ROLE OF THE Δ–ISOBAR IN THE (p,π) REACTION

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In the two-nucleon mechanism model of nuclear pion production, the (p,π^+), (p,π^0) and (p,π^-) reactions are treated on an equal footing, and it has been generally assumed in calculations to date that these reactions are dominated by pion rescattering through the Δ(3,3) resonance. It is well known that positive pion production at intermediate energies is dominated by the elementary NN → NΔ → NNπ process, but recent studies[1–5] of the pn ↔ π^-pp and A(p,π^-)A+1 reactions indicate that the Δ contribution to negative pion production is suppressed when the final proton pair is constrained to be in a $^1S_0$ state.

We have applied a microscopic meson–exchange model[6–8] of nuclear pion production developed at IUCF to the ^{16}O(p,π^+) and ^{12,13,14}C(p,π^-) reactions at bombarding energies in the 183 → 354 MeV range (corresponding to pion center–of–mass energies of 31 → 190 MeV) in order to further elucidate the role of the Δ isobar in nuclear pion production.

Our model of nuclear pion production includes microscopically both the one–nucleon mechanism and the resonant p–wave rescattering part of the two–nucleon mechanism, which is assumed to proceed through formation of the intermediate Δ(3,3) resonance induced by π and ρ meson exchange between the projectile and one target nucleon. Higher order processes are included through proton–nucleus and pion–nucleus optical model distortions. In previous papers,[6–8] we have shown that this model gives a reasonably good description of the ^{3}He(p,π^+)^{4}He and ^{4}He(π^-,n)^{3}H reactions in the near threshold region ($T_\pi^{cm} \sim 10 - 110$ MeV). These calculations suffered somewhat, however, from their sensitivity to the interference between the one–nucleon and two–nucleon mechanisms. In the present work, we apply our model to (p,π^+) and (p,π^-) transitions leading to final states having relatively pure two–particle one–hole configurations with respect to the target nucleus, which provide a separate test of the two–nucleon mechanism part of the model.

For the (p,π^+) tests, we chose the ^{16}O(p,π^+) reaction leading to the high–spin, 2p–1h final states in ^{17}O at 7.76 MeV (11/2$^-$) and 15.8 MeV (13/2$^-$). We assumed the dominant configurations of these two states to be:

$$| \, 13/2^-; T = 1/2\rangle \; = | \, [^{16}\mathrm{O} \otimes (\pi p_{3/2})^{-1}]_{3/2^-;1/2}[(\nu d_{5/2})(\pi d_{5/2})]_{5^+;0}\rangle$$

and

$$| \, 11/2^-; T = 1/2\rangle \; = | \, [^{16}\mathrm{O} \otimes (\pi p_{1/2})^{-1}]_{1/2^-;1/2}[(\nu d_{5/2})(\pi d_{5/2})]_{5^+;0}\rangle \; .$$

Transitions to both of these states can proceed through the elementary pp → NΔ → dπ^{+} process and are among the strongest transitions in the ^{16}O(p,π^{+}) spectrum.[9,10]

The initial proton distorted waves were obtained from standard non-relativistic optical model fits to p + ^{16}O elastic cross section and analyzing power data at 200, 318, and 500 MeV employing smooth interpolation techniques to obtain the parameters at $T_p = 250$ and 354 MeV. The pion distorted waves were generated using a pion-nucleus optical model code[11] employing the configuration space pion-nucleus optical potential of Johnson and Siciliano.[12]

The results of the $^{16}O(\vec{p},\pi^+)$ calculations at $T_p = 200, 250$, and 354 MeV are compared with data[9,10] in Fig. 1. The agreement between theory and experiment is reasonably good for the 15.8 MeV $13/2^-$ state at all three energies. Perfect agreement is not expected because of possible small s–wave rescattering contributions not included in the model. The somewhat poorer agreement for the 7.76 MeV $11/2^-$ state may be due to a small $(d_{5/2})^2(p_{3/2})^{-1}$ configuration admixture, which we have neglected.

