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PION NUCLEUS REACTIONS AT HIGH ENERGIES

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ABSTRACT

We investigate the inclusive pion nuclear reactions, at energies above the Δ resonance, up to energies of 1.5 GeV. We have developed a cascade model that uses the elementary πN cross sections, and includes some medium effects, like Fermi motion and Pauli-blocking. The absorption is implemented using a theoretical model. It has a very small effect, at high pion energies, for most observables. We present some results, specially those that we have found interesting, either because of the discrepancies with the experimental data, or because we think they open new opportunities to look for medium effects, or alternative exotic mechanisms.

1. Introduction

Pion-nuclear physics above the region dominated by the Δ resonance is a relatively unexplored field. However, there are several characteristics which make it very interesting. At higher energies, the pion wavelength becomes shorter. That implies a larger sensitivity to spatial distributions. In fact, the wavelength is short enough to be able to probe details smaller than one fm, and therefore, to study modifications of the nucleon properties inside the nuclear medium, and to analyze short-range effects.

A second relevant feature is the weakness of the $\pi - N$ interaction. After the very prominent peak produced by the Δ, the cross section of all channels falls down rapidly. That means that pions are able to penetrate deeper into the nuclei, and to explore high baryon density regions, unreachable by pions at resonance, that are a very peripheral probe. See, for instance, the ref. 1, where this topic is nicely discussed.

There is very little work done, both theoretically and experimentally, in this energy region. We will mention some of it along this paper. At this quite preliminary stage, it is useful to begin by creating simple models, that should include all trivial effects, and then proceed to look for clear discrepancies with the experiments, that could point out to some new physics.

In this work, we will present, results obtained by a cascade code. We will compare them, when possible, with experimental data. In our presentation we will concentrate specially on some of the problems and difficulties, in understanding the experimental data, that have been found by us and others. Some calculations,[2] similar to the one presented here, described quite well all π-nucleus inclusive reactions around the Δ-resonance: absorption, quasielastic scattering, single charge exchange, and double charge exchange. At these higher energies the wavelength of the pion is shorter and therefore quantum interference effects should be less important, and the calculation more reliable.

2. Model

Pions travelling inside the nuclear medium can undergo several different processes. They can be absorbed, can change direction, energy, or charge. They also can produce more pions. The basic inputs for our code are the probabilities per unit length of each of these channels to happen. How we obtain these probabilities is briefly described below. Technical details on the simulation itself, will be published elsewhere.

2.1. $\pi N \longrightarrow \pi N$

The probability per unit length of quasielastic scattering (or single charge exchange) is given by

$$P_{N(\pi^\lambda,\pi^{\lambda'})N'} = \sigma_{N(\pi^\lambda,\pi^{\lambda'})N'}\,\rho_N \qquad (1)$$

where N stands for neutron or proton, ρ_N is the density of nucleons of type N, and $\sigma_{N(\pi^\lambda,\pi^{\lambda'})N'}$ is the elementary cross section for the reaction $\pi^\lambda + N \rightarrow \pi^{\lambda'} + N'$. The proton density is taken from experiment, and the neutrons density is assumed to be proportional to the proton density.

When, a quasielastic scattering takes place, we choose randomly a nucleon, of the type N, from the Fermi sea, then we boost the π and N to their center of mass. Then, we select the scattering angle and energy of the outgoing particles using the experimental cross sections, and boost the momenta back to the lab system. When the momentum of the outgoing nucleon in the lab system is below the fermi level, the event is Pauli-blocked and therefore we keep the pion initial charge and momentum unchanged.

It should be mentioned here, that the $\pi N \rightarrow \pi N$ amplitude could be considerably modified in the nuclear medium. That is the case at energies around the Δ resonance. In fact, one of the first surprises in high energy pion-nuclear physics has been the discrepancy, unexplained yet, between theoretical calculations and data for elastic scattering in ^{12}C at 800 MeV.[4] See for instance refs..[1,3] Also, some discrepancies have been found for the single charge exchange channel at 500 MeV.[5] See ref.[6] for a possible explanation.

2.2. Pion absorption

Pion absorption is supposed to be a relatively small effect at high energies. That is suggested by the rapid decrease of the pion-deuteron absorption cross section at the energy range from $0.5 - 1.0$ GeV.[7] In any case, there is always a large number of pions at lower energies generated both by the quasielastic rescatterings and the pion production processes. The proportion of these pions that eventually comes out of the nucleus is essentially determined by the absorption strength.

