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Neutral pion photoproduction in a phenomenological isobar doorway model

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The phenomenological isobar doorway model of Kisslinger and Wang is applied to the reaction $^{12}C(\gamma,\pi^0)^{12}C$ for photon energies between 220 and 360 MeV. The parameters of the model are determined by fitting pion elastic scattering data. Over most of thee energy range the isobar model gives a total photoproduction cross section substantially larger than distorted-wave impulse approximation with a static first order optical potential. The calculated cross sections are compared to experimental data at photon energy 250 MeV.

[NUCLEAR REACTIONS $^{12}C(\pi^-,\pi^-)$, $^{12}C(\gamma,\pi^0)$, resonance region, isobar doorway model.]

Static first order optical potential models are quite successful in describing medium energy pion-nucleus elastic scattering.[1] On the other hand distorted wave impulse approximation (DWIA) calculations using these same optical potentials do not always yield satisfactory results for inelastic reactions. The best known example is the reaction $^{13}C(\pi^+,\pi^0)^{13}N$ (g.s.) where due to the strong absorption in the elastic channel DWIA calculations yield cross sections much smaller than the experimental values.[2,3] In a recent paper Blomqvist *et al.*,[4] presented their results for $^{27}Al(\gamma,\pi^+)^{27}Mg$ and $^{51}V(\gamma,\pi^+)^{51}Ti$. Here also DWIA calculations give cross sections much smaller than experiment. This similar behavior for different reactions involving different nuclei suggests that the problem with the calculations lies in the static optical model treatment of the pion nucleus interaction and not, for example, in mechanisms which are specific to a particular reaction such as the two-step process for charge exchange suggested by Gal and Eisenberg.[5]

In a recent paper Auerbach[6] has applied the isobar doorway model of Kisslinger and Wang[7] (KW) to the reaction $^{13}C(\pi^+,\pi^0)^{13}N$. Using parameters fitted to π ^{12}C elastic scattering, the model yields a total charge exchange cross section which is in much better agreement with experiment than DWIA.

In this paper we use the Kisslinger-Wang model for the (γ,π^0) reaction which we suggest should be a very good testing ground for the isobar doorway formalism. In the energy range of interest here, π^0 photoproduction is completely dominated by $\Delta(1232)$ production. Also, neutral pions can be produced coherently, so at least within the KW model one can use the same isobar-nuclear form factor for π^0 production as for pion elastic scattering. The isobar model results are compared with a DWIA calculation and with data which are now available at only one energy. We hope that this work will stimulate more experimental study of the energy dependence of nuclear (γ,π^0) reactions.

The reader is referred to the papers of Kisslinger and Wang[7] for a complete discussion of the isobar doorway model and only the results are given here. The KW model for the pion-nucleus elastic scattering T matrix is

$$T(\vec{k},\vec{k}')=T^{NR}(\vec{k},\vec{k}')+n\frac{\langle\vec{k}'|t|\vec{k}\rangle(E-E_0+\frac{1}{2}i\Gamma_0)F_\Delta(\vec{k},\vec{k}')}{E-E_0+\overline{\Delta E}+\frac{1}{2}i\overline{\Gamma}}\,, \qquad (1)$$

where T^{NR} is the contribution to the T matrix from nonresonant interactions and $\langle\vec{k}'|t|\vec{k}\rangle$ is the pion-nucleon T matrix. The quantity $\langle\vec{k}'|t|\vec{k}\rangle(E-E_0+\frac{1}{2}i\Gamma_0)$ describes the formation and decay of the isobar, and the isobar-nuclear form factor F_Δ is a product of nucleon and isobar densities. The denominator of the second term describes the propagation of the isobar doorway state. The normalization factor n is $Z+\frac{1}{3}N$ for π^- scattering from a target of Z protons and N neutrons.

In this paper we restrict ourselves to pion scattering and photoproduction from ^{12}C which is also the nucleus considered by Kisslinger and Wang.[7] The parameters of the free Δ were taken to be $E_0=180$ MeV and $\Gamma_0=120$ MeV. The parameter $\overline{\Delta E}$ was fixed at 20 MeV (in agreement with Auerbach[6]), and $\overline{\Gamma}$ was varied with energy to fit the integrated elastic cross section. The parametrization used for the form factor was

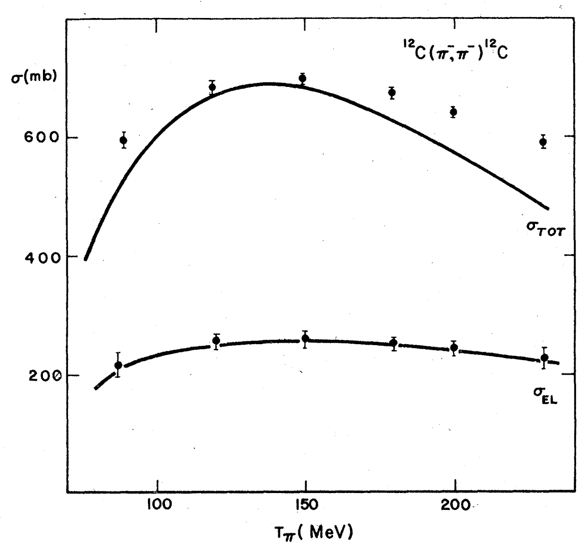

FIG. 1. Total and elastic cross sections for $^{12}C(\pi^-, \pi^-)^{12}C$ as a function of pion laboratory kinetic energy. Data from Binon *et al.* (Ref. 10).