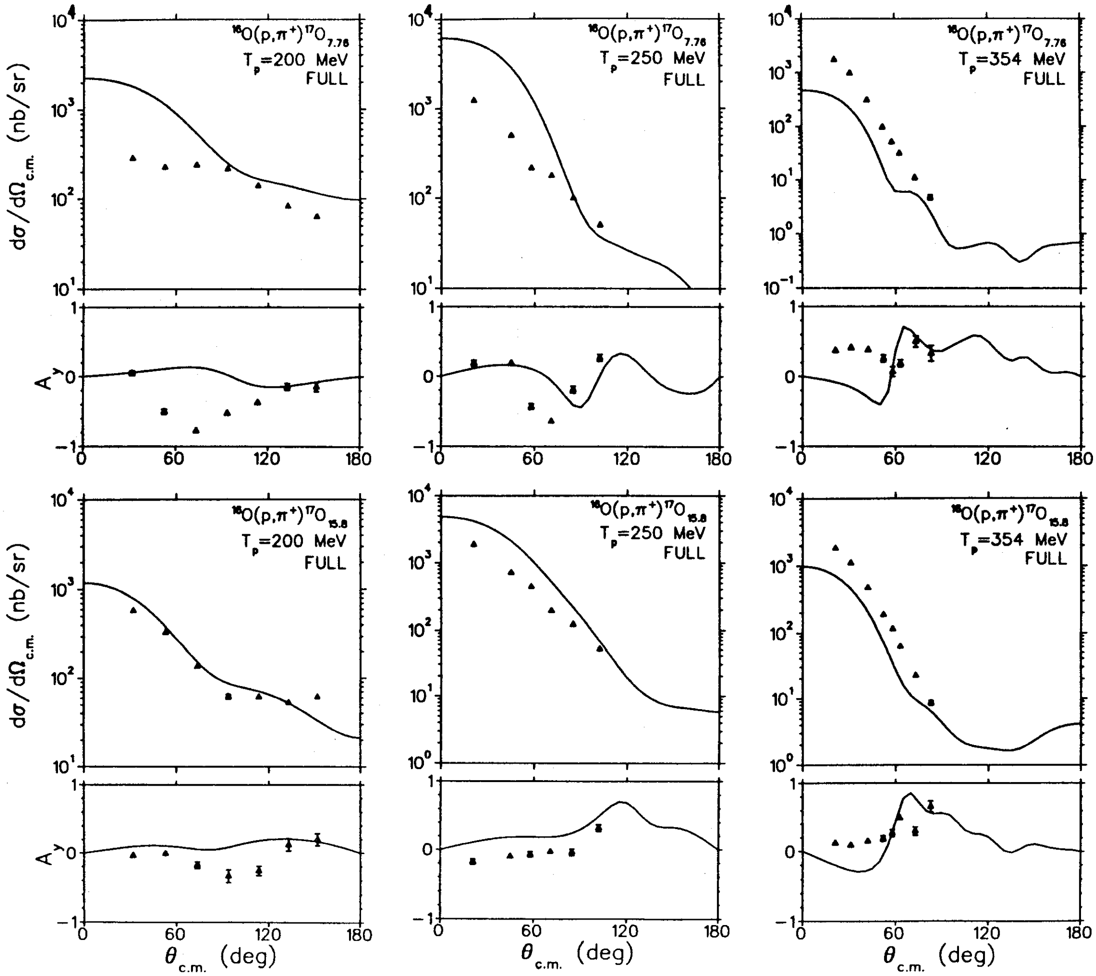

Figure 1. Two–nucleon model calculations of the $^{16}O(\vec{p},\pi^+)^{17}O^*$ reaction leading to final states at 7.76 MeV (top) and 15.8 MeV (bottom) at proton bombarding energies of 200, 250 and 354 MeV. The 200 MeV data are from Ref. 10 and the 250 and 354 MeV data are from Ref. 9.

