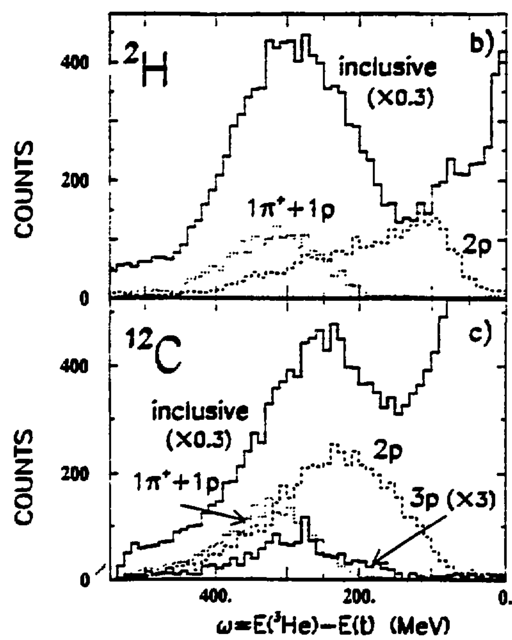
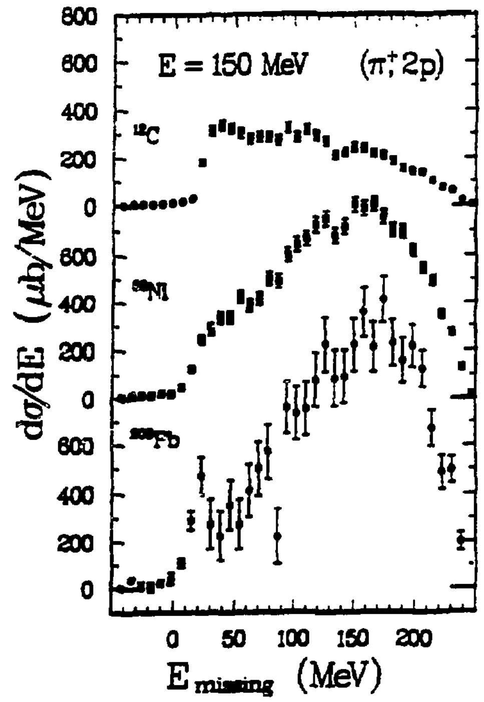


Fig 5. Top: Energy transfer spectra for the deuterium target for π^++p (dotted line) and 2p events (dashed line) are compared to the inclusive spectrum (full line). Bottom: Energy transfer spectra for all events (full line), π^++p (dotted line), 2p (dashed line) and 3p events (lower full line) are shown for the ^{12}C target.



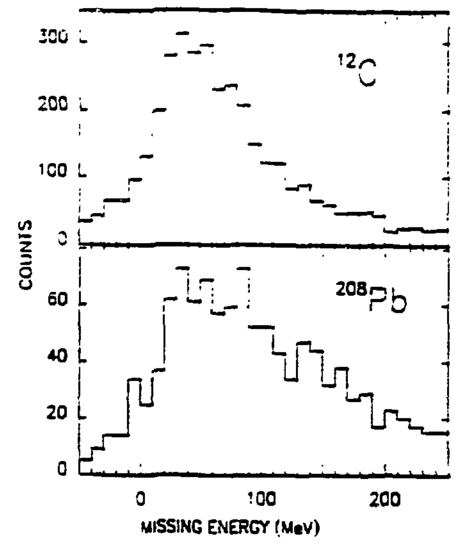


Fig 6. Missing energy spectra for the 2p channel. The left part shows the real pion reaction on ^{12}C, ^{90}Zr and ^{208}Pb at 150 MeV incident energy. On the right is shown the corresponding spectra for the virtual pion.

