Δ^{++} resonance in a ^{11}B nucleus

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We have measured the cross section of the reaction $^{12}C(\pi^+,\pi^+p)^{11}B$ in the region of the Δ^{++} resonance to determine whether the width or central energy of the resonance are modified if π,p scattering takes place inside a nucleus. No significant changes were found within the accuracy of our experiment.

INTRODUCTION

The Δ or $(\frac{3}{2},\frac{3}{2})$ spin-isospin resonance is the dominant feature of the interaction of pions and nucleons at intermediate energies. Its position (1233 MeV/c^2) and width (116 MeV/c^2) are well known from numerous experiments that have determined the phase shifts for pion nucleon scattering over a wide range of energies. This resonance also appears in the total cross section of elastic and inelastic pion nucleus scattering where, however, its width and central energy are changed. The question of whether these changes reflect changes in the basic π^+,p resonance, caused by the presence of the other nucleons, is not easily answered by inclusive pion-nucleus scattering experiments because they involve many nucleons as direct participants. Although there are some indications in the literature that the basic resonance might be narrowed,[1,2] no systematic study of the subject seems to have been made. To shed more light on this problem we have designed an experiment in which, as nearly as possible, only one proton participates directly whereas the others are merely spectators which provide the nuclear potential whose influence on the Δ^{++} we wish to study. In this experiment we have measured the energies of both the outgoing pion and proton from the reaction

$$^{12}C(\pi^+,\pi^+p)^{11}B \qquad (1)$$

in coincidence.

The Δ^{++} manifests itself as a dramatic peak only in the total π^+,p cross section. Since it would be quite impractical to obtain a total (π^+,π^+p) cross section from a series of coincidence measurements, it is necessary to have a theoretical model that links the parameters of the Δ^{++} with the measured differential cross sections. Such a model, based on the distorted wave impulse approximation (DWIA), was developed by Chant *et al.*[3] and found to satisfactorily describe the measured cross sections[2] of reaction (1) over a wide range of parameters.

The scattering of a pion by a nuclear proton is complicated by initial and final state interactions of the incident pion and the outgoing π^+,p pair, respectively. While Chant's model tries to account for these interactions it seemed prudent to us, especially in view of the strong energy dependence of the pion-nucleon scattering cross section, not to put undue demands on the model. For this reason we have kept the variations of the experimental parameters to a minimum, subject to the requirement that the invariant mass m_{23} of the detected π^+,p pair should vary over the Δ^{++} resonance. Fortunately the number of degrees of freedom in the three-body final state is so large that it is possible to keep most kinematic parameters constant and still change the invariant mass of the π^+,p pair over a considerable range.

We found it feasible to fix the beam energy $T1$ (for the notation, see Fig. 1), the energies of the outgoing pions and protons T_2 and T_3, as well as some other important parameters, as shown in Table I, while changing the invariant mass m_{23} over a range of 50 MeV/c^2 straddling the resonance. We also fixed the recoil momentum p_4 (which is equal and opposite to the momentum of the exchange proton in the impulse approximation) at 100 MeV/c, the value at which the momentum distribution of the p-shell protons in carbon reaches its maximum value.

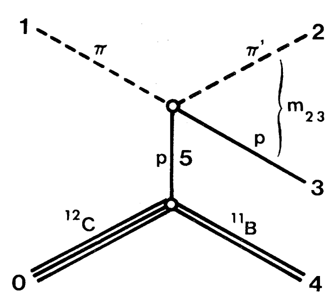

FIG. 1. Diagram of the $(\pi,\pi p)$ reaction in the impulse approximation. 0 equals the target nucleus, 1 equals the incident pion, 2 equals the scattered pion, 3 equals the ejected proton, 4 equals the residual nucleus, and 5 equals the exchange proton (off shell).

TABLE I. Values of the kinematic parameters as functions of the scattering angles.