In proton–induced π^- production via a two–nucleon mechanism, the incident proton must interact with a target neutron. For the calculations of the $^{12,13,14}C(p,\pi^-)$ transitions to the ground states of ^{13}O, ^{14}O and ^{15}O, we adopted a simple shell–model picture in which the active target neutron is in the $p_{1/2}$ orbit for ^{13}C and ^{14}C and the $p_{3/2}$ orbit for ^{12}C, and the final two protons are in the $p_{1/2}$ orbit. We assumed for the $7/2^+$ state at 7.28 MeV excitation energy in ^{15}O the pure shell–model configuration $\{[(\pi d_{5/2})(\pi p_{1/2}]_3 \text{-} (\nu p_{1/2})^{-1}\}_{7/2}$ with respect to the ^{14}C ground state. The proton and pion distorted waves were obtained employing the procedures described above.

The $^{12,13,14}C(p,\pi^-)^{13,14,15}O$(g.s.) calculations are compared with data[13] in Fig. 2. In contrast to the $^{16}O(p,\pi^+)$ results, the $^{12,13,14}C(p,\pi^-)$ calculations underestimate the

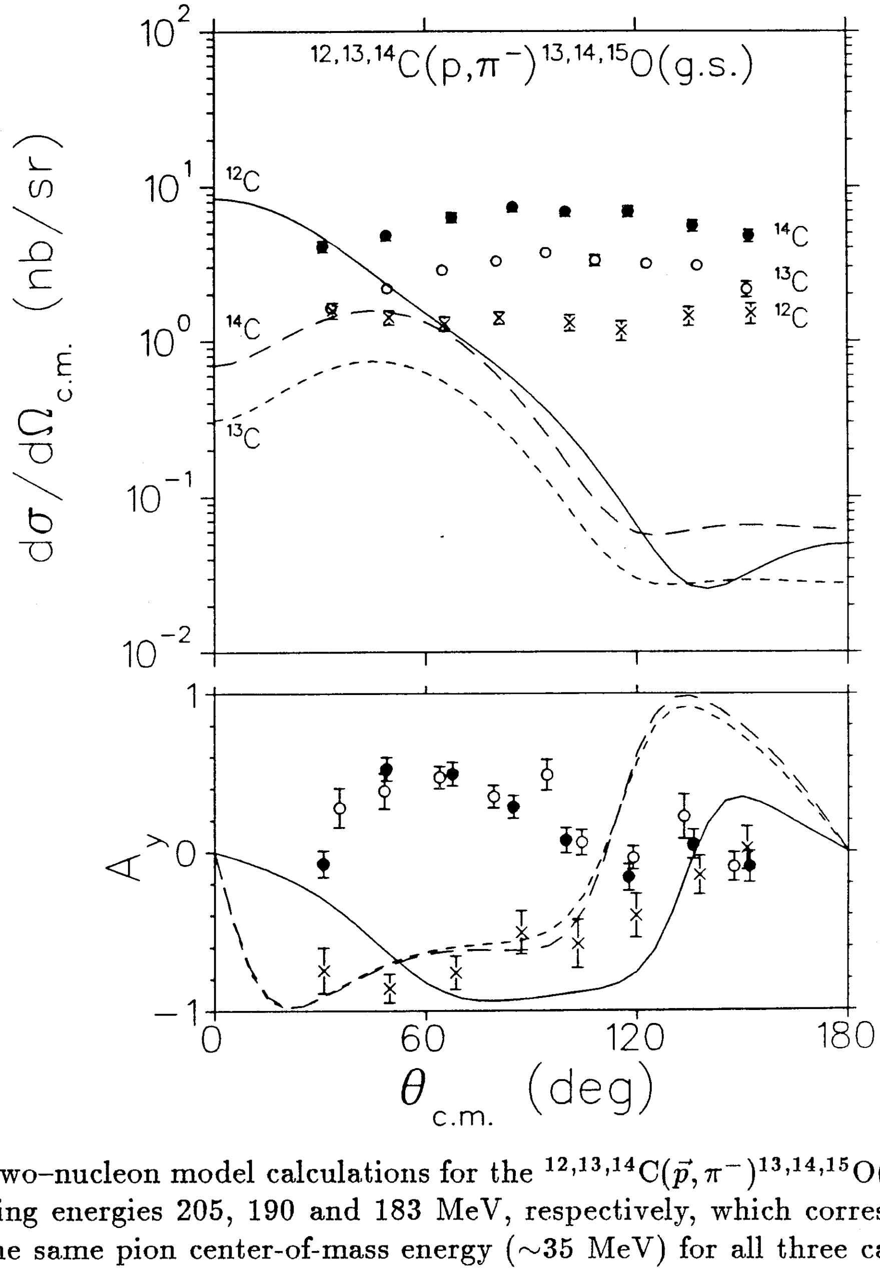

Figure 2. Two–nucleon model calculations for the $^{12,13,14}C(\vec{p},\pi^-)^{13,14,15}O$(g.s.) reactions at bombarding energies 205, 190 and 183 MeV, respectively, which correspond approximately to the same pion center-of-mass energy (~35 MeV) for all three cases. The data are from Ref. 13.