Although the pion absorption has been extensively studied at energies below 0.3 GeV, there is little theoretical work done, and very little experimental information about pion absorption by complex nuclei at high energies. In ref.[6] the effect of pion absorption on the pion-nucleus elastic and the SCX scattering has been studied in the energy range of 250 to 650 MeV. The model contains both two- and three-nucleon absorption mechanisms. Their results show a quite weak absorption at high energies.

The imaginary part of the pion self-energy, related to two-nucleon pion absorption, which has been calculated in ref.[6] is of the form

$$Im\Pi^{(2)}_{abs}(k) = -D_2 \frac{s\,\bar{\sigma}}{q}\,\rho^2 \qquad (2)$$

Here, $D_2 = 0.0116\,fm^5\,mb^{-1}$. k is the pion momentum in the lab system, s is the square of the c.m. energy of a pion of momentum k and a nucleon at rest, $\bar{\sigma} = (\sigma_{3/2} + \sigma_{1/2})/3$ is the spin-isospin averaged unpolarized πN cross section, and the momentum of a virtual pion q that appears in their model is determined as

$$q = \{[\frac{(k^0 + 2m)^2 - \vec{k}^2}{2(k^0 + 2m)}]^2 - m^2\}^{1/2}$$

which in the nonrelativistic actually used in[6] goes to

$$q = [m(k^0 - \vec{k}^2/2m)]^{1/2}$$

where m is mass of a nucleon.

The three-nucleon pion absorption has been calculated[6] in a similar fashion, and the contribution to the self energy is given by

$$Im\Pi^{(3)}_{abs}(k) = -D_3 \frac{s\,\bar{\sigma}}{q'} \frac{s'\,\bar{\sigma}'}{q'}\,\rho^3 \qquad (3)$$

with

$$q' = [\frac{m}{2}(k^0 - \vec{k}^2/2m)]^{1/2}$$

and $s', \bar{\rho}'$ have the same meaning as s and $\bar{\rho}$, but are evaluated at a kinetic energy of the pion equal to two thirds of the real one ($T'_\pi = \frac{2}{3}T_\pi$).

The pion selfenergy pieces of eqs. (2) and (3) can readily be translated to a probability per unit length by the relation $P_{abs} = -Im\,\Pi_{abs}(k)/k$.

A different estimation of the pion absorption can be found in ref..[3] Although the two prescriptions give quite different results, both of them get a quite weak absorption at high energies, and most of the observables are insensitive to which of the two models is chosen.

2.3. *Pion production*

Pion production is a determinant feature in the high energy pion nucleus reactions. Actually, the inelastic channels have a cross section comparable, or even larger than the elastic channels at energies above 0.6 GeV. At the energies we are considering, the inelastic cross section is clearly dominated by the single pion production.[8] Thus, we will neglect the multipion production channels in this work.

At low energies there is a considerable wealth of data for most isospin channels of this process, including differential cross sections. Unfortunately, our knowledge is more fragmentary in the energy regime we address here. We use data taken from the compilation[8] and from.[9,10] to obtain parametrizations of the $\pi N \to \pi\pi N$ total cross sections. Then, for each channel, the probability per unit length is given by the equation

$$P_{N(\pi,2\pi)N'} = \sigma_{N(\pi,2\pi)N'}\,\rho_N \qquad (4)$$

When, according to this probability, a pion production event takes place, we choose randomly a nucleon, of the type N, from the fermi sea. Then we select the scattering angles and energies of the outgoing particles, using the 3-body phase space distribution. When the momentum of the outgoing nucleon is below the fermi level, we consider the event to be Pauli-blocked and therefore keep the pion initial charge and momentum unchanged, and do not produce any new pion.

3. Results

We will begin by comparing the results of our program with some data at 0.5 GeV, for quasielastic scattering and single charge exchange. In fig. 1 we show our results for quasielastic π scattering in ^{12}C, compared with experimental data from of Zumbro et al..[11] Of course we do not reproduce the elastic peak, important at low angles, given that we do not have collisions of the pions with the nucleus as a whole.

The quasielastic peak is fairly well reproduced, at all angles. The size, being absorption of little importance at this energy in our model, is governed by the elementary πN cross sections and by the fermi motion of the nucleons.

