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Short note

Evidence for narrow $\Delta^0(1232)$ states in the $^{12}C(e,e'p\pi^-)^{11}C$ Reaction

P. Bartsch[1], D. Baumann[1], J. Bermuth[2], K. Bohinc[3], R. Böhm[1], D. Bosnar[4], N. Clawiter[1], S. Derber[1], M. Ding[1], M.O. Distler[1,a], A. Ebbes[1], I. Ewald[1], J. M. Friedrich[1], J. Friedrich[1], P. Jennewein[1], M. Kahrau[1], M. Kohl[5], A. Kozlov[1], K.W. Krygier[1], M. Kuss[5,b], A. Liesenfeld[1], H. Merkel[1], P. Merle[1], U. Müller[1], R. Neuhausen[1], T. Pospischil[1], M. Potokar[3], D. Rohe[2], G. Rosner[1], H. Schmieden[1], S. Širca[3], A. Wagner[1], T. Walcher[1], M. Weis[1], S. Wolf[1]

[1] Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
[2] Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
[3] Institut "Jožef Stefan", University of Ljubljana, SI-1001 Ljubljana, Slovenia
[4] Department of Physics, University of Zagreb, HR-10000 Zagreb, Croatia
[5] Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany

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Abstract. The reaction $^{12}C(e,e'\Delta^0)^{11}C \rightarrow {}^{12}C(e,e'p\pi^-)^{11}C$ was investigated at the Mainz Microtron MAMI in a triple coincidence measurement using the three spectrometer setup of the A1 Collaboration. The good missing mass resolution of $\sigma_\mathrm{m} = 0.27\,MeV/c^2$ allowed to select the events belonging to the ground state of ^{11}C. Cutting on these events the excitation energy spectra of $^{12}C_{\Delta^0}$ show evidence for two peaks of about $4\,MeV$ width (FWHM) at $282\,MeV$ and $296\,MeV$ with a significance of about 4.5 standard deviations. The peaks are interpreted in a simple weak coupling model as bound Δ^0 states in $^{12}C_{\Delta^0}$.

PACS. 24.30.Gd Nuclear physics: Resonance reactions – 25.30.Rw Electroproduction reactions – 14.20.Gk Baryon resonances with $S = 0$ – 21.80.+a Hypernuclei

1 Introduction

The question of hadron properties in the nuclear medium is one of the most intriguing in hadron physics. Quite a few observables have been proposed and investigated. A larger electric root mean square radius of the nucleon in the medium has been derived from quasi free scattering in the $A(e,e'p)$ reaction [1] or arguments based on the incomplete exhaustion of the Coulomb sum rule [2]. However, this evidence was recently questioned [3]. Another line of search is the so called "Colour transparency" [4, 5], which is up to now also inconclusive. The effect of the medium discussed most intensively today is the "chiral restauration" mechanism [6] for which some indirect evidence was recently found in the e^+e^- pair production in heavy ion reactions [7].

There is a different indication of medium effects in the production of Σ hypernuclei in the $A(K^-,\pi^-)$ reaction found at the low energy separated kaon beam of the CERN PS by a Heidelberg-Saclay collaboration (for summaries see [8,9]). In these experiments narrow Σ hypernuclear states were observed in ^9Be and ^{12}C [10] and in ^{12}C and ^{16}O [11]. These observations came as a great surprise since in the nuclear medium the strong $\Sigma N \rightarrow \Lambda N$ reaction should damp these states to a width typical of strong interactions of about $100\,MeV$ and make them effectively unobservable. No explanation of the narrowness was tried at this time.

The salient features of that experiment were the small momentum transfer of $|\boldsymbol{q}| \leq 100\,MeV/c$ and a good missing mass resolution of $\sigma_m \approx 0.8\,MeV/c^2$. Subsequently an attempt was made to confirm these results with the same reaction but at much larger momentum transfer $|\boldsymbol{q}| \approx 300\,MeV/c$ and resolution $\sigma_m \approx 2\,MeV/c^2$ at the Brookhaven AGS [12] [13] with negative results. Also the stopped K^- experiment at the KEK laboratory in Tsukuba, Japan, could not confirm the existence of narrow Σ hyper nuclei in medium heavy nuclei ($A > 8$) [14] [15]. Only in ^4He a state was found but interpreted as an exceptional conspiracy due to the spin-isospin part of the Σ-N interaction [16].

After the vain attempts to confirm the CERN results they were questioned and it was shown on the basis of a

[a] *Present address:* M.I.T., Cambridge, USA
[b] *Present address:* Jefferson Lab, Newport News, USA

quasi free reaction model that the narrow Σ hyper nuclear states could not exist [17]. In this model the on shell ΣN cross sections were averaged with the off shell momentum distribution, somewhat outside the laws of quantum mechanics.

The negative reception lead to an early closure of the separated beam at CERN and a repetition of the search under its favourable conditions was excluded. Despite this negative situation a Heidelberg-SIN/PSI collaboration tried an even more speculative reaction by investigating the π^+ absorbtion on ^{12}C and looking for the reaction $\pi^+ + {}^{12}C \rightarrow {}^{11}C_{\Delta^+} + p_{\text{forward}} \rightarrow X + p_{\text{sideward}} + p_{\text{sideward}} + p_{\text{forward}}$ at a π^+ energy of $E_\pi \approx 380\,MeV$ [18].

