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Δ DECAY AND ABSORPTION IN NUCLEI

S. ROUSTEAU[1], B. RAMSTEIN [1],
T. HENNINO[1] et al...

[1] IPN - IN2P3 (CNRS), 91406 Orsay Cedex, France

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S. Rousteau(1), B. Ramstein(1), T. Hennino(1), J.L. Boyard(2), R. Dahl(4), C. Ellegaard(4), C. Gaarde(4), J. Gosset(3), J.C. Jourdain(1), M. Kagarlis(4), J.S. Larsen(4), M.C. Lemaire(3), D. L'Hôte(3), H.P. Morsch(2), M. Österlund(5), P. Radvanyi(2), M. Roy-Stephan(1), T. Sams(2,4), M. Skousen(4), W. Spang(2), P. Zupranski(1,2,6)

(1) IPN, IN2P3(CNRS) 91406 Orsay Cedex, France
(2) LNS, IN2P3(CNRS), DSM(CEA) CE-Saclay, 91191 Gif-sur-Yvette Cedex, France
(3) DAPNIA/SPhN, CE-Saclay, 91191 Gif-sur-Yvette Cedex, France
(4) Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
(5) University of Lund, S-22362 Lund, Sweden
(6) Soltan Institute for Nuclear Studies, 00681 Warsaw, Poland

Abstract

We present data on the decay and absorption of the Δ resonance excited in ^1H, ^2H, ^4He, ^{12}C and ^{208}Pb by the (^3He, t) reaction at 2 GeV incident energy. The quasi-free Δ decay and the absorption process on a (p,n) pair are clearly observed. We also find evidence for coherent pion production.

1. Introduction

Since 1982, a large program has been carried out at Laboratoire National Saturne to study the Δ resonance excited in nuclei through charge exchange reactions.

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).

At Saturne, inclusive (^{3}He, t), ($\vec{d}$, 2p[^{1}S$_0$]), ($^6\vec{Li}$, ^{6}He) and heavy ion charge exchange reactions at intermediate energies (0.6 - 1.1 GeV/nucleon) were performed using SpesIV 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. Moreover, the Δ width is found to be independent of the target (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].

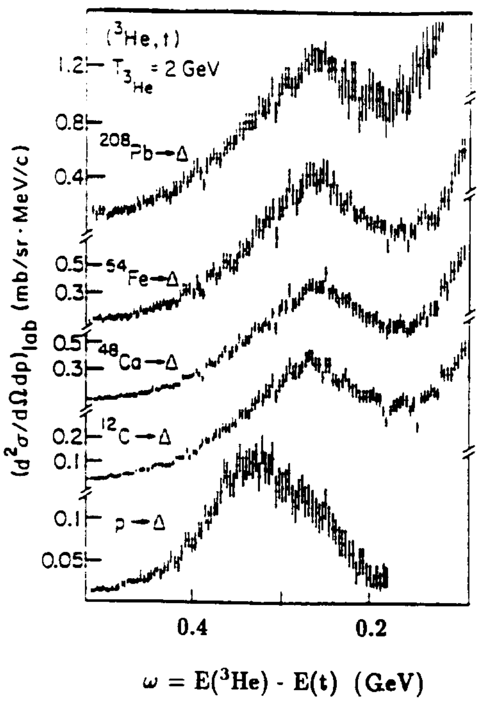

Fig.1 : Energy transfer spectra in (^{3}He, t) reaction at 2 GeV on hydrogen and on nuclei from ^{12}C to ^{208}Pb.

Theoretical calculations show that the shift of the Δ peak position has two different origins. The first one comes from mean field effects (Δ binding), Fermi broadening combined with the steep (^{3}He, t) form factor. These effects account for ~ 40 MeV of the shift, leaving 30 MeV unexplained. This latter part is thought to be due to Δ-hole correlations in the spin longitudinal response where the Δ hole interaction is attractive [4, 5, 6]. On the contrary, no shift is expected in the spin transverse response since the effective interaction in this channel is weakly repulsive. Another contribution to the shift is due to Δ excitation in the projectile [7].

In order to elaborate further on these effects, the decay and absorption modes of the Δ-hole states have been investigated at Saturne by performing (^{3}He, t) coincidence experiments at 2 GeV with a "4π" detector called DIOGENE.