cross sections considerably and fail to reproduce the main features of the analyzing power angular distributions – for example, the opposite signs of the analyzing powers for the $^{13,14}C(p,\pi^-)$ and $^{12}C(p,\pi^-)$ reactions. One might expect this qualitative feature of the data to be reproduced by the model calculations, even if they give the wrong absolute magnitudes for the cross sections; however, in contrast to the (p,π^+) reaction, which is dominated by the two-nucleon channel $pp(^1D_2) \rightarrow N\Delta(^5S_2) \rightarrow pn(^3S_1) + \pi^+(\ell=1)$, the (p,π^-) reaction is not dominated by a single spin–isospin amplitude and is sensitive to the delicate interference between two (or more) weak amplitudes of comparable magnitude (see below). This amplifies the sensitivity of the calculations to any inadequacies of the input – e.g., the proton and pion distortions, which are responsible for the sidedness of the reaction in a classical picture[13].

Results of calculations for the $^{14}C(p,\pi^-)$ transition to the 7.28 MeV $(7/2^+)$ state in ^{15}O are compared with data[14] in Fig. 3. Here also, as for the ground state transitions, the calculations underestimate the cross sections and fail to reproduce the analyzing power angular distribution.

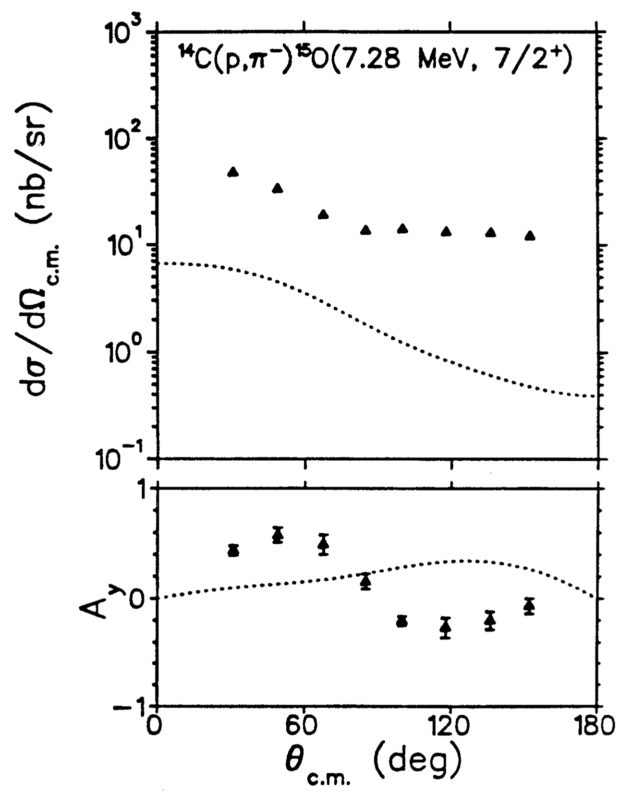

Figure 3. Two–nucleon model calculation for the $^{14}C(\vec{p},\pi^-)^{15}O$(7.28 MeV) reaction at a bombarding energy of 183 MeV. The data are from Ref. 14.