The idea was to substitute a p-shell nucleon in ^{11}C by a $\Delta(1232)$ by transmitting the momentum of the absorbed π^+ to a fast proton knocked out in the forward direction. The forward proton was measured with the good resolution spectrometer SUSI of the Paul Scherrer Institut (PSI) in Villigen, Switzerland. The decay of the $\Delta(1232)+N \rightarrow p+p$ was measured in coincidence with the forward proton in a "tunnel" of big blocks of plastic scintillators. However, statistics and overall resolution of this experiment were inadequate and only the fragmentation of the excited $^{11}C_\Delta$ state could be investigated [19].

The idea of a narrow Δ bound state in the nucleus is of course even more at variance with current ideas than the narrow Σ hypernuclear states. Beside the reaction $\Delta N \rightarrow NN$ possible in the nuclear medium already the decay width of the free $\Delta \rightarrow N\pi$ of $\Gamma_{\text{FWHM}} \approx 120\,MeV$ [20] seems to exclude narrow Δ states. Nevertheless, after completion of the high resolution, large solid angle three spectrometer setup at MAMI [21] an investigation of the reaction $e + {}^{12}C \rightarrow {}^{12}C_{\Delta^0} + e' \rightarrow {}^{11}C + e' + p + \pi^-$ was started in 1995 [22]. This paper presents surprising evidence that narrow Δ^0 states may exist and can be observed when kinematical conditions favour the production of bound Δ^0 states and suppress the final state interaction of the outgoing p and π^-.

2 Basic ideas

In Fig. 1 two reaction mechanisms are illustrated. In the reaction usually called "quasi free" a Δ^0 is produced from a bound neutron as a quasi free wave packet. This Δ^0 takes all the momentum transfer and flies in its direction with a large velocity. Consequently, the decay particles p and π^- are emitted forward in the laboratory frame. In contrast, if a bound Δ^0 is produced, i. e. one that substitutes a neutron in the s or p shell, the whole nucleus takes the momentum transfer and the Δ^0 is slower by a factor of about $m_\Delta/m_{^{12}C} \approx 1/10$. Therefore, the decay particles p and π^- will more frequently appear at large angles in the laboratory system. In the experiment of this paper the electron is measured in spectrometer B (solid angle $\Omega = 5.6msr$), the proton in spectrometer A ($\Omega = 28msr$) and the π^- in spectrometer C ($\Omega = 28msr$) of the three spectrometer setup at MAMI in triple coincidence. By setting spectrometers A and C to large angles relative to the momentum transfer $\boldsymbol{q}$ one can effectively suppress the quasi-free reaction.

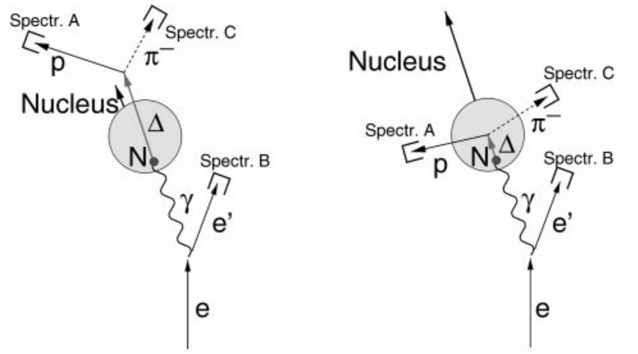

Fig. 1. Kinematics for "quasi free Δ" (left) and "bound Δ" (right), schematically

A more quantitative representation of this idea is presented in Fig. 2 which shows a Monte-Carlo simulation of the two reaction mechanisms. In this simulation an on-shell p-wave momentum distribution for the initial neutron has been assumed [23]. The energy to put the initial neutron on shell is taken from the large energy transfer of the electron to the system. The upper panels show the calculations for a bound Δ^0 whose p wave momentum distribution is assumed to be isotropic in the $^{12}C_{\Delta^0}$ rest frame. The lower panels show the same calculation for quasi free production with the momentum distribution isotropic in the frame of the initial target nucleus. The momentum distributions are boosted by $\boldsymbol{q} \cdot m_\Delta/m_{^{12}C}$ in the first case and by $\boldsymbol{q}$ in the second. In both reaction mechanisms the $\Delta(\frac{3}{2}^+, \frac{3}{2})$ decay has the typical M_{1+} angular distribution in the p-π^- system. The small boxes indicate the acceptances of the spectrometers for the chosen kinematics.

By measuring the 4-momenta of all three particles e', p, and π^- the 4-momentum of the residual system can be determined through energy and momentum conservation. From these the missing mass

$$m_{\text{miss}} = \sqrt{(\omega + m_{^{12}C} - E_p - E_\pi)^2 - (\boldsymbol{q} - \boldsymbol{p}_p - \boldsymbol{p}_\pi)^2}$$

can be determined. The excellent resolution of the three spectrometer setup gives an rms resolution of $\sigma_{m_{\text{miss}}} = 0.27\,MeV/c^2$. The smallest missing mass possible is that of the ^{11}C ground state with $\Delta m_{\text{miss}} = m_{\text{miss}} - m_{^{11}C} = 0$.

This means that if triple coincidence events ($e' \wedge p \wedge \pi$) in the described kinematics are selected by two cuts, one on the coincidence time, and one on the missing mass $\Delta m_{\text{miss}} = 0$, possibly narrow Δ^0 states should appear in the spectrum of the energy transfer ω, or, taking the recoil energy of the ^{11}C nucleus into account, more precisely in

$$\hat{\omega} = W - m_{^{12}C}$$

where W is the invariant total mass.