θ_π	θ_p	m_{23} (MeV/c^2)	T_2 (MeV)	T_3 (MeV)	p_4 (MeV/c)	m_5 (MeV/c^2)[a]
51°	−33.7°	1200	140	54	100	916.4
64°	−27.3°	1207.5	140	54	100	916.4
73°	−25.8°	1215.8	140	54	100	916.4
81°	−25.7°	1224.4	140	54	100	916.4
88°	−26.9°	1233	140	54	100	916.4
94°	−30.0°	1242	140	54	100	916.4
60°	−64.3°	1242	140	54	100	916.4
76°	−58.2°	1250	140	54	100	916.4

[a]m_5 is the (off-shell) mass of the scattering proton (5) in Fig. 1.

THE EXPERIMENT

The experiment was performed at the EPICS channel of the Los Alamos Meson Physics Facility (LAMPF). The EPICS channel was set to a pion energy of 210 MeV. A 300 mg/cm^2 polyethylene absorber at the intermediate focus of the channel served to eliminate the proton contamination from the incident beam. The target was a 15 cm by 23 cm sheet of graphite of 131.4 mg/cm^2 area density, mounted in a He filled scattering chamber of 74 cm diam. The beam intensity was monitored with an ionization chamber mounted behind the scattering chamber.

The EPICS spectrometer was set to a central momentum of 242.2 MeV/c, corresponding to a pion energy of 140 MeV. The EPICS pion channel is designed to spread a beam with a wide momentum range ($\Delta p/p = \pm 1\%$) over a large target. For a coincidence experiment such as ours, this results in an awkwardly large range of angles and we reduced the momentum acceptance of the channel to $\pm 0.5\%$.

The protons were detected in three solid state detector telescopes, each consisting of a 1 mm thick Si detector followed by two 12 mm thick high purity Ge detectors of 35 mm diam, that were all mounted in the same cryostat. The middle telescope was positioned in the beam plane and the two others were located 7° above and below. Protons with the nominal energy of 54 MeV (see Table I) all stopped in the first of the two Ge slices. The Si detector preceding the Ge allowed positive identification of the protons.

For proton angles of 30° or more the overall energy resolution of the experiment was such that we were able to resolve the first excited state of ^{11}B at 2.25 MeV, see Fig. 2(a). At smaller angles the proton detectors entered the beam halo and the energy resolution deteriorated due to pileup, see Fig. 2(b). In the final analysis we set a cut at an excitation energy of 3.5 MeV for all runs. This included the first excited state of ^{11}B, but excluded almost all events that left the residual nucleus in one of the higher excited states or in the continuum.

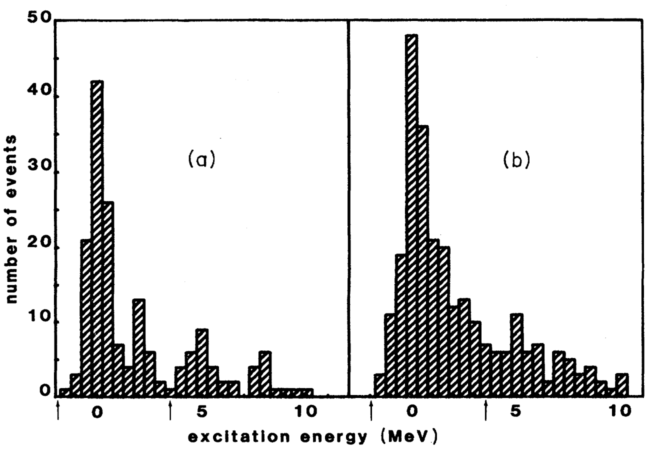

FIG. 2. Excitation energy spectra. (a) Optimum resolution, (b) resolution reduced by pileup. Only events between the arrows were accepted in the analysis.

DATA ANALYSIS

The kinematic conditions set forth in Table I prevail only at a single point in the multidimensional space spanned by the parameters of our experiment. To avoid a vanishing count rate we must accept events that violate these ideal conditions. The limits of acceptance for the various parameters are listed in Table II.

