RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 32, NUMBER 1 JULY 1985

N* model for the reaction $^{12}C(p,\pi^-)^{13}O_{g.s.}$ far above the 33 resonance

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(Received 27 March 1985)

The differential cross section for $^{12}C(p,\pi^-)^{13}O_{g.s.}$ at 613 MeV has been calculated in the framework of a microscopic two-nucleon model including the nucleon resonances $\Delta(1232)$, $N^*(1440)$, and $N^{*\prime}(1520)$. The good agreement with the experimental cross section both in magnitude and in shape strongly indicates that, in addition to the Δ isobar, the $N^{*\prime}$ (1520) resonance contributes substantially to the (p,π^-) reaction at this energy.

For more than ten years an impressive amount of effort, both experimentally and theoretically, has been devoted to the study of pion production in proton-nucleus collisions. Despite many experimental difficulties due to its very low cross section, the (p,π^-) reaction, particularly near threshold, has already been investigated about a decade ago.[1] More recently, spectacular results from this process provided strong evidence for the production of the π^- by a pair of interacting nucleons inside the nucleus.[2] Unfortunately, theoretical efforts so far do not match the experimental situation; though the (p,π^-) reaction seems to be a rather promising tool to unravel the reaction mechanism of the pion production process, very few attempts have been made so far to calculate the (p,π^-) cross section.

Since a negatively charged pion cannot be radiated off directly by the incoming proton, any microscopic model for the (p,π^-) reaction has to involve the interaction of the projectile with one or more target nucleons to account for the (p,π^-) double charge exchange. To date, only a few papers give predictions for the (p,π^-) differential cross section. The first papers consider three different models:[3] a model including Jastrow correlations, an extended distorted-wave Born approximation (DWBA) approach including two-step processes and a microscopic two-nucleon model. Characteristically, all these models involve severe phenomenological elements; furthermore, all these calculations are restricted to energies near the pion threshold. At higher energies, around or above the (3.3) resonance, calculations were only made by Kisslinger and Miller;[4] their model includes—beyond the two-step processes in the DWBA—the direct transfer of a Δ^{++} to the nucleus. Unfortunately, their predictions by far overestimated the experimental cross section,[5] as also confirmed in recent further (p,π^-) experiments.[6,7]

As an attempt to narrow the gap between theory and experiment, we present in this Rapid Communication the first calculation of a (p,π^-) differential cross section far above the (3,3) resonance, within the framework of a microscopic two-nucleon model (TNM).

With a detailed formulation of our model given elsewhere,[8] we present only the main steps of our calculation. In the two-nucleon model[3,9] pion production is assumed to proceed through the excitation of an intermediate baryon resonance induced by π and ρ exchange between the projectile and one bound nucleon. As a consequence, the transition potential of the elementary $NN\to NN\pi$ process,

$$V_{NN\to NN\pi}(\mathbf{r}_1,\mathbf{r}_2)=V_{12}(\mathbf{r}_1,\mathbf{r}_2)+V_{21}(\mathbf{r}_1,\mathbf{r}_2) \quad , \tag{1}$$

involves projectile and target emission diagrams (Fig. 1). Since we are dealing with energies well above the (3,3) resonance, we expect that beyond the $\Delta(1236)$ isobar, nucleon resonances with larger masses yield non-negligible contributions. Guided by the kinematics of the reaction and by the πN total cross section, we include in our approach the three low lying resonances, $\Delta(1232)$, $N^*(1440)$, and $N^{*\prime}(1520)$; the corresponding two-body transition potential in momentum space is then given by

$$\begin{aligned}V(\mathbf{q},\omega;\mathbf{k}_\pi)=&V_\Delta(\mathbf{q},\omega;\mathbf{k}_\pi)\\&+V_{N^*}(\mathbf{q},\omega;\mathbf{k}_\pi)+V_{N^{*\prime}}(\mathbf{q},\omega;\mathbf{k}_\pi) \quad .\end{aligned} \tag{2}$$