It should be noted that within the kinematical conditions imposed by the two cuts the final state interaction of the proton and pion is minimal. The cut on the triple

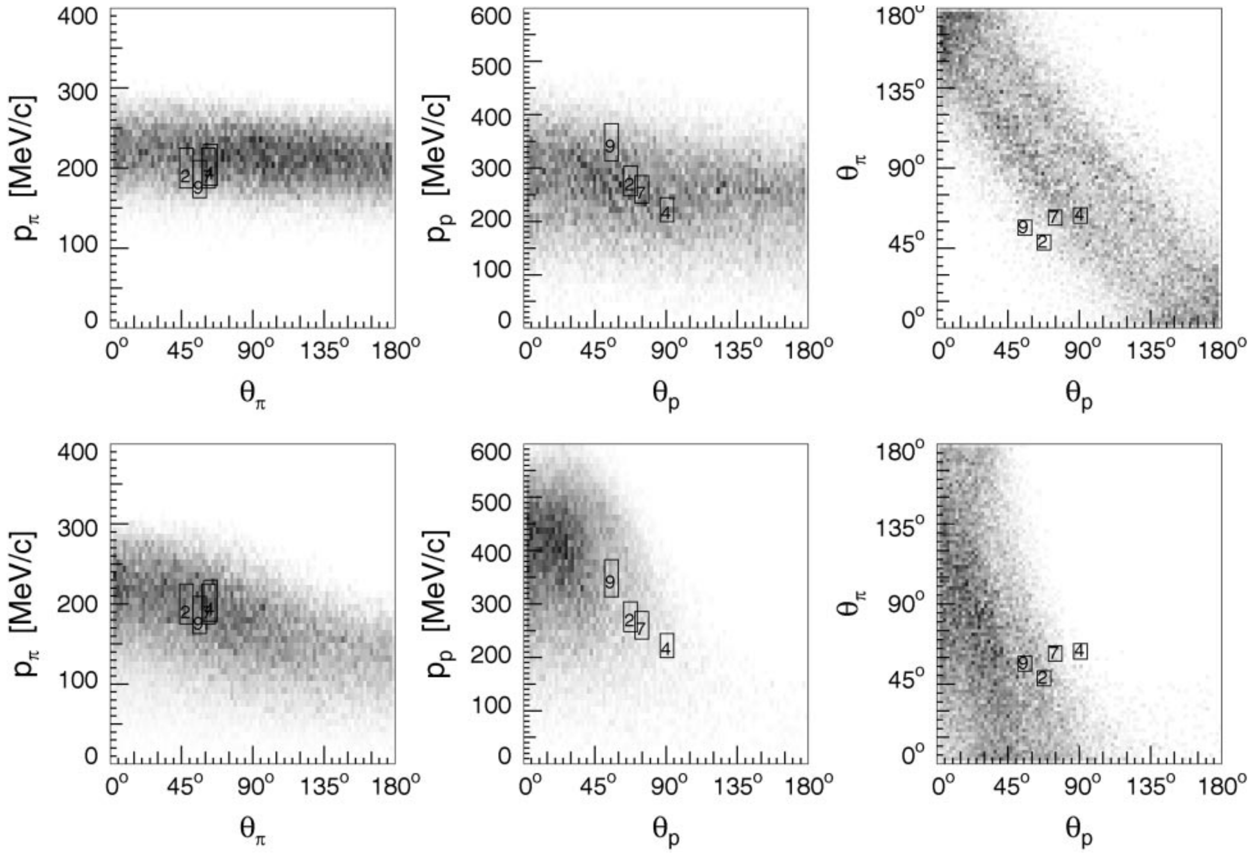

Fig. 2. Scatter plots of the simulated frequency distribution for the two different reaction mechanisms: a "bound Δ^0" (upper panels) and a "quasi free Δ^0" (lower panels) produced in ^{12}C. The quantities p_π, θ_π and p_p, θ_p denote the respective laboratory momenta and angles of the decay proton and pion with respect to the beam axis. The boxes indicate the spectrometer acceptance for different settings (see tab. 1)

coincidence time selects proton-pion pairs strictly correlated by the back to back decay in the cm system of the Δ^0. The spectrometers are positioned at the respective laboratory angles given by the moving $^{12}C_{\Delta^0}$. Considering their small angular acceptances events with angular scattering in the final state destroy the correlation and are effectively suppressed.

An equivalent argument applies to the energy transfer in the final state interaction. The energy transfer ω is determined with a FWHM resolution of 0.5 MeV and, therefore, the states in ^{11}C are well resolved. The cut on the ^{11}C ground state excludes any energy transfer due to final state interactions.

3 Experiment and Analysis

An experiment exploiting these ideas was performed in 1996 and 1997 at the Mainz Microtron MAMI. A carbon target with a thickness of $45\,mg/cm^2$ and a beam current of up to $60\,\mu A$ giving a luminosity of $0.9\,\mathrm{MHz}/\mu b$ were used. The performance of the three spectrometer setup was standard as described in [21] and mentioned above.

In a first approximation one expects that the transition form factor from a neutron in the p shell to a Δ^0 in the p shell behaves roughly like the elastic form factor of ^{12}C. This means that the first minimum occurs at $|\boldsymbol{q}| = 0.36\,GeV/c$. At the beginning of the investigation this was not fully realized and the bulk of the statistics was taken at $|\boldsymbol{q}| = 0.36...0.38\,GeV/c$. Later one measurement to the left of the minimum at $|\boldsymbol{q}| = 0.33\ GeV/c$, the smallest achievable, and one at the top of the second maximum at $|\boldsymbol{q}| = 0.44\,GeV/c$ were performed, both, however, with insufficient statistics, i. e. beam times of less than 2 weeks. As will be discussed in section 5.2 the transition form factor behaves much more favourably and for the chosen kinematics it was at the top of its second maximum. The details of the kinematics of all usable runs are listed in Tab. 1. For the final analysis, however, not all runs were considered. Runs 12 and 13 were taken at a high beam current ($60\mu A$) resulting in a very bad true to accidental triple coincidence ratio. Runs 14 and 15 were taken at large momentum transfers at which the rate was very small and the transition formfactors (see Section 5: Discussion) change their relative strength making the interpretation difficult. A similar argument applies to run 17 which was taken at low electron energy. Run 16 has insignificant statistics. All runs together represent a beam time of 975 hours.