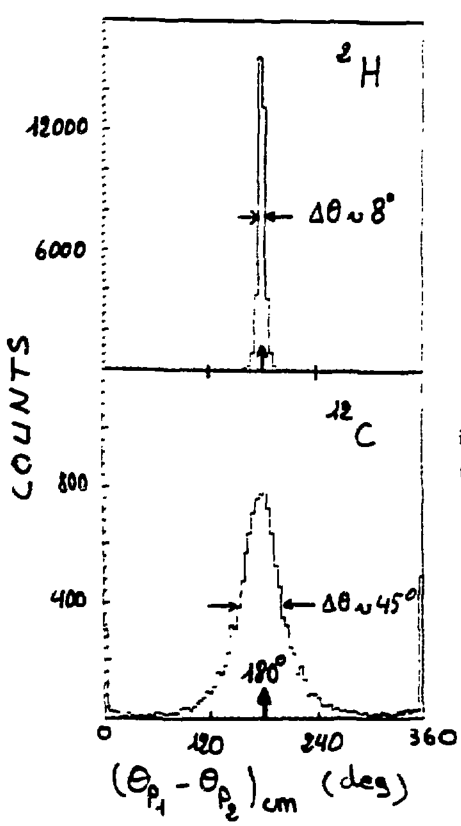


Fig 7. Angular correlation between the two protons in the quasi deuteron frame (see text for definition) for the reaction (^{3}He,t2p) on ^{12}C at 2 GeV.

simple cascade calculations [14].

The 2p spectrum shows another interesting feature. The spectrum is found to stretch into the dip region between quasielastic and Δ peak. The kinematics for the two protons suggest a strong coupling of the Δ-hole states to 2p-2h states and we would therefore conclude that such configurations are important in the dip region.

An other very important variable is the missing energy. Summing up the detected energy, such spectra can be formed. They show that for a large fraction of the 2p events, the remaining nuclear system is left in a very low excitation state (typically 10 MeV). This is in extreme constrast to the findings of the real pion absorption [4]. This is demonstrated in figure 6, where missing energy spectra are compared for (π,$2p$) and ("π",$2p$) reactions. The kinetic energy of the residual nucleus is very small (of the order or less than 1 MeV) and the spectrum therefore shows the excitation energy. In real pion absorption multi-nucleon processes play a much larger role. The Δ^{++} decay into two protons, through NΔ $\rightarrow$NN, seems in this respect a simpler process.

With such a detector, much more detailed information is in fact available. For example the angular correlation between the two protons in the quasi deuteron frame (defined by a virtual pion + a pn pair at rest) is peaked at 180 degrees (see figure 7). The width of the angular correlation on the deuterium is very small ($\sim 8^o$) and given by the detector resolution. For ^{12}C the width is larger, as one would expect from Fermi motion effects, but still reasonably small ($\sim 46^o$) indicative again of the weakness of multi-nucleon processes (more than two) and well reproduced by cascade calculations [13] which do show actually that the width is almost entirely given by the Fermi motion. Even more detailed informations could be obtained from the angular distributions of protons. unfortunately, the extraction of reliable, acceptance cut corrected data is difficult and presently not finished.

The coherent pion process

The last class of events I would like to discuss in detail is the 1 π^+ one. It is defined by a single positive pion detected in Diogene. Figure 8 shows the corresponding ω spectrum as compared to $\pi^+ + p$ and 2p events. Again, one notes a relatively narrow width. The peak position (ω=250 MeV) is intermediate between the quasi-free and the 2p absorption peaks.

Among these events, there are certainly incomplete ones, i. e. events for which either a proton or a neutron was not seen by the detector, like for example quasi free decay of a Δ^+ or of a Δ^{++} with the proton in the Diogene dead zone. A particular interest has been brought to the process where the transferred quantum ($\vec{q}$,ω) is transmitted through the nucleus and materializes as an on-shell pion leaving the target nucleus in its ground state or in general in a low lying excited state. A similar process has already been considered in coherent photoproduction of π^0 on nuclei [15]. Although of great theoretical interest, its experimental difficulty has precluded from obtaining precise

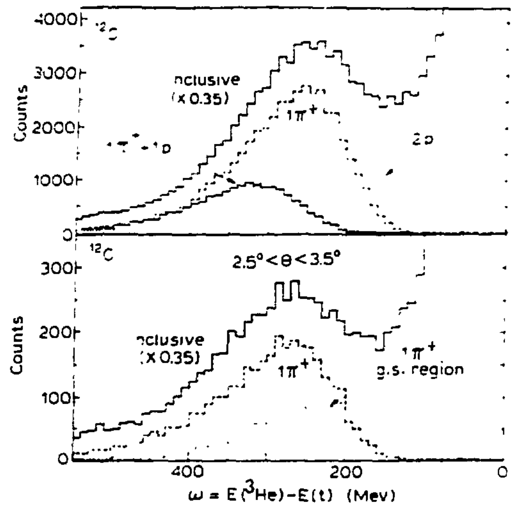


Fig 8. Energy transfer spectra for different channels. Top: spectra integrated over the triton angles are given for inclusive events (full line). $1\pi^+$ (dashed), ($\pi^+ + p$) (full) and 2p events (dotted). Bottom: Only events with $\Theta_{triton} \in [2.5^\circ - 3.5^\circ]$ are shown. Inclusive (full line), $1\pi^+$ (dashed), $1\pi^+$ with a gate on the ^{12}C ground state region.