As a specific example we obtain, with the standard Lagrangians $L_{NN\pi}$ and $L_{NB\pi}$ (Ref. 10), for the excitation of the baryon resonance B by π exchange

$$\begin{aligned}V_B(\mathbf{q},\omega;\mathbf{k}_\pi)=&L_{NB\pi}(\mathbf{k}_\pi)G_B(\omega,E_B)L_{NB\pi}(\mathbf{q})\\&\times D_\pi(q^2)L_{NN\pi}(\mathbf{q})F_\pi(q^2)F_B(k_\pi^2)\end{aligned} \tag{3}$$

(note $q^2=\mathbf{q}^2-\omega^2$). Above, the form factors F_π and F_B ac-

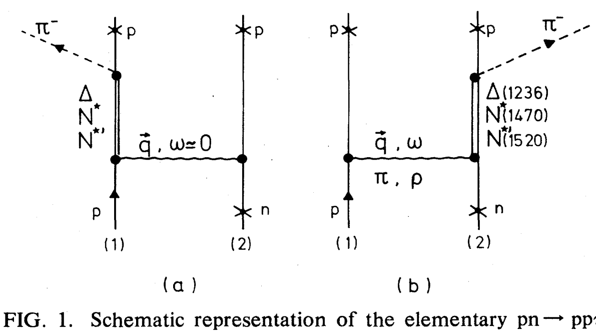

FIG. 1. Schematic representation of the elementary $pn\to pp\pi^-$ amplitude. Both the projectile (a) and the target emission diagram (b) represent six different time ordered pieces. The crosses on the nucleon lines denote bound nucleons.

TABLE I. Parameters of the baryon resonances used in our model (Ref. 18).

Resonance	T	J^π	1	M^* (MeV)	Γ_0 (MeV)	k_π^* (MeV/c)	$b_{N\pi}$(%)
$\Delta(1232)$	$\frac{3}{2}$	$\frac{3}{2}^+$	1	1232	115	227	99.4
$N^*(1440)$	$\frac{1}{2}^+$	$\frac{1}{2}^+$	1	1440	200	397	60
$N^*(1520)$	$\frac{1}{2}$	$\frac{3}{2}^-$	2	1520	125	456	55

count for off-shell corrections; actually they are parametrized as monopole forms. The functions $D_\pi(q^2)$ and $G_B(\omega,E_B)$ represent nonstatic pion and isobar propagators (in practice they include all time ordered diagrams), with ω given by the scattering energy in the center-of-mass system. The total energy of the resonance, entering in $G_B(\omega,E_B)$, is defined as

$$E_B = M^* + \frac{k_p^2+k_\pi^2}{2M^*} + i\frac{\Gamma^*}{2}\left|\frac{\mathbf{k}_\pi}{\mathbf{k}_\pi^*}\right|^{2l+1} F_B(\mathbf{k}_\pi^2) , \tag{4}$$

with the mass M^* of the baryon resonance, its free width Γ^*, the pion momentum k_π^* from the $B\rightarrow N\pi$ decay of the resonance energy, and the internal orbital momentum 1 given in Table I. The kinetic energy of the resonance has been averaged over the energy of the incoming proton and outgoing pion.

Finally, within the forward scattering approximation, we calculate the two-body transition potential in $\mathbf{r}$ space as

$$V_B(\mathbf{r}_1,\mathbf{r}_2;\omega,\mathbf{k}_\pi) = \delta(x_1-x_2)\delta(y_1-y_2) \times\frac{1}{2\pi}\int V_B(q_z;\omega,\mathbf{k}_\pi)e^{iqz(z_1-z_2)}dq_z . \tag{5}$$

We feel that this approximation, which assumes that the intermediate pion is emitted along the direction of the projectile, is well justified for small pion angles in view of the large projectile energy.