Table 1. Kinematical settings.

		Spectrometer B			Spectrometer A		Spectrometer C		Events		
#	$\frac{E_0}{MeV}$	θ_e	$\frac{E'}{MeV}$	$\frac{\lvert q\rvert}{MeV/c}$	θ_p	$\frac{p_p}{MeV/c}$	θ_π	$\frac{p_\pi}{MeV/c}$	total	$^{11}C_{GS}$	Time
2.	855	15.5°	519.6	369	67.7°	270.0	48.2°	210.0	36898915	161	127h 35'
3.	855	15.0°	539.6	348	88.5°	223.9	65.6°	206.3	28676789	45	91h 07'
4.	855	18.0°	539.6	369	90.8°	222.0	63.3°	203.7	15572546	33	76h 58'
5.	855	18.5°	544.5	363	91.6°	217.5	62.2°	198.9	11108450	28	60h 27'
7.	855	18.0°	534.8	372	74.7°	260.0	62.1°	200.0	7321878	66	36h 11'
8.	855	18.0°	534.8	372	62.4°	304.0	58.7°	185.0	5741101	88	23h 53'
9.	855	18.0°	520.0	385	55.7°	348.0	56.5°	186.2	6111006	65	33h 18'
10.	855	18.0°	529.2	374	102.5°	215.0	67.9°	214.0	13216808	10	40h 27'
11.	855	18.0°	539.5	375	99.6°	217.5	59.5°	213.0	9131506	21	39h 38'
12.	855	18.0°	539.5	368	90.8°	222.0	63.3°	203.7	13177183	36	69h 43'
13.	855	18.0°	549.1	367	90.8°	222.0	63.3°	203.7	5720594	30	34h 31'
14.	855	26.4°	549.1	440	82.2°	225.0	64.8°	202.0	25313635	8	95h 38'
15.	855	26.4°	549.1	434	82.2°	225.0	64.8°	202.0	11734249	21	106h 59'
16.	855	18.0°	539.7	369	90.8°	222.0	63.3°	203.7	2427081	8	26h 55'
17.	600	18.0°	297.8	330	96.4°	226.5	58.4°	212.5	12338803	65	111h 43'

In the analysis the raw data were first cleaned from incomplete events. Using the information of the detector package the focal plane coordinates were then reconstructed. From these the coordinates of the events at the reaction vertex were calculated using the known transfer matrices [21]. A further cleaning of background events from instrumental scattering was achieved by cutting on the target position and the angles of the nominal spectrometer acceptance. The coincidence time was corrected for the pathlength differences in the spectrometers. The coincidence peaks have a width of $\sigma = 0.25\,ns$ and the cuts were placed at $\pm 2\sigma$. They were varied between $\pm 2\sigma$ and $\pm 4\sigma$ without any remarkable change of the spectra.

After these steps, spectra of the missing mass from the four-momenta of the in- and outgoing electron, the decay proton and the decay pion were constructed. The missing mass is effectively the excitation energy in ^{11}C. As long as $\Delta m_{\rm miss} < \epsilon$, the binding energy of the nucleons in ^{11}C, the residual system is a ^{11}C nucleus. Figure 3 shows this spectrum for $|\boldsymbol{q}| = 0.385\,GeV/c$ after the cut on the triple coincidence time.

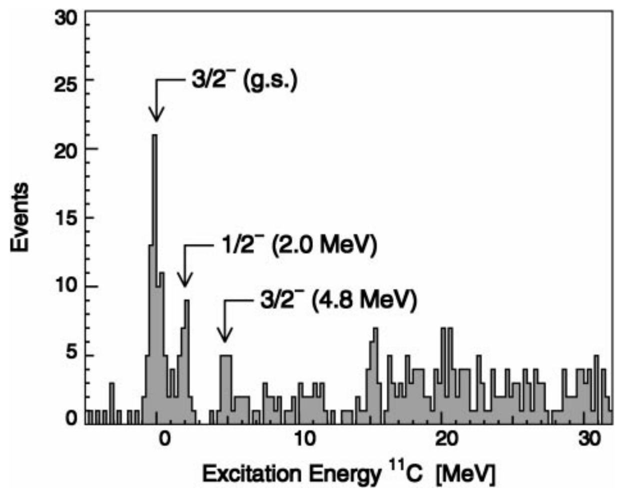

Fig. 3. The missing mass, i.e. the excitation energy of the residual ^{11}C nucleus for $|\boldsymbol{q}| = 0.385\,GeV/c$. Plotted are the data of run 9 having the highest proton momentum and consequently the best resolution

4 Results

The overall energy resolution in Fig. 3 is $\sigma = 0.27\,MeV$ as can be seen from the clearly dominant ground state of ^{11}C. Higher lying states are excited much more weakly and will be dealt with in the future.