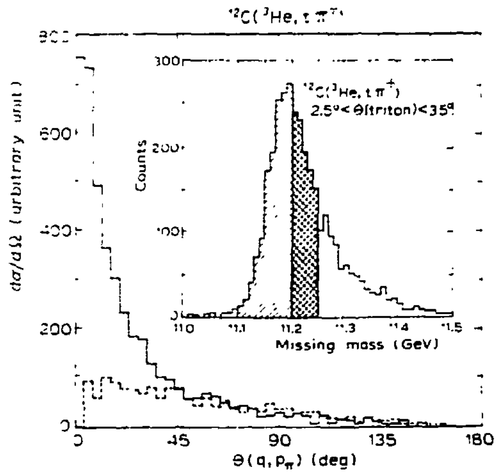


Fig 9. The angular correlation between the transferred quantum $\vec{q}$ and the momentum of pions with different conditions on the missing mass for the $1\pi^+$ events with $\Theta_{triton} \in [2.5^\circ, 3.5^\circ]$. The gates on the missing mass spectrum are indicated in the insert. The g.s. mass of ^{12}C is 11.175 GeV and the gate around the g.s. includes events with missing mass less than 11.200 GeV (full drawn curve in angular correlation spectrum). The other gate includes events in the 11.200 GeV to 11.250 GeV interval (dashed line). The first particle emission threshold corresponds to a missing mass of 11.191 GeV.

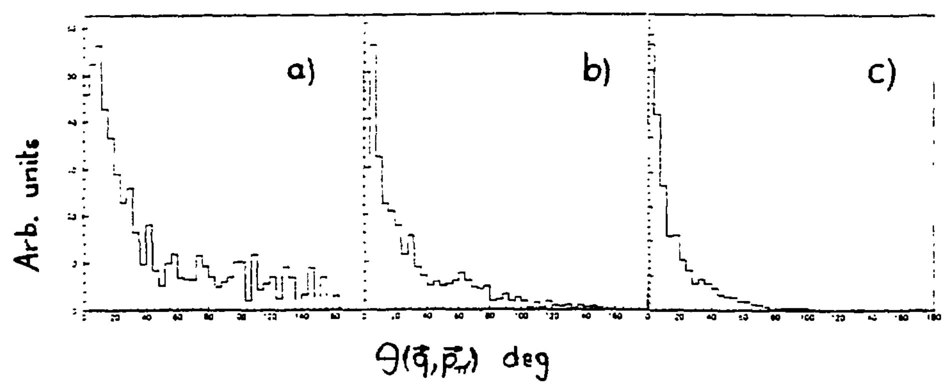


Fig 10. Angular correlation between the transferred quantum $\vec{q}$ and the momentum of pions for different energy transfer bins. The gate on the missing mass has been put on the ^{12}C ground state region. a) 140 MeV$\leq \omega \leq$210 MeV. b) 210 MeV$\leq \omega \leq$280 MeV. c) 280 MeV$\leq \omega \leq$350 MeV.