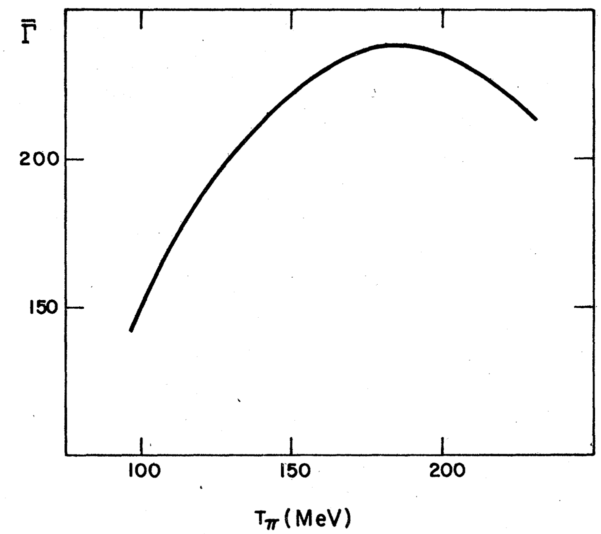

FIG. 2. Energy variation of the parameter $\bar{\Gamma}$ (units of MeV).

$$F_\Delta(\vec{k},\vec{k}') = (1+\lambda Q^2b^2/24)e^{-Q^2b^2/4}\,, \tag{2}$$

where $\vec{Q}=\vec{k}-\vec{k}'$. For $\lambda=-3$, F_Δ equals the nuclear form factor for a harmonic oscillator wave function. The parameter b was taken as 1.64 fm in agreement with analysis[8] of electron scattering data. The parameter λ was adjusted to fit the pion scattering differential cross section. The value $\lambda=4$ was used at all energies.

The pion-nucleon T matrix in the Δ channel was calculated from the (3, 3) phase shift, and Coulomb and frame transformation effects were neglected. The nonresonant part of the amplitude $T^{\rm NR}$ was calculated with a static first order optical potential using the momentum space pion scattering code PIPIT.[9] The results for the total and elastic π^- ^{12}C cross sections are shown in Fig. 1 along with the data of Binon *et al.*[10] The variation of the parameter $\bar{\Gamma}$ as a function of pion laboratory kinetic energy is shown in Fig. 2.

Using the (KW) model the π^0 photoproduction amplitude for a spin zero target becomes

$$\mathfrak{M} = i\vec{\epsilon}\cdot(\hat{k}\times\hat{q}) \times\left[M^{\rm NR}+\frac{(N+Z)\mathfrak{F}(\vec{k},\vec{q})(E-E_0+\frac{1}{2}i\Gamma_0)F_\Delta(\vec{k},\vec{q})}{E-E_0+\overline{\Delta E}+\frac{1}{2}i\bar{\Gamma}}\right]\,, \tag{3}$$

where $\vec{\epsilon}$ is the photon polarization vector, and $\hat{k}$ and $\hat{q}$ are unit vectors in the direction of photon and pion momentum. The amplitude $M^{\rm NR}$ describes pion photoproduction and rescattering through nonresonant interactions. In fact this term is very small and will not be included in the calculation. $\mathfrak{F}(\vec{k},\vec{q})$ is the function which multiplies $i\vec{\epsilon}\cdot(\hat{k}\times\hat{q})$ in the elementary (single nucleon) photoproduction amplitude[11] and takes the place of the pion-nucleon T matrix in Eq. (1). For an isospin zero target only the isospin (+) component of $\mathfrak{F}$ (see Ref. 11) will contribute. Keeping only the $l=1$ multipole

$$\mathfrak{F} = 2M_{1+}^{(+)}+M_{1-}^{(+)}\,. \tag{4}$$

The multipole amplitudes are obtained from the energy independent analysis of Pfeil and Schwela.[12]

In DWIA the photoproduction amplitude can be written

$$\mathfrak{M}_{\rm DW} = i\mathfrak{F}(\vec{k},\vec{q})\mathfrak{M}_\lambda\,, \tag{5}$$

with

$$\mathfrak{M}_\lambda = \sum_{J\geq 1}\left[\frac{2\pi J(J+1)}{2J+1}\right]^{1/2} Y_{J\lambda}(\hat{q})T_J\,, \tag{6}$$

where $Y_{J\lambda}$ is a spherical harmonic, and λ denotes the polarization of the incoming photon. The multipole amplitude T_J is given by

$$T_J \doteq \int dr\,r^2\rho(r)\left[\left(\frac{d}{dqr}-\frac{J}{qr}\right)f_J(r)j_{J+1}(kr) + \left(\frac{d}{dqr}+\frac{J+1}{qr}\right)f_J(r)j_{J-1}(kr)\right]\,, \tag{7}$$

where $\rho(r)$ is the nuclear density, and $f_J(r)$ is the distorted pion wave function. Distortion was included for partial waves up to $J=5$ and the pion wave functions were calculated using a static first order optical potential model.[9] In the medium energy region the effective result of distortion is