The results underestimate the cross section at pion energies below the quasielastic peak. This seems to be a fact common to other cascade codes as it is remarked in ref.[11] and as it was explained at this conference in the talk by C.L. Morris,[12] indicating possibly, some piece of physics missing in our description of the pion-nucleus reactions. One could ascribe the missing cross section to several causes that should certainly be investigated further. Because of the position in the spectra one would suggest that pion production channels should be much larger. Interestingly enough, at lower energies (T_π = 280MeV), a sizeable enhancement of the $(\pi, 2\pi)$ cross sections, when comparing to quasifree calculations, was found in ref..[13] The effect was related to the change of the dispersion relation of the pions in the medium. Speaking in simple terms, the pions are attracted by the medium. Unfortunately, it is not trivial to extrapolate that result to higher energies, where we do not know so well the pion propagation properties. In ref.[11] Zumbro et al. suggest the formation of a narrow σ meson, with little interaction with the medium, that would leave the nucleus

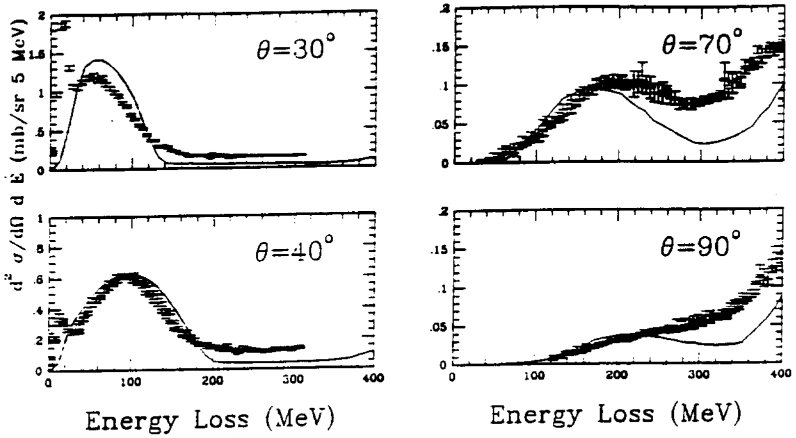

Fig. 1. Quasielastic scattering: $^{12}C(\pi,\pi)X$. T_π=800 MeV. Data from Zumbro et al. in ref. 11.

prior to its decay into two pions. One should mention that the obvious candidate, a weaker pion absorption, it is difficult to reconcile with the agreement obtained in the quasielastic peak, that for different angles is situated at the same energy, and also with the pion absorption data in the resonance energy region.

In fig. 2, we show results of single charge exchange scattering at 500 MeV. Again, the quasielastic peak size and width are in a good agreement with data. Below the quasifree peak, one can observe the same behavior found in quasielastic scattering. There are some pions missing in that region. In this figure, we show separately the pions coming from π production, which are not enough to agree with the data from ref.[15] Even the total suppression of pion absorption it is not enough to improve significantly the agreement with data.

Now, we will present some results for pion-nucleus reactions at higher energies. Our purpose is to identify the main features of these processes. In fig. 3 we analyze the reaction $\pi^+ + ^{208}Pb \rightarrow \pi + X$ at a pion kinetic energy of 1200 MeV. In the figure we split the total cross section into two pieces: a quasifree piece, given by those pions that come out of the nucleus after having only quasifree scatterings, and a pion production piece, given by the pions coming from events in which at least a pion production took place. Note that in this latter case, quasifree scatterings, prior or subsequent to the pion production itself, could have occurred.

Fig. 3 shows the energy spectra of the outgoing pions. Let us begin discussing the quasielastic channel. In it, we can separate a region of high energies, where only pions coming from one (or several) quasifree scatterings contribute, and a second region