To obtain the differential cross section for the (p,π^-) reaction on a spin-zero target,

$$\frac{d\sigma}{d\Omega}(\mathbf{k}_p,\mathbf{k}_\pi) = \frac{1}{(2\pi)^2}\frac{E_pE_AE_{A+1}}{(E_p+E_A)^2}\frac{k_\pi}{k_p}\frac{1}{4}\sum_{\mu M}|M_{fi}(\mathbf{k}_p,\mathbf{k}_\pi)|^2 , \tag{6}$$

we have to evaluate the transition amplitude,

$$M_{fi}(\mathbf{k}_p,\mathbf{k}_\pi) = \sum_n \langle f|V_{pn\rightarrow pp\pi^-}(\mathbf{r}_1,\mathbf{r}_2)|i\rangle \tag{7}$$

(the sum includes all target neutrons participating in the elementary $p+n\rightarrow p+p+\pi^-$ subprocess). For the initial state with a spin and isospin saturated ^{12}C target nucleus we obtain

$$|i\rangle = |e^{i\mathbf{k}_p\cdot\mathbf{r}_1}\chi^\sigma_{1/2\mu}(1)\chi^\tau_{1/2\,1/2}(1)\rangle\,|0^+,0\rangle , \tag{8}$$

whereas the final ^{13}O ground state, which we represent as two-particle one-hole configurations coupled to the ^{12}C core with $|J^\pi,T\rangle = |0^+,0\rangle$, is given by

$$|f\rangle = \sum_\nu C_\nu(2p1h)\{\alpha(1)[\beta(2)\bar{\beta}'(2)]^{J_\beta^\pi}\}^{JM,TM_T}|0^+,0\rangle . \tag{9}$$

Above, $\chi^{\sigma(\tau)}_{1/2\lambda}$ denote Pauli spinors in the spin and isospin space; the coefficients $C_\nu(2p1h)$ weigh the different $2p1h$ configurations in the ^{13}O ground state.

With the appropriate spin and isospin factors F_σ and F_τ, respectively, the transition amplitude can be reduced to the following schematical form

$$M_{fi}(\mathbf{k}_p,\mathbf{k}_\pi) = D(k_p,k_\pi)F_sF_\tau\sum_\nu C_\nu(2p1h)\frac{1}{(2\pi)^3}\int V_B(\mathbf{q},\omega;\mathbf{k}\pi)I_\alpha(\mathbf{k}_p-\mathbf{q})I_{\beta\beta'}(\mathbf{q}-\mathbf{k}_\pi)\,d\mathbf{q} , \tag{10}$$

whereby

$$I_\alpha(\mathbf{k}_p-\mathbf{q}) = \int e^{i(\mathbf{k}_p-\mathbf{q})\mathbf{r}}\psi_\alpha^*(r)\,dr ,$$

$$I_{\beta\beta'}(\mathbf{q}-\mathbf{k}_\pi) = \int e^{i(\mathbf{q}-\mathbf{k}_\pi)\mathbf{r}}\psi_\beta^*(\mathbf{r})\psi_{\beta'}(\mathbf{r})\,d\mathbf{r} .$$

Here the $\psi_j(\mathbf{r})$ represent single particle wave functions with the quantum numbers $\gamma=\{n,l,j,m\}$.

As at kinetic energies above the (3,3) resonance, the corrections due to initial and final state interactions are mainly absorptive; they have been included above in the spirit of the factorized eikonal approximation as a damping factor: $D(k_p,k_\pi)$ was calculated as the ratio of the nuclear overlap integral with distorted and plane waves. In practice the DWBA code DWUCK5 (Ref. 11) was used, with slight modifications to account for the particular form of the overlap integral in the TNM in the zero range limit.

As input for our numerical calculations we used the following coupling constants:[12] $f_\pi^2/4\pi=0.081$ for the πNN coupling and $f_\pi^{*2}/4\pi=0.37$, 0.0075, and 0.0027 for the $\pi N\Delta(1232)$, $\pi NN^*(1440)$, and $\pi NN^{*\prime}(1520)$ vertices, respectively; for the cutoff masses in the monopole form factors, $\Lambda_\pi=800$ MeV (Ref. 13) and $\Lambda^*=400$ MeV for the pion and the isobars, respectively, was taken (unless specified explicitly). Lacking any reliable information on the ground state wave function of ^{13}O (Ref. 14), it was represented by a single $(1p\frac{1}{2})^2(1p\frac{3}{2})^{-1}$ configuration with spin and isospin quantum numbers $J^\pi=\frac{3}{2}^-$ and $(T,M_T)=(\frac{3}{2},-\frac{3}{2})$, coupled to the $|0^+,0\rangle\,^{12}C$ core.