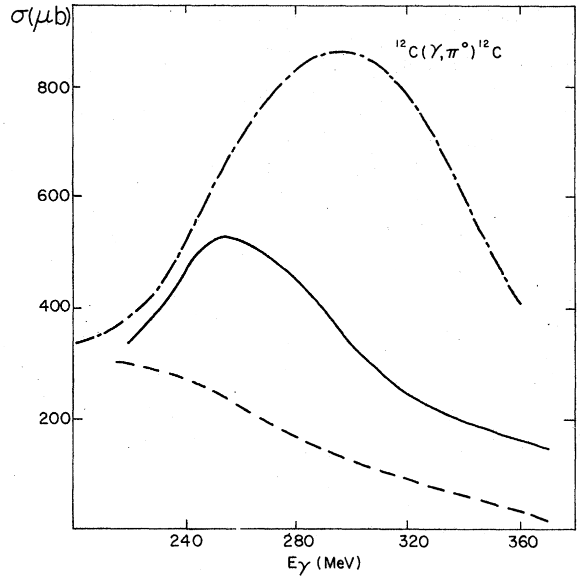

FIG. 3. Total cross section for $^{12}C(\gamma,\pi^0)^{12}C$ as a function of photon energy. Solid curve is the isobar doorway result. PWIA (dot-dashed) and DWIA (dashed) results are also shown.

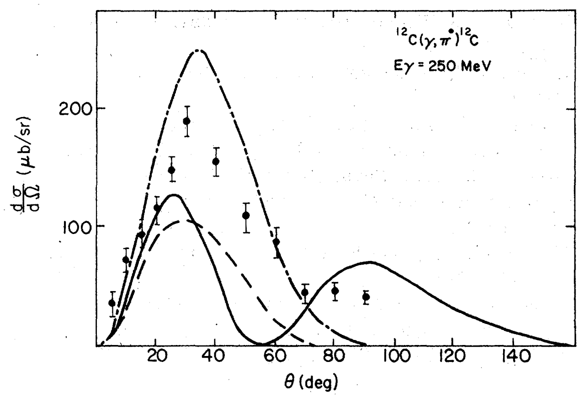

FIG. 4. Angular distribution for $^{12}C(\gamma,\pi^0)^{12}C$ at a photon energy of 250 MeV in the isobar doorway (solid curve), PWIA (dot-dashed) and DWIA (dashed) models. The data are taken from Saunders (Ref. 15).

to eliminate the low pion partial wave contributions to $\mathfrak{M}_\lambda$.

Figure. 3 shows the isobar doorway model result for the $^{12}C(\gamma,\pi^0)^{12}C$ total cross section as a function of photon energy (solid curve). Also shown are the PWIA and DWIA predictions (dot-dashed and dashed curves). Clearly the same pattern of strong absorption in the DWIA approach as observed in (π^+,π^0) and (γ,π^+) reactions also emerges here.

The angular distribution at photon energy 250 MeV is shown in Fig. 4 along with PWIA and DWIA results. The data of Davidson[14] (as quoted by Saunders[15]) are also shown. The fact that the isobar model gives a substantial cross section at large angles where DWIA is essentially zero is encouraging. On the other hand the data show no evidence of a dip around 50°. In the isobar doorway model this dip reflects the first diffractive minimum of the pion-nucleus elastic scattering differential cross section and is very difficult to avoid in a model of the KW type where the total amplitude (all partial waves) is parametrized by a single form factor. Treating each partial wave separately may provide a way around this difficulty. The double spin-flip contributions which were found to be important by Osland and Rej[16] could then also be included.

To summarize we suggest the (γ,π^0) reaction as a good test for the isobar doorway approach to pion-nucleus interactions. In this paper the phenomenological Kisslinger-Wang isobar doorway model is applied to $^{12}C(\gamma,\pi^0)^{12}C$ and compared to a DWIA calculation. Comparing the calculated angular distribution with the available data clearly shows the limitations of the KW type of model where one parameterizes the amplitude as a whole rather than dealing with partial waves separately. On the other hand the isobar model yields a total photoproduction cross section which over the energy range $220 < E_\gamma < 360$ MeV is substantially larger than the static optical potential DWIA indicating a lessening of the absorptive effects. This is similar to what has been found for the reaction $^{13}C(\pi^+,\pi^0)^{13}N$. Clearly it would be very interesting to have experimental information on the energy dependence of nuclear π^0 photoproduction cross sections.

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