2. Δ decay and absorption modes

The following decay and absorption channels of the Δ resonance in nuclei are expected :

- **Quasi-free decay** : in this process, the Δ does not interact with other target nucleons.

$$\Delta \rightarrow \pi + N$$

- **Absorption process** : the final state consists of two nucleons without any pion.

$$\Delta + N \rightarrow N + N$$

- **Coherent pion production** : the exchanged virtual pion propagates through the nucleus coherently and then 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 forward peaked around the momentum transfer direction.

$$A_{g.s.}\ \pi_{virtual} \rightarrow A_{g.s.}\ \pi_{real} \quad (A_{g.s.} = \text{target nucleus in the ground state})$$

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

In the (^{3}He, t) experiment at 2 GeV bombarding energy (Fig.2), the charged particles (pions and/or protons) resulting from Δ deexcitation are detected in the large acceptance detector DIOGENE, in coincidence with the forward scattered triton [8]. A (p,n) experiment at 800 MeV incident energy has also been performed at KEK [9].

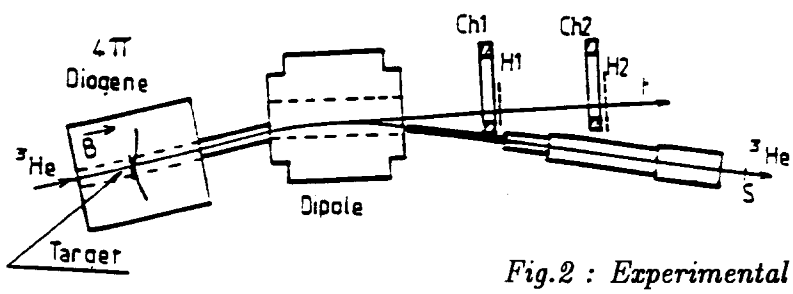

Fig.2 : Experimental set-up.

The detecting arm for tritons consists of a dipole magnet (L_{magn}=1.33 m) operating at 1.9 T, and two sets of drift chambers [10] which allow energy and angle measurements in the range [1.4, 2.0] GeV and [0, 4] deg respectively. The angular opening is -20 to 70 mrad in the horizontal plane and ± 14 mrad in the vertical plane. Two helium bags are used to reduce multiple scattering. The triton energy resolution, which has been recently revalued, amounts to 25 MeV for solid targets and 35 MeV for liquid targets (FWHM), and the angular resolution is about 0.5

mrad (FWHM).

Originally built for nucleus-nucleus collision studies, the cylindrical "4π" detector DIOGENE consists of 10 trapezoidal drift chambers in a 1 Tesla longitudinal magnetic field [11]. Combination of track reconstruction and pulse height analysis allows particle identification and momentum vector measurement for particles with a polar angle between 20^0 and 132^0 without azimuthal angular cuts. The momentum resolution (FWHM) is typically 10% for pions and 18% for protons, 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 with the following purposes. On ^{1}H target, the only possible decay channel is the free decay ($\Delta^{++} \rightarrow \pi^+ +$ p). Therefore, the measurement of both energy and angle of the two decay products gives an overdetermination which allows to check DIOGENE calibration. A comparative analysis on ^{2}H, ^{4}He, ^{12}C and ^{208}Pb targets gives information about the Δ decay dependence on nuclear density. All data have not been fully analysed yet, especially on ^{2}H and ^{208}Pb targets.

Events are classified according to different types. The rates of the different event types measured in DIOGENE in coincidence with a forward emitted triton are shown in Table 1. These events correspond to the Δ peak, i.e. 140 MeV $< \omega =$ E(^{3}He) - E(t) $<$ 600 MeV.

Event type	^{1}H	^{4}He	^{12}C	^{208}Pb
none	20.5	23	30	38.8
$1\pi^+ + 1p$	36	8.2	6	2.4
$1\pi^+$	31	27	18	11
$1p$	5	18.5	24	32.5
$2p$	2	15.8	13	7.1
$3p$	0.0	1.3	1.4	0.5
others	5.5	6.2	7.6	7.7
total	100.0	100.0	100.0	100.0

Table 1 : Percentage of the different types of events measured in DIOGENE in coincidence with the forward scattered triton for ^1H, ^4He, ^{12}C and ^{208}Pb targets. A gate is put on energy transfer (140 MeV $< \omega <$600 MeV) to select events in the Δ peak.