It is interesting to compare the missing momentum distribution of the ^{11}C ground state in this $^{12}C(e,e'\Delta^0)^{11}C$ reaction to the corresponding distribution in the $^{12}C(e,e'p)^{11}B_{g.s.}$ reaction. For this purpose one assumes that the Δ^0 is produced quasi free and the missing momentum is defined by

$$\boldsymbol{p}_{\rm miss} = \boldsymbol{q} - \boldsymbol{p}_\Delta = \boldsymbol{q} - \boldsymbol{p}_\pi - \boldsymbol{p}_p.$$

In order to obtain the missing momentum distribution of the quasi free Δ^0 the additional degrees of freedom of the p-π^- system are integrated out by assuming a Breit-Wigner mass distribution and an M_{1+} decay angular distribution for this system using the same model as for Fig. 2. Such a comparison is presented in Fig. 4. It appears that the Δ^0 spectrum is decreasing more slowly than the missing momentum distribution of the proton which could be a hint for an additional reaction mechanism at large $|\boldsymbol{p}_m|$. Since at large $|\boldsymbol{p}_m|$ the velocity of the residual ^{11}C is small this region overlaps with the kinematical region of the bound Δ^0 states. Therefore this enhancement may be due to these states.

A more sensitive search represents of course a direct inspection of the mentioned excitation spectrum of $^{12}C_\Delta$ in the variable $\hat{\omega} = W - m_{^{12}C}$. Figure 5 shows this spectrum before and after the cut on the triple coincidence time and the ground state energy of ^{11}C.

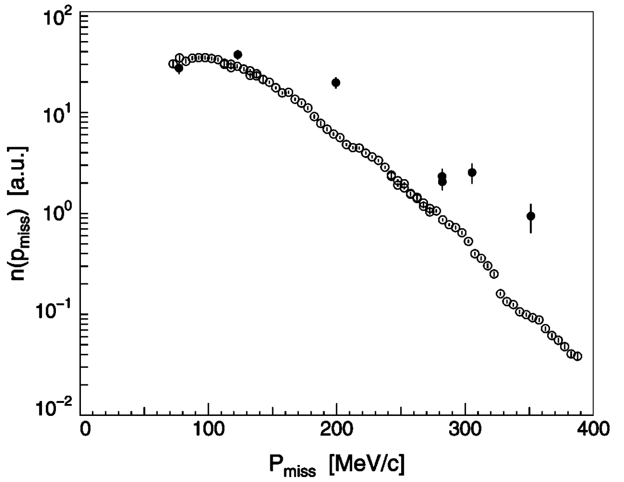

Fig. 4. The missing momentum distribution of a Δ^0 in the $^{12}C(e,e'\Delta^0)^{11}C_{g.s.}$ reaction (solid points) compared to a proton in the $^{12}C(e,e'p)^{11}B_{g.s.}$ reaction (open points)

Two peaks at $\hat{\omega} = 282\,MeV$ and $\hat{\omega} = 296\,MeV$ stay out of the statistical fluctuations. They are supported by four high adjacent channels, each $1.5\,MeV$ wide. The statistical significance d is calculated by [24]

$$d = S/\sqrt{B + \sigma_B^2} = S/\sqrt{2 \cdot B}$$

where S is the sum over 5 bins of counts in the signal above a background B with variance σ_B. Table 2 summarises the result for the spectrum at $|\boldsymbol{q}| = 0.37\,GeV/c$ in Fig. 5. All other fluctuations are three or less bins wide and have a statistical significance of less than 2 standard deviations.

Table 2 also gives the odds against appearance of a statistical fluctuation with d standard deviations. Assuming the same background over the full range covered in Fig. 5 of $270 < \hat{\omega} < 345$ MeV one has 10 intervals of $5 \cdot 1.5\ MeV = 7.5\ MeV$ width. The odds against appearance of one fluctuation above the assumed background have to be reduced by this factor 10. However, the combined probability that two fluctuations with the observed standard deviations occur in the given number of intervals is [24]

$$P(d_1 > d_{\alpha_1}, d_2 > d_{\alpha_2}) = \binom{10}{2}\alpha_1\alpha_2 \approx 3 \cdot 10^{-10}$$

where $d_{\alpha_1}, d_{\alpha_2}$ are the observed standard deviations and α_1, α_2 the respective probabilities, i.e. the odds in Tab. 2. This probability together with the natural explanation given in Sect. 5.2 represents the basis for the evidence of narrow Δ^0 states. The possibility that the apparatus produces narrow structures by instrumental scattering, difficulties with the optics of the spectrometers or the drift chambers was carefully checked. No hints for faking of narrow structures were found.

In order to check this unexpected narrow peaks other momentum transfers as mentioned have been measured. Figure 6 shows the same as Fig. 5 but for a completely independent measurement at $|\boldsymbol{q}| = 0.36\,GeV/c$. Again