experimental data. With charge exchange reactions, the pion is charged and then much easier to measure with good angular and energy resolutions. Another important point is that the coupling at the first Δ-hole vertex is transverse in the case of the photon whereas it is a mixture of a longitudinal (π exchange) and a transverse component (ρ exchange) in charge exchange reactions. A simple examination of the structure of the production and emission vertices gives a yield proportional to $\vec{q} \cdot \vec{p}_\pi \mathcal{F}(\vec{q} - \vec{p}_\pi)$ for a pure longitudinal probe. $\mathcal{F}(\vec{q} - \vec{p}_\pi)$ is the target nucleus form factor. The angular distributions of pions is then forward peaked with respect to $\vec{q}$ On the other hand, for a transverse probe, the structure $\vec{q} \times \vec{p}_\pi \mathcal{F}(\vec{q} - \vec{p}_\pi)$ gives an angular distribution peaked at 25^o. For that reason, the longitudinal contribution is expected to dominate over the transverse one, so that the coherent pion channel can be used to constrain the theory. How does it appear in the data? Figure 9 (insert) shows the missing mass spectrum for the ^{12}C nucleus. The gate on the triton angle is set in such a way that the corresponding $\vec{q}$ vectors point to phase space region where the Diogene detection efficiency is close to 100 %. The estimated missing mass resolution is $\sim$ 25 MeV and does not allow a clear separation of the ground state contribution. However, when selecting a broad energy region ($E^* \leq 25MeV$), the correlation spectrum shows a strong peaking for a relative angle of 0 (see figure 9). On the contrary, when gating for high excitation energies, the angular distribution is smooth and structureless. This forward peaked angular distribution is considered as a strong evidence for the coherent process. The widths measured on ^{12}C and ^{4}He nuclei are 14^o and 20^o respectively. An additional interesting point is the following. When selecting the ground state region, the ω spectrum peaks at ω=235 MeV independantly of the triton angle. This value is slightly lower than the value for the total $1\pi^+$ spectrum (see figure 8). On the contrary, when gating on events in the ^{12}C continuum, a clear angle dependance is seen , as one expects from a quasi free process. Monte Carlo calculations including the known detector acceptance and the Fermi momentum of nucleons in the target nucleus shows actually that the angular distribution of pions from quasi-free Δ decay is much wider and that no contribution is expected in the target ground state region. From all these reasons, it is claimed that evidence for coherent pions is demonstrated. A virtual pion propagates coherently in the target nucleus along the $\vec{q}$ direction until it materializes and reaches the dectector. In the (^{3}He,t) reaction, $\vec{q}$ and ω can be varied independantly, so that one can consider the reaction as a tagged virtual pion source. Figure 10 shows the angular distributions of the coherent pions for different slices in ω. A clear ω dependance is seen. In particular one notes the very narrow distribution ($\sim 8^o$ at half maximum) in the slice $280MeV \leq \omega \leq 350MeV$, corresponding to an average pion kinetic energy of 175 MeV. Monte Carlo calculations indicate that these distributions are very little affected by acceptance cuts.

The extrapolated total yield for the coherent pion mode is of the order of 5 %. This observation together with the isospin conservation rule which forbids the projectile excitation make this process unique to investigate the pionic mode.

Recent theoretical calculations on this coherent mode are being carried out by at least four different groups. Two of them have definite predictions. F. Osterfeld et al [16]. produce angular distributions in fair agreement with the data. They also claim that the position of the peak in ω and the total yield of the coherent process may give informations on the short range part (the $g'_{\Delta\Delta}$) of the residual Δ-hole interaction. E. Oset et al [10].probably overestimate the coherent pion yield by a sizeable factor, but the dependance of the pion angular distribution width with respect to ω is fairly good. T. Ericson [17] pointed out recently to the importance of this process to obtain informations on the pion nucleus dynamics in a new kinematical regime.

Experimental outlook and summary

An important program to further investigate the coherent process is actually underway. This summer, an exploratory measurement with limited phase space acceptance is planned at LNS with the SPES4 spectrometer using the (^{3}He,tπ^+) reaction. In the mid future, a proposal to build a large solid angle detector system in coincidence with SPES4 at Saturne has been submitted. It consists of a large gap C-magnet with a magnetic field oriented perpendicularly with respect to the incident beam, equipped with multiwire proportional chambers and scintillation hodoscopes. The resolution which is aimed at with this new instrument, of the order of a few MeV, will permit a clear separation of the ground state for light and medium nuclei. A full program including the use of ^{3}He, $\vec{d}$, $^6\vec{Li}$ and ^{12}C beams is under consideration. By varying the experimental conditions, angle, incident energy and projectile, we shall have a virtual pion beam with an adjustable offshellness probing the nucleus at different densities.

In summary, I have presented results of experiments in which the interaction with the nucleus of the simplest and best known isobar, the $\Delta(1232)$, was studied. Several processes compete to build to nuclear response. Two of them deserve particular attention. The absorption process and the coherent pion mode. The former provides a natural shift and proofs that the coupling of Δ-hole states to 2p-2h configurations is very important in the context of the $\pi\Delta N$ dynamics. Thanks to the strong selectivity of the later, new informations could be obtained on the pionic mode in nuclei.

Acknowledgements

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