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 originate from the liquid hydrogen target windows.
On ^{4}He, ^{12}C and ^{208}Pb targets, $\pi^+ + $ p event rate drops as compared to ^{1}H, because 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 since the absorption process is likely to involve several nucleons.

In the remaining, we focus on three event types with low missing energy : $\pi^+ +$ p events to investigate the quasi-free Δ^{++} decay, 2p events to study the absorption process on a (p,n) pair, and π^+ events in which we expect to find indications of coherent pions.

4. $\pi^+ +$ p events

For $\pi^+ +$ p events, energy transfer spectra on ^{1}H, ^{2}H, ^{4}He, ^{12}C and ^{208}Pb targets are 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 the one hand, the invariant mass for ^{1}H is peaked 40 MeV lower than the free mass value. This is explained by the (^{3}He, t) form factor effect [12]. On the other hand, the invariant mass for ^{12}C is shifted by 25 MeV towards lower values as compared to hydrogen target, which 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.

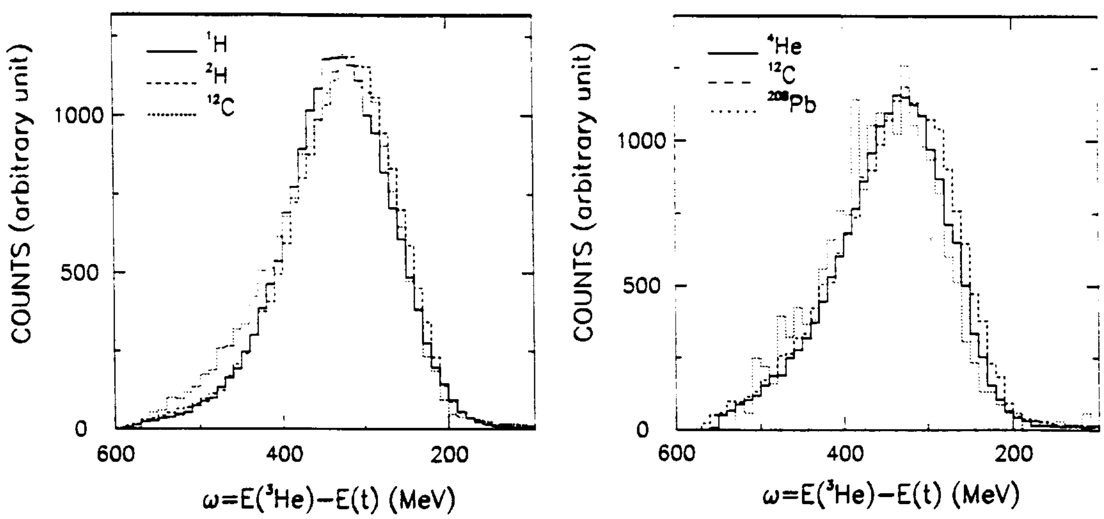

Fig.3 : Energy transfer spectra for $\pi^+ + p$ events on ^1H, ^2H, ^4He, ^{12}C, and ^{208}Pb targets.

The Δ decay channel in $\pi^+ + p$ 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.

5. 2p events

For 2p events, on ^{4}He, ^{12}C and ^{208}Pb targets, a clear Δ bump in the energy transfer spectrum shows up, and their yield is large. For ^{12}C, 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 the major part of the shift as shown by cascade calculations [13]. An additional contribution to this shift may result from strength concentration in pionic collective states at lower energy transfer, which decay in 2 particle - 2 hole states.