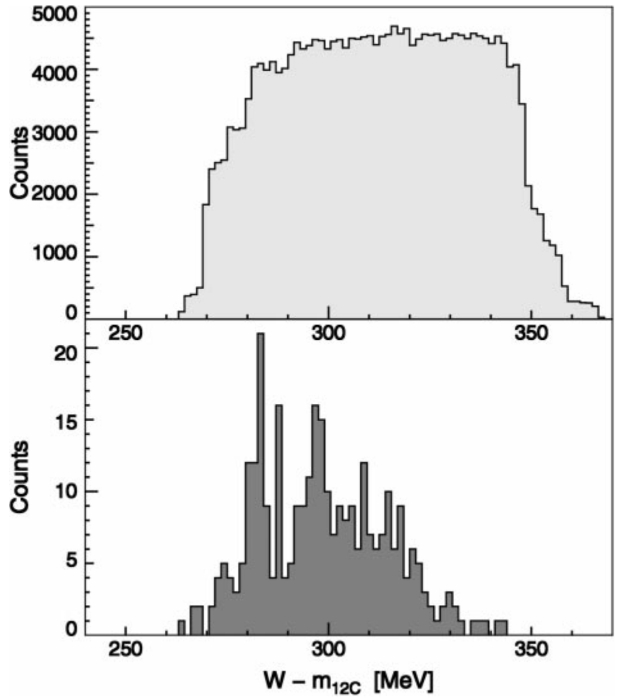

Fig. 5. The $^{12}C_{\Delta^0}$ excitation spectrum with no cuts (upper panel) and the two cuts on the triple coincidence time and the ^{11}C ground state at $|\boldsymbol{q}| = 0.37\,GeV/c$ (lower panel). The bin width is 1.5 MeV. Plotted is the sum of runs 4, 5, 7, 8, 9, 10, and 11

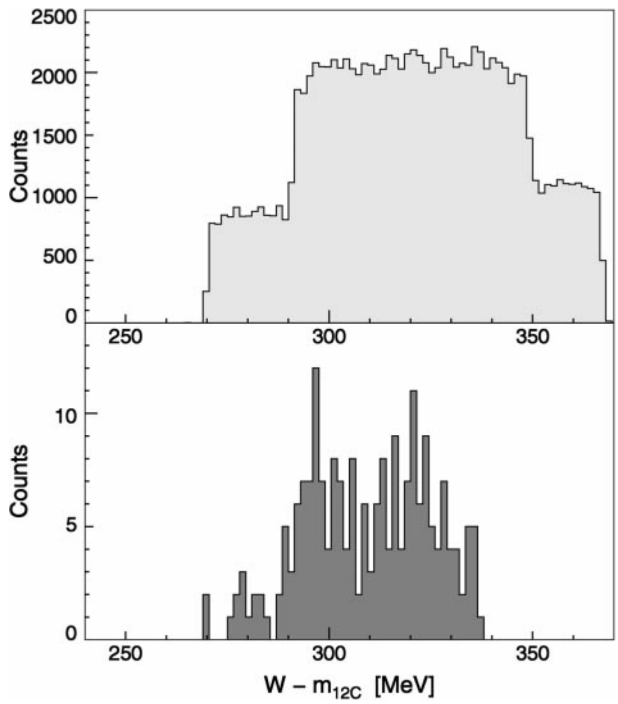

Fig. 6. The same as Fig. 5 at $|\boldsymbol{q}| = 0.36\,GeV/c$. Plotted is the sum of runs 2 and 3

a peak is seen at $\hat{\omega} = 296\,MeV$ with a significance of $d = 19/\sqrt{2 \cdot 20} = 3.0$. Unfortunately, a mismatch of a spectrometer setting caused a reduction of the statistics

Table 2. Statistical significance of peaks in $\hat{\omega}$ for $|\boldsymbol{q}| = 0.37\,GeV/c$ in Fig. 5

$\hat{\omega}$/MeV	S+B	B	S	$d = S/\sqrt{2 \cdot B}$	odds
282	59	24	35	5.0 ± 0.3	$1:5\cdot 10^6$
296	61	30	31	4.0 ± 0.3	$1:3\cdot 10^4$

below $290\,MeV$ by a factor of 2.5. Nevertheless, the data are consistent with a peak at $282\,MeV/c$.

At $|\boldsymbol{q}| = 0.44\,GeV/c$ the count rate becomes very small and no significant statistics was observed, the highest counts per bin being 5 at $\hat{\omega} = 298\,MeV$.

5 Discussion

There are two questions which arise immediately. Why could the $\Delta^0(1232)$ be narrow in nuclear matter against all believes so far? And why do two peaks appear at the observed energy transfers?

5.1 Why could the $\Delta^0(1232)$ be narrow?

The answer to this question must lie in the realization that the Δ^0 is produced in a bound state rather than quasi free. The initial Δ^0 is not prepared as a wave packet of sharp momentum (i.e. a plane wave in the limit of infinitely sharp momentum) but as a bound state with sharp energy and spatial localisation (i.e. a quite different spectral composition). The Δ is characterized by its very strong coupling to the π and one might at first assume that a change of the π-field in the nuclear medium is at the origin of the quenching of the width. But, if such classical ideas fail fancier models based on the standard picture of hadrons as composed of quarks and gluons may have to be tried. As outlined in the introduction the observation of narrow Δ^0 states challenges our understanding of bound hadron systems.

5.2 Why do two peaks appear at the observed energies?

In order to see whether the observed energy transfers can be understood a highly simplified weak coupling model for a bound Δ^0 is discussed in the following.

It is assumed that the Δ^0 is narrow and bound as the neutron from which it originates in an average central potential of standard three dimensional Woods-Saxon form

$$V(r) = V_{WS}(r) + V_{LS}(r) + V_C(r)$$

$$V_{WS}(r) = V_0\left(1 + e^{\frac{r-R}{a}}\right)^{-1}$$

$$V_{LS}(r) = \frac{c_{ls}}{r}\frac{d}{dr}V_{WS}(r)\langle \boldsymbol{l}\cdot\boldsymbol{s}\rangle$$

$$V_C(r) = e^2(Z-1)\cdot\begin{cases} r^{-1} & r \geq R \\ \frac{3}{2R} - \frac{r^2}{2R^3} & r < R \\ 0 & \text{for neutron and } \Delta^0 \end{cases}$$