The finite acceptance raises the question of how to count events away from the ideal kinematics. The simplest approach would certainly be to sum all events over the accepted ranges of the parameters. This would give unbiased results only if the cross section changed linearly with all the variables involved, which is not the case. For this reason we decided to proceed as follows.

Using the DWIA program of Chant *et al.*,[3] we calculated the cross section σ_k, using the measured parameters T_1, T_2, T_3, θ_π, θ_p, and ϕ, of each event. We also calcu-

TABLE II. Ranges of acceptance for the kinematic parameters.

T_1 (MeV)	T_2 (MeV)	$\Delta\theta_\pi$[a]	$\Delta\phi$[b]	ΔE_{exc} (MeV)[c]	Δm_{23} (MeV/c^2)[a]
208–210	135–145	±3.5°	±10°	−2, +3.5	±12

[a]Deviation from the nominal values given in Table I.
[b]This is the angle by which the scattered pion and proton of a particular event deviate from coplanarity.
[c]See Fig. 2.

TABLE III. Corrections made for the finite acceptance of the apparatus.

Invariant mass	1200	1207.5	1215.8	1224.4	1232.9	1242	1242	1250
Correction factor	1.15	1.10	1.05	1.07	1.30	1.04	1.15	1.05

lated for each run the cross section σ_0 at the nominal values of the kinematic parameters in Table I. We then gave each measured event a weight,

$$W_k = \frac{\sigma_0}{\sigma_k} ,$$

and determined the experimental cross section by counting each event according to its weight. The correction factors obtained in this manner are listed in Table III. Clearly, some of them are larger than one would wish due to the large angular range that we were forced to accept at the LAMPF EPICS channel.

To see whether or not the Δ^{++} resonance is modified as to width or centroid we again used the program of Chant *et al.*[3] This program factorizes the cross section, i.e., it expresses it as the product of the free (π^+,p) cross section, a kinematic factor, and the momentum density of the scattering protons at the lower vertex of Fig. 1. The free (π,p) cross section is calculated from the parametrized phase shifts of Rowe *et al.*[4] The parametrization of the phase shifts contains the central energy and width of the Δ^{++} resonance explicitly and it is a simple matter to substitute values that differ from the accepted ones (1233 MeV/c^2, 116 MeV/c^2). We have done this in calculations of the cross sections at the values of the kinematical parameters given in Table I. The results of these calculations in comparison with the experimental cross sections are given in Table IV.

The use of the impulse approximation implies the use of the free (π,p) cross section at some appropriate energy. There is a certain degree of arbitrariness connected with the choice of this energy. In agreement with Chant *et al.*[3] we have used the free (π^+,p) cross sections belonging to those incident pion energies that gave the value for the invariant mass m_{23} that we actually observed in $(\pi^+,\pi^+\mathrm{p})$ scattering.

We have made no effort to obtain absolute experimental cross sections, and for the purpose of calculating the values of χ^2 given in Table IV we have normalized the calculated cross sections in each column with a common factor in order to minimize the value of χ^2. These normalization factors did not vary from each other by more than $\pm 16\%$.

In Fig. 3 we represent the results of Table IV graphically, giving a few selected "theoretical curves." It should be emphasized that the values of the invariant mass plotted on the abscissa of Fig. 3 can be realized with many different values of the kinematic parameters. The theoretical curves simply connect the points calculated at the actual experimental parameters in order to guide the eye.

An example of this kinematic freedom is provided by the two experimental points belonging to an invariant mass of 1241.7 MeV/c^2. One was taken at angles of $\theta_\pi = 94°$ and $\theta_\mathrm{p} = -30°$ for the pion and proton, respectively, while the other, marked with a triangle, was taken at $\theta_\pi = 60°$ and $\theta_\mathrm{p} = -64.3°$. The ratio of the two experimental cross sections is exactly reproduced by that of the two calculated ones so that the two seemingly different experimental points actually support our approach strongly. The calculated value used in the curves is, of course, the one belonging to the lower of the two experimental points.