A comparison with the $^{12}C(p,\pi^-)^{13}O_{g.s.}$ data at 613 MeV (Ref. 6) is shown in Fig. 2. We find fairly good agreement for both the shape of the experimental angular distribution and the magnitude of the cross section. The dashed areas indicate the typical uncertainty introduced by ambiguities in the nucleon wave functions. To demonstrate the sensitivity on the nuclear wave functions, we increased the harmonic oscillator parameter from its "standard value" $a=1.635$ fm (as extracted for ^{13}C from electron scattering data[15]) up to 5%; evidently the moderate sensitivity reflects the momen-

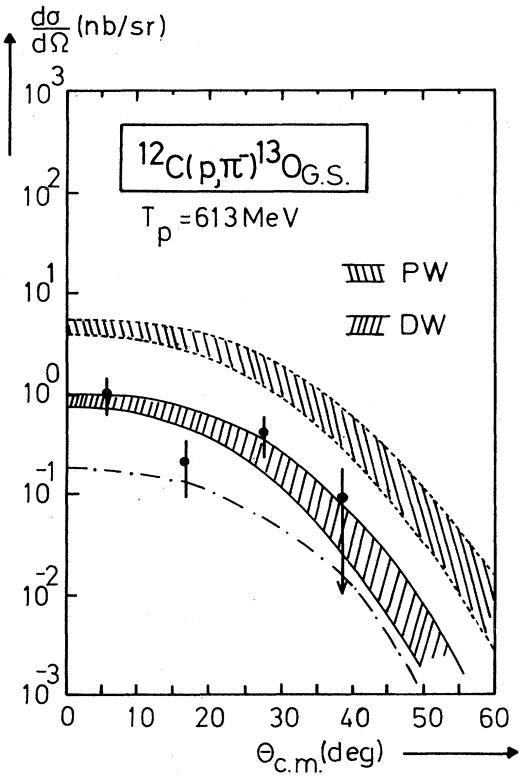

FIG. 2. Differential cross section for the $^{12}C(p,\pi^-)^{13}O_{g.s.}$ reaction at $T_p = 613$ MeV with plane (PW) and distorted waves, generated from a pion potential of Laplacian (DW) or *s*-wave form (dashed-dotted line). For the dashed areas the oscillator parameter in the nuclear wave function was increased up to 5% (see the text for details). The experimental results are from Ref. 6.

tum sharing in the TNM. Ambiguities in the distortions dominantly reflect the lack of pion scattering data at energies far above the (33) resonance; to explore the sensitivity we compare a parametrization of the pion-nucleus potential as an effective local *s*-wave potential or as a local Laplacian form, including *s* and p waves together with absorptive corrections.[16] Opposite to the pion distortions, the optical proton-nucleus potential is well known from elastic proton-^{12}C scattering around 600 MeV.[17] Overall, distortions reduce the plane wave cross section typically by a factor of 5.

A further serious uncertainty in our model arises from off-shell effects as demonstrated in Fig. 3. Since most calculations drop off-shell corrections for the isobars, the parameter Λ^* is poorly determined; fortunately we find that its influence is fairly small (it is comparable to the sensitivity on the nuclear wave function as discussed above; compare Figs. 2 and 3). In contrast, the pion cutoff has a significant influence on the cross section; the value $\Lambda_\pi = 800$ MeV, as favored in our calculation, agrees with findings from the pp→ $d\pi^+$ process, provided ρ exchange is not included explicitly in the rescattering amplitude.[13]

The contribution from the various baryon resonances is shown in Fig. 4. Despite the relatively large scattering energy, the Δ isobar is still very important. Beyond that, however, we find a strong influence from the excitation of the N*′(1520); its contribution to the cross section is compar-