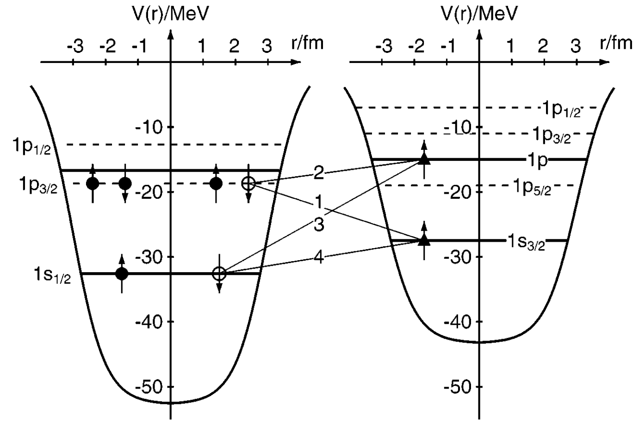

Fig. 7. Energy eigenvalues in the Woods-Saxon potential for neutrons (left) and a bound Δ^0 (right)

The parameters $R = 3.0\,fm$ and $V_0 = -52.7\,MeV$ have been adjusted to give the $1p_{3/2}$ proton separation energy of 16.0 MeV. The spin orbit parameter c_{ls} is fixed by the measured spin-orbit splitting of 6 MeV. We assumed the diffuseness parameter to be $a = 0.5\,fm$. With the same set of parameters, but without Coulomb interaction, the neutron separation energy of $18.7\,MeV$ can be reproduced.

The wave functions calculated with this potential also give the correct elastic form factor for ^{12}C and are in reasonable agreement with refs. [26,27]. It has, however, to be noted that their parameters represent fits to the form factor [27] or momentum distributions [23], but do not reproduce single particle energies consistently.

The Δ-nucleus central potential is known to be weaker by about a factor of 2/3 [28]. Therefore, the situation is as sketched in Fig. 7. Assuming in distinction to ref. [28] that the spin orbit strength $c_{ls}^{\Delta^0} = 0$ one can consider the four transitions in the $e + {}^{12}C \rightarrow {}^{11}C + \Delta^0 + e'$ reaction given in Tab. 3.

In order to compare the calculated and observed transition energies

$$\Delta E_{kl} = \epsilon_k^n - \epsilon_l^\Delta = \Delta m - \omega_{kl}$$

one has to decide about the value assigned to $\Delta m = m_{\Delta(1232)} - m_n$. It is well known that the maximum of the $\Delta(1232)$ resonance is shifted by about $20\,MeV$ in the p-π^- channel due to the damping of the resonance by its decay and by the interference of the resonant Δ amplitude with non resonant background amplitudes [25]. However, if the hypothesis that the peaks are bound Δ^0s, the

Table 3. Calculated transition energies for the reaction $e + {}^{12}C \rightarrow {}^{11}C + \Delta^0 + e'$

i	kl	transition	$\frac{\Delta E_{kl}}{MeV}$	$\frac{\omega_{kl}}{MeV}$
1	ps	$n; 1p_{3/2} \rightarrow \Delta; 1s_{3/2}$	+8.7	283.3
2	pp	$n; 1p_{3/2} \rightarrow \Delta; 1p$	-3.8	295.8
3	sp	$n; 1s_{1/2} \rightarrow \Delta; 1p$	-17.6	309.6
4	ss	$n; 1s_{1/2} \rightarrow \Delta; 1s_{3/2}$	-5.1	297.1

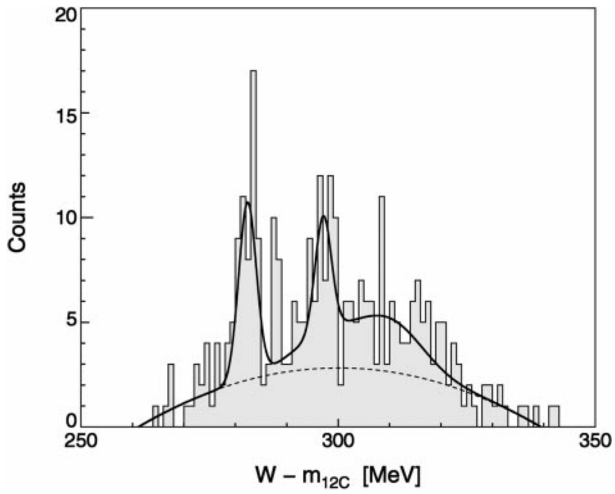

Fig. 8. The $^{12}C_{\Delta^0}$ excitation energy for $|\boldsymbol{q}| = 0.37\,GeV/c$. The same data as in Fig. 5 binned with 1.0 MeV. The line is a fit with a quadratic background, two gaussian peaks, and two broad peaks with width and position given by the model of Sect. 5.2

decay of which is suppressed and consequently are narrow, is used, the shift will vanish. Therefore, the value $\Delta m = 292.0\,MeV/c^2$, where the Δ resonance phase passes 90° has been adopted [25]. With this the single particle energy

$$\epsilon_p^{\Delta} = \epsilon_p^n - \Delta E_{pp} = -14.5\,MeV$$

where $\epsilon_p^n = -18.7\,MeV$ has been calculated and V_0^{Δ} has been adjusted to reproduce roughly this energy.