TABLE IV. Comparison of measured and calculated cross sections.

Experiment			Theoretical values											
			$\omega_0=1220$[a]				$\omega_0=1233$				$\omega_0=1250$			
m_{23}	σ_{exp}	Γ[b]	58	116	174	232	58	116	174	232	58	116	174	232
1200	7.2±0.6		8.2	9.2	9.5	9.7	4.5	6.9	8.0	8.6	2.7	4.6	6.0	6.9
1208	7.6±0.6		8.3	7.7	7.4	7.3	5.4	6.6	6.9	7.4	3.5	5.0	5.9	6.3
1216	7.5±0.5		8.9	7.5	7.1	6.9	7.0	7.2	7.1	7.0	4.8	6.1	6.6	6.8
1224	7.9±0.6		9.0	8.1	7.8	7.7	9.3	8.5	6.2	7.9	7.2	8.1	8.2	8.1
1233	8.6±0.5		8.1	8.7	8.7	8.7	10.7	9.8	9.4	9.2	10.2	10.3	10.0	9.7
1242	9.4±0.6		5.5	8.0	8.4	8.6	8.7	9.2	9.1	9.1	11.6	10.6	10.1	10.1
1250	6.7±0.4		2.8	4.2	4.5	4.6	3.9	4.7	4.8	4.7	5.8	5.4	5.2	5.0
C[c]			0.94	1.02	1.02	1.02	1.24	1.14	1.09	1.07	1.19	1.20	1.16	1.13
χ^2[d]			166	61	53	51	122	42	35	37	159	77	45	35

[a] ω_0 equals the centroid of Δ^{++} resonance in MeV/c^2.
[b] Γ equals the width of Δ^{++} resonance in MeV/c^2.
[c] C equals the correction factor to minimize χ^2.
[d] χ^2 equals the reduced χ^2.

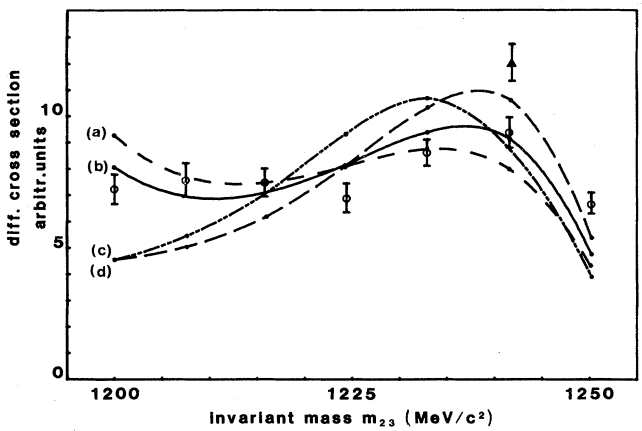

FIG. 3. Measured cross sections in comparison with cross sections calculated in the DWIA using various values for the width Γ and centroid ω_0 for the resonance. (a) $\omega_0=1220$ MeV/c^2, $\Gamma=116$ MeV/c^2; (b) $\omega_0=1233$ MeV/c^2, $\Gamma=174$ MeV/c^2; (c) $\omega_0=1233$ MeV/c^2, $\Gamma=58$ MeV/c^2; (d) $\omega_0=1250$ MeV/c^2, $\Gamma=110$ MeV/c^2. The theoretical curves are defined only for those values of the abscissa that belong to measured values. The difference in the ordinate of the two points at $m_{23}=1242$ MeV/c^2 is exactly reproduced by the DWIA.

CONCLUSIONS

While the agreement between theory and experiment is not good enough to draw any firm conclusions as to the details of a possible modification of the Δ^{++} resonance in a nucleus, it is apparent from our data that in a nucleus the resonance is (1) not shifted substantially, (2) not narrowed substantially, but (3) (possibly) widened.

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