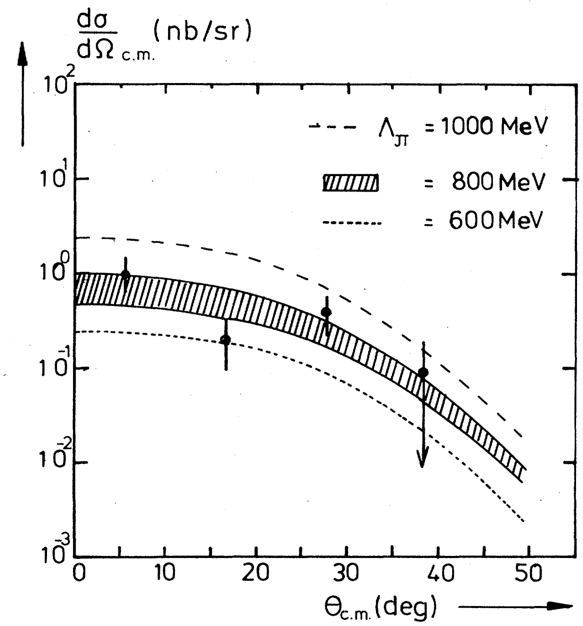

FIG. 3. Sensitivity on the cut-off masses Λ_π and Λ^* for the off-shell continuation of the pion and the baryon resonances. Compared are three typical values for the pion cutoff; for $\Lambda_\pi = 800$ MeV the shaded area demonstrates the influence of Λ^* for $\Lambda^* = 0$ (upper boundary) and $\Lambda^* = 400$ MeV (lower boundary).

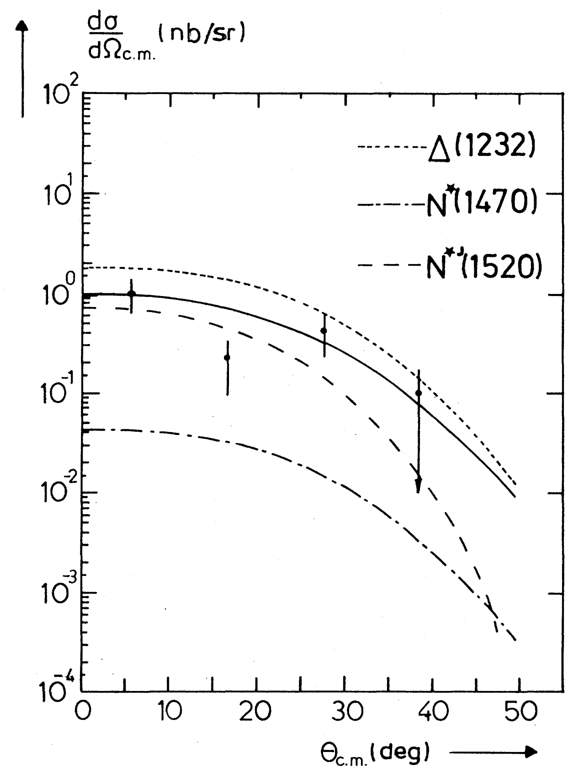

FIG. 4. Contribution of the various baryon resonances to the differential cross section. The full result (solid line) is the coherent sum of the three contributions.

able to the Δ-isobar piece. Finally, as expected from its small coupling constant (see Table I), the influence of the Roper resonance N*(1440) is found to be negligibly small.

In conclusion, we have presented a first microscopic calculation of the double charge exchange reaction (p,π^-) around 600 MeV. Within our meson exchange model we obtain qualitative agreement with the data; furthermore we find a strong influence not only of the Δ(1232) isobar, but also of the N*(1520) resonance on the cross section. From a continuing study of the various amplitudes—further calculations are underway—we hope to end up with a detailed understanding of the dynamics of baryon resonances in nuclei.

One of us (M.D.) would like to thank the Departement of Physique Nucleaire/Moyenne Energie at the Centre d'Etude Nucléaire, Saclay, for their hospitality. This work was supported in part by the German Bundesministerium für Forschung und Technologie.

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