The resulting $V_0^{\Delta} = -43.3\,MeV$ is a factor of 0.8 smaller than V_0^N. With this V_0^{Δ} the ΔE_{kl} and ω_{kl} of Tab. 3 are calculated. They have to be compared with the values of the two observed narrow peaks at

$$\hat{\omega}_1 = (282.4 \pm 0.5)MeV$$
$$\hat{\omega}_2 = (296.2 \pm 0.5)MeV$$

in surprisingly good agreement. The two transitions *sp* and *ss* are broad since the neutron hole can be filled by the *p* state neutron. This width measured in $^{12}C(e, e'p)$ [23] is $\Gamma \approx 15\,MeV$. Figure 8 shows a fit to the spectrum with a quadratic background approximating the form of the quasi free Δ^0 production in the acceptance of the experiment and with the four transitions using all information mentioned so far. The results are shown in table 4. The data are the same as in Fig.5, but this time binned with $1.0\,MeV$. The FWHM resolution as given solely by the electron arm (spectrometer B) is better than $0.5\,MeV$. The fit is again surprisingly good and shows consistency with the model.

Finally, to complete the picture, the transition probabilities, i. e. the transition form factors, have been calculated using the numerically calculated wave functions of this model and are shown in Fig. 9. The relative values of the quantity $\Gamma \cdot h/n_n$ can be directly compared to the values of these form factors squared at $|\boldsymbol{q}| = 0.37\,GeV/c$. This comparison shows again an astonishing consistency

Table 4. Fit parameters for Fig. 8. Γ stands for the width (FWHM) and h for the height of the respective peak. (a) is fixed by model, and (b) is fixed by the value from $^{12}C(e, e'p)$ of ref. [23]. n_n is the number of neutrons in the initial state.

ı	kl	$\hat{\omega}/MeV$	Γ/MeV	h	$\Gamma \cdot h$	$\Gamma \cdot h/n_n$
1	ps	282.4	4.5	4.2	18.9	4.7
2	pp	296.2	3.7	2.7	10.0	2.5
3	sp	$309.6^{(a)}$	$15^{(b)}$	1.2	18.0	9.0
4	ss	$297.6^{(a)}$	$15^{(b)}$	0.7	8.4	4.2

and provides further support to the proposed interpretation.

At the same time, these form factors demonstrate a basic difficulty. In order to get the highest possible flux of virtual photons one would like to go to the smallest possible momentum transfer $|\boldsymbol{q}|$ which is bound by $|\boldsymbol{q}| > \omega$. Unfortunately, just in this region the *pp* transition form factor has its minimum. At $|\boldsymbol{q}| \approx 0.40\,GeV/c$ one is at the optimal situation as regards the transition form factor but virtual photon flux is low.

An alternative interpretation of the spectra for a finite spin orbit interaction $c_{ls}^{\Delta^0}$ can also be given. If one assumes as indicated by the dashed lines in Fig. 7 that $c_{ls}^{\Delta^0} = c_{ls}^n$ the Δ^0 of transitions 2 and 3 could go to the $1p_{5/2}$ state of the Δ^0. A slightly more shallow $V_0^{\Delta^0}$ brings the energies of transition 1 and 2 in an, however worse, accord with the observed energies. The transitions to the $1p_{3/2}$ and $1p_{1/2}$ states would be broad because for them the energy of a transition of the Δ^0 from $1p_{3/2} \rightarrow 1s_{3/2}$ or $1p_{1/2} \rightarrow 1s_{3/2}$ would be large enough to knock out a proton or neutron. In other words, these Δ^0 states would be broad due to the decay width of the Δ-hole state in the $^{12}C_{\Delta^0}$ nucleus and would appear in the wide bump at energies $\hat{\omega} > 300\,MeV$.

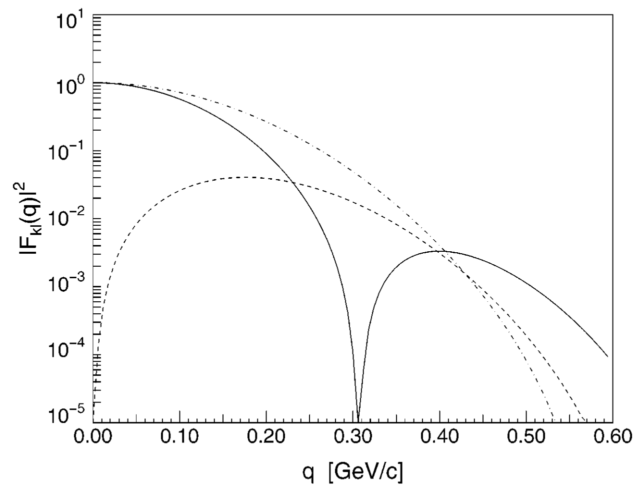

Fig. 9. The transition form factors for the Woods-Saxon potential. The solid line is the *pp* transition, the dashed line the *ps* transition and the dash-dotted line the *ss* transition

Of course, since $m_{\Delta^+} - m_{\Delta^0} \approx 1\ MeV$ more models including isospin mixing have to be tried before realistic conclusions about the Δ-nucleus interaction can be drawn.

In summary, this first measurement of the reaction $^{12}C(e, e'p\pi^-)^{11}C$ in triple coincidence with a resolution good enough to resolve nuclear states indicates the observation that the $\Delta^0(1232)$ is narrow if bound in ^{12}C. This observation will be corroborated by higher statistic measurements in the next years at MAMI. It is, furthermore, tempting to speculate about using the same method to investigate the $\rho^0 \to \pi^+\pi^-$, $\phi \to K^+K^-$, or $\Sigma^0 N \to \Lambda N \to p\pi^- N$ transitions in nuclear matter. The method offers the possibility to insert a hadron in a cold nucleus as a complement to the production of hadrons in dense and hot nuclear matter in heavy ion collisions.

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