For negative pion production, $T_i = 0$ or 1 for the initial pn pair and $T_f = 1$ for the final pp pair. With the restriction of only s– and p–wave pions and $^1S_0$ and ^3P_j(J=0,1,2) final pp states, the allowed final, initial and intermediate state quantum numbers for the $pn \rightarrow N\Delta \rightarrow pp\pi^-$ reaction are those listed in Table I. For the ground state transitions, the final two protons are constrained by nuclear structure to be in a relative $^1S_0$ state, and consequently only the $^3P_0$, $^3S_1$, and $^3D_1$ states are allowed for the initial pn pair. For the transition to the 7.28 MeV $(7/2^+)$ final state, this nuclear structure constraint does not apply, but the large momentum transfer, short–range nature of the (p,π) reaction still tends to favor a relative s–state for the final two protons.[15–17]

Table I

Quantum numbers allowed by the generalized Pauli principle for the elementary two-nucleon pion production process p + n → ΔN → p + p + π^- . The notation for the pp, pn and ΔN states is $^{2S+1}L_J$.

#	Final State (pp)	ℓ_π	J^p	Initial State (pn)	T	Intermediate ΔN State
1	$^1S_0$	0	0^-	$^3P_0$	1	$^3P_0$
2		1	1^+	$^3S_1$	0	
3				$^3D_1$	0	
4	$^3P_0$	0	0^+	$^1S_0$	1	$^5D_0$
5		1	1^-	$^3P_1$	1	$^3P_1$
6				$^1P_1$	0	
7	$^3P_1$	0	1^+	$^3S_1$	0	
8				$^3D_1$	0	
9		1	0^-	$^3P_0$	1	$^3P_0$
10			1^-	$^3P_1$	1	$^3P_1$
11			2^-	$^3P_2$	1	$^3P_2$
12			1^-	$^1P_1$	0	
13	$^3P_2$	0	2^+	$^1D_2$	1	$^5S_2$
14				$^3D_2$	0	
15		1	1^-	$^3P_1$	1	$^3P_1$
16			2^-	$^3P_2$	1	$^3P_2$
17			3^-	$^3F_3$	1	$^3P_3$
18			1^-	$^1P_1$	0	
19			3^-	$^1F_3$	0	

The most definitive experiments bearing on the question of the dominant channels in the pn ↔ ppπ^- reaction are those of Aniol et al.[1] on π^- absorption by $^1S_0$ proton pairs in ^{3}He and Ponting et al.[5] on the $\vec{p}$n → π^-pp($^1S_0$) reaction. The pion production analyzing power measurements combined with a partial wave analysis[2] of the π^-pp($^1S_0$) → pn angular distributions extracted from ^{3}He(π^-,pn)n data show that there are roughly equal strengths in the T=0 channels #2 and #3 listed in Table I, for which an intermediate NΔ (T=1,2) state is not allowed by isospin conservation. Our present model calculations, which include only the Δ contribution to the π^- production process, seriously underestimate the cross sections and support the conclusion that the (p,π^-) reaction in the near threshold region is dominated by non–resonant contributions.

The present results (combined with those obtained earlier[6–8]) confirm that intermediate Δ formation dominates the (p,π^+) process in nuclei at intermediate energies but that other channels need to be included in microscopic models of the (p,π^-) reaction. The latter conclusion is consistent with the experimental[1,2,5] and theoretical[17] studies of the elementary pn $\leftrightarrow$ ppπ^- reaction mentioned above, as well as recent (pπ^-) calculations by Kume[18] that include both resonant and non–resonant rescattering.

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