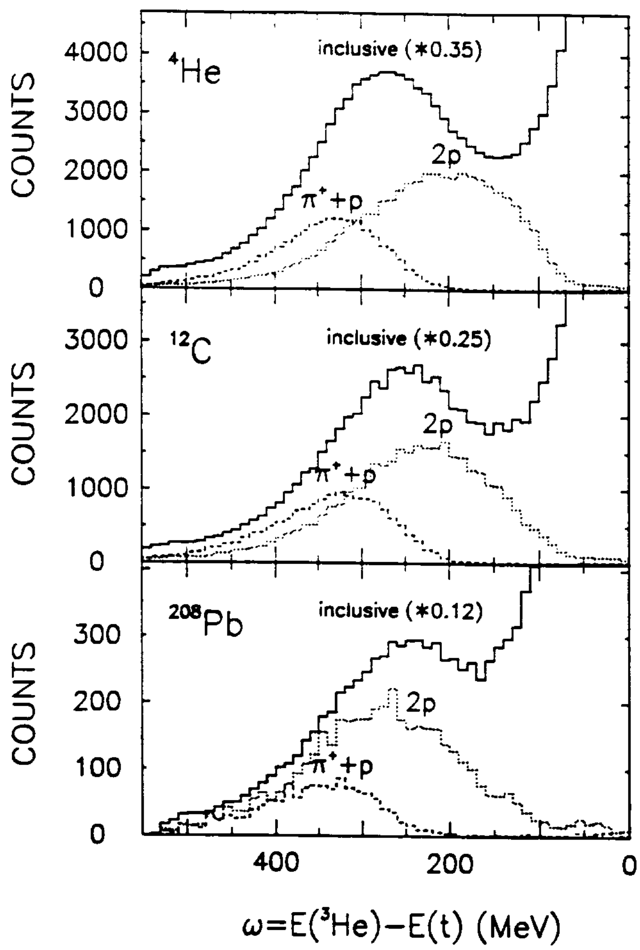

Fig.4 : Energy transfer spectra for $\pi^+ + p$ events (dashed line) and 2p events (dotted line) on ^{4}He, ^{12}C, and ^{208}Pb targets are compared. The full line curve represents the energy transfer spectrum for all events (inclusive).

As shown in Fig.4, the Δ peak shift between $\pi^+ + p$ and 2p events decreases with the target mass. This feature can be qualitatively explained by multiple scattering in the nucleus which is all the more likely as the energy transfer is low and the nucleus is heavy. Therefore, as the target mass increases, more and more protons are lost in the low energy transfer region, and initial 2p events become 1p or none events.

6. π^+ events

Among $1\pi^+$ events, some arise from incoherent processes, such as π^+n or π^+p quasi-free decay events where the neutron is not measured or the proton has not been detected because of the detector acceptance, or such as projectile excitation events ($\Delta^+ \rightarrow$ n + π^+). A significant fraction of π^+ events is expected to come from the coherent process.

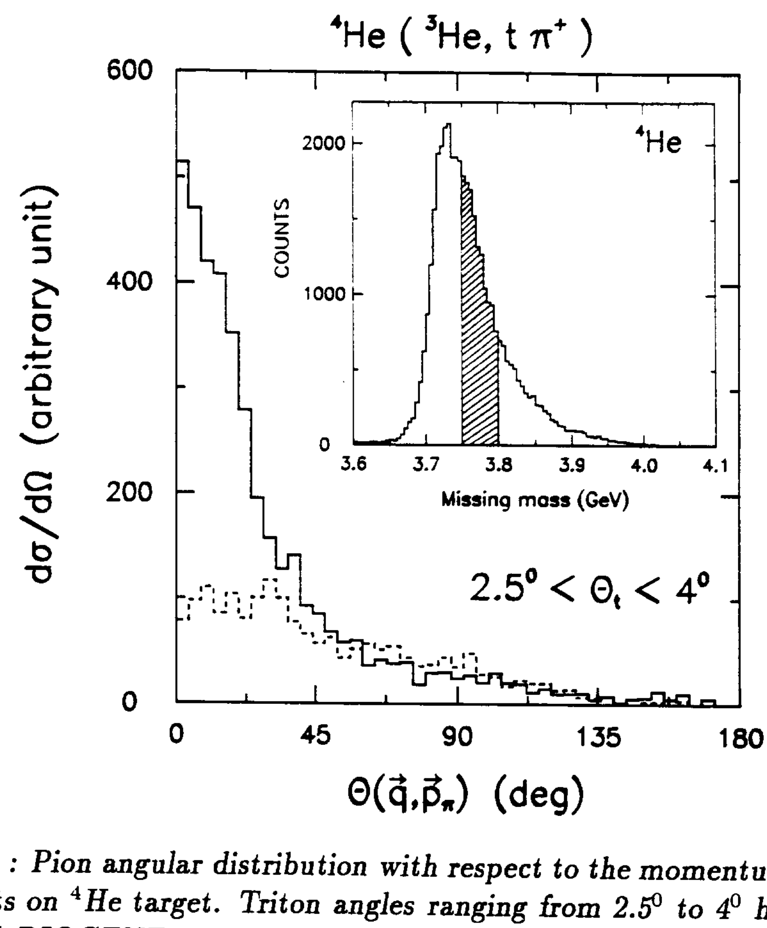

Fig.5 : Pion angular distribution with respect to the momentum transfer $\vec{q}$, for $1\pi^+$ events on ^{4}He target. Triton angles ranging from 2.5^0 to 4^0 have been selected to avoid DIOGENE angular cuts. Full curve : $1\pi^+$ events with missing mass below 3.75 GeV. Dashed curve : $1\pi^+$ events with missing mass between 3.75 GeV and 3.80 GeV. The gates in missing mass are indicated in the insert figure.

The missing mass spectrum on ^{4}He (Fig.5 insert) is peaked lower than what is expected from cascade calculations with only incoherent pion production [14]. This strength concentration around ^{4}He ground state is a first indication of the coherent pion production for which a real pion is emitted and the target nucleus is left in its ground state. Unfortunately, the experimental resolution of about 45 MeV in missing mass is not good enough to isolate the ground state.

To study the angular distribution of the detected pion momentum $\vec{p}_\pi$ with respect to the momentum transfer $\vec{q}$, two types of pions are compared : they consist of π^+ events corresponding to missing masses respectively below 3.75 GeV ("pions around the g.s."), and between 3.75 and 3.80 GeV ("pions above the g.s."). As DIOGENE is blind at small angles (no particle is detected below 20^0 in the laboratory), we plot the pion angular distribution for triton angles ranging from 2.5^0 to 4^0. With this choice and for a 250 MeV energy transfer, $\vec{q}$ direction is out of DIOGENE angular dead zone and we can specifically cover small relative angles between $\vec{q}$ and $\vec{p}_\pi$.

Fig.5 shows a striking difference between the angular distributions of pions "around the g.s." and "above the g.s." on ^{4}He target. The angular distribution of pions "around the g.s." is sharply peaked at small relative angles (23^0 FWHM), whereas the other one is completely flat. On ^{12}C, we find the same features and the angular distribution of pions in the g.s. region is narrower (14^0 FWHM).
Recent theoretical calculations [15, 16] for coherent pion production account for the experimental angular distribution of pions in the g.s. region.

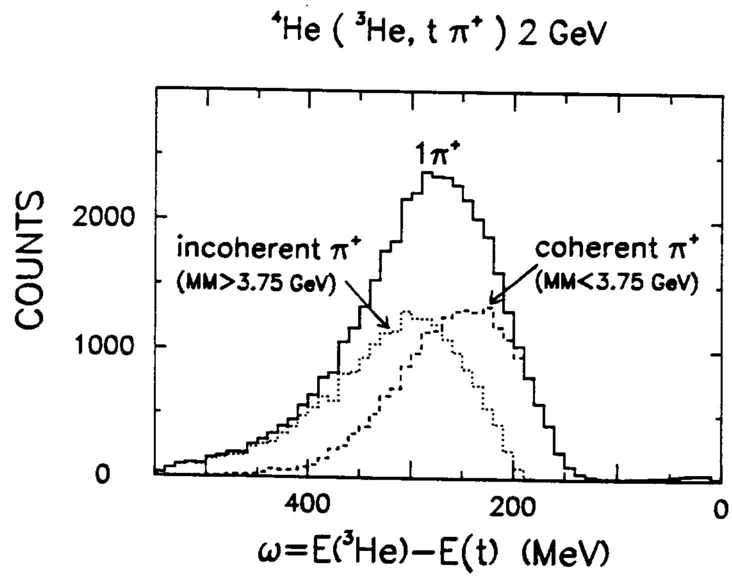

Fig.6 : Energy transfer spectra on ^{4}He target, for all $1\pi^+$ events (full line), for pions around ^{4}He g.s. (dashed line), and for pions with missing mass above 3.75 GeV (dotted line).

Finally, energy transfer spectra on ^{4}He and ^{12}C peak respectively at 240 MeV and 230 MeV for pions selected in the target nucleus g.s. region (Fig.6). This is about 90 MeV lower than for $\pi^- - p$ events. According to Ref.[15], the peak position of the coherent pion component is significantly shifted towards lower excitation energies by the Δ-hole correlations.

7. Conclusion

The (^{3}He, 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. The present results can be summarized in the following way :

- $\pi^+ + p$ 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 ^{4}He, ^{12}C and ^{208}Pb targets are direct evidence of the coupling of Δ-h states to 2p-2h states. Their yield is large and they contribute to the low energy part of the resonance.

- In π^+ 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 then emerged as real, leaving the target nucleus in its ground state. As expected, the experimental angular distribution of the detected pion is found to be sharply peaked in the momentum transfer direction. Theoretical calculations show that coherent pion production is a unique signature of the nuclear pionic mode [15].

A new project called SpesIVπ is being carried out at Saturne to specifically study the coherent process. By combining the existing SpesIV spectrometer with a new detection around the target, there will be no experimental cuts at small pion angles and we are aiming at the required resolution to resolve the target ground state.

References

[1] D. Contardo *et al.*, Phys. Lett. **B168** (1986) 331.

[2] D. A. Lind, Can. J. Phys. **65** (1987).

[3] C. Gaarde, Ann. Rev. of Nuclear and Particle Science **41** (1991) 187.

[4] G. Chanfray and M. Ericson, Phys. Lett. **B141** (1984) 163.

[5] J Delorme and P. A. M. Guichon, Phys. Lett. **B263** (1991) 157.

[6] T. Udagawa, S. W. Hong, and F. Osterfeld, Phys. Lett. **B245** (1990) 1.

[7] P. Fernandez de Cordoba, and E. Oset, Nucl. Phys. **A544** (1992) 793.

[8] T. Hennino, B. Ramstein, D. Bachelier, H. G. Bohlen, J. L. Boyard, C. Ellegaard, C. Gaarde, J. Gosset, J. C. Jourdain, J. S. Larsen, M. C. Lemaire, D. L'Hôte, H. P. Morsch, M. Österlund, J. Poitou, P. Radvanyi, M. Roy-Stephan, T. Sams, K. Sneppen, O. Valette, and P. Zupranski, Phys. Lett. **B283** (1992) 42.

[9] J. Chiba, T. Kobayashi, T. Nagae, I. Arai, N. Kato, H. Kitayama, A. Manabe, M. Tanaka, K. Tomizawa, D. Beatty, G. Edwards, G. Glasshauser, G. J. Kumbarzki, R. D. Ransome, and F. T. Baker, Phys. Rev. Lett. **67** (1991) 1982.

[10] M. Österlund *et al.*, to be published.

[11] J. P. Alard *et al.*, Nucl. Instr. and Meth. **A261** (1987) 379.

[12] C. Ellegaard, C. Gaarde, J. S. Larsen, V. Dmitriev, O. Sushkov, C. Goodman, I. Bergqvist, A. Brockstedt L. Carlén, P. Ekström, M. Bedjidian, D. Contardo, J. Y. Grossiord, A. Guichard, R. Haroutunian, J. R. Pizzi, D. Bachelier, J. L. Boyard, T. Hennino, M. Roy-Stephan, M. Boivin, and P. Radvanyi, Phys. Lett. **B154** (1985) 110.

[13] K. Sneppen and C. Gaarde, submitted to Physical Review C.

[14] T. Hennino, B. Ramstein, D. Bachelier, J. L. Boyard, C. Ellegaard, C. Gaarde, J. Gosset, J. C. Jourdain, J. S. Larsen, M. C. Lemaire, D. L'Hôte, H. P. Morsch, M. Österlund, J. Poitou, P. Radvanyi, S. Rousteau, M. Roy-Stephan, T. Sams and P. Zupranski, Phys. Lett. **B303** (1993) 236.

[15] P. Oltmanns, F. Osterfeld, T. Udagawa, Phys. Lett. **B299** (1993) 194.

[16] P. Fernandez de Cordoba, J. Nieves, E. Oset and M.J. Vicente-Vacas, Phys. Scr. **47** (1993), in print.