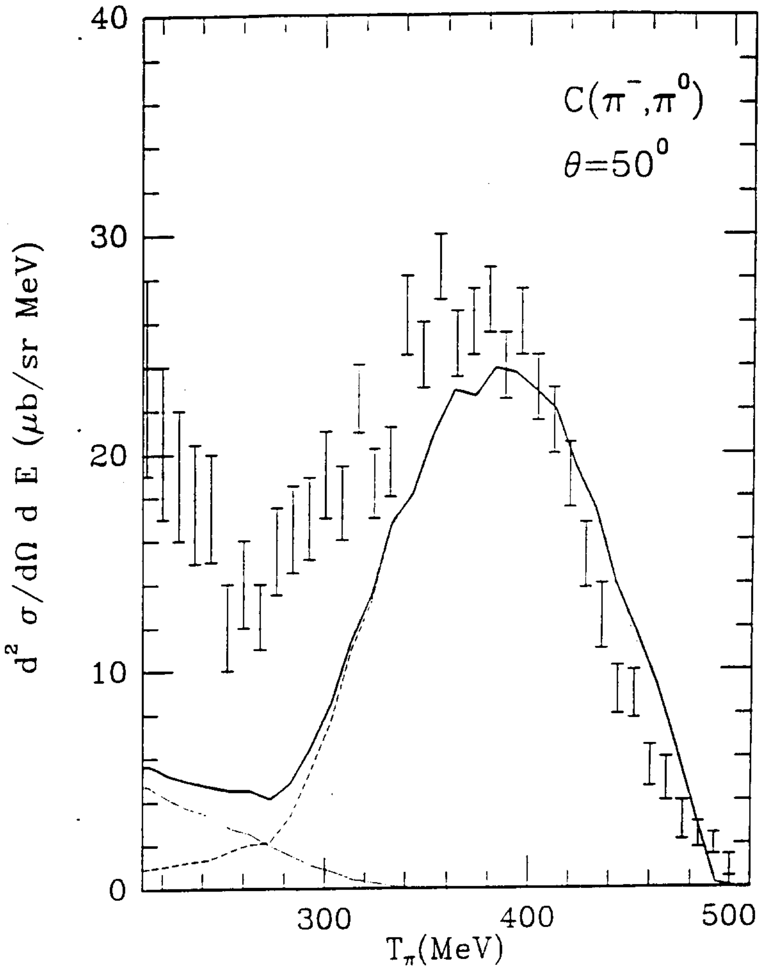

Fig. 2. Single charge exchange: $^{12}C(\pi^-,\pi^0)X$. T_π=500 MeV. Data are taken from Peterson et al. in ref. 15.

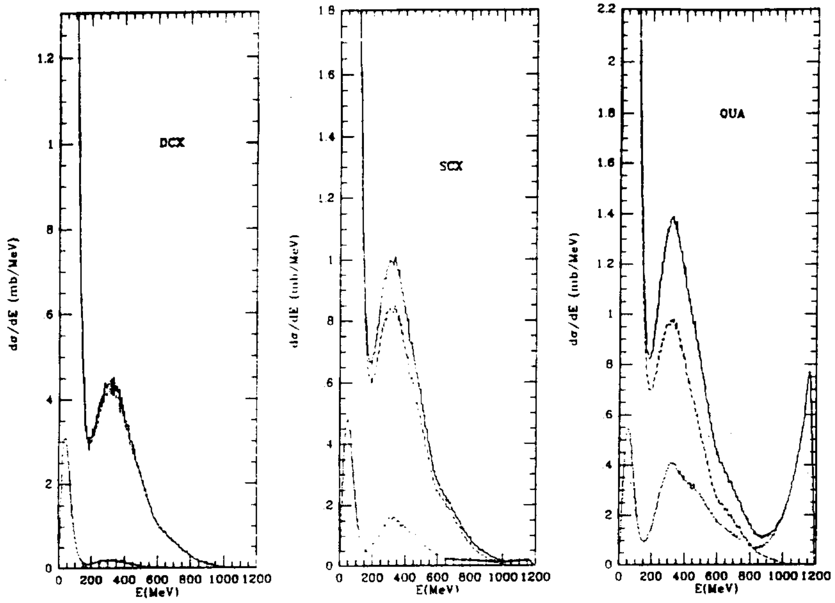

Fig. 3. Pion spectra in the $^{208}Pb(\pi^+,\pi^-)X$ reaction, for double charge exchange, single charge exchange and quasielastic scattering. Solid line: total, dashed line: pion production, dots line: quasifree scattering. See explanation in the text

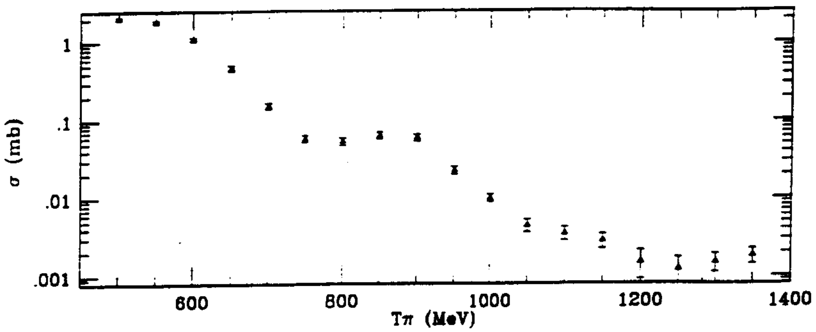

Fig. 4. Predicted cross section for the DCX reaction $^{40}Ca(\pi^+,\pi^-)X$. See details in the text.

dominated by pions coming from π production events. Note the little dip around 150 MeV in the "quasifree" part, and also the change of curvature in the same region of the "production" part. Both are due to the strong absorption in the Δ resonance region. At energies above 200 MeV absorption effects are practically negligible. The situation is similar for the SCX channel, although the quasifree peak is smaller. As expected, because DCX requires at least two scatterings, the quasifree peak is much smaller, practically negligible, in its case. The importance of pion production channels contribution to DCX has already been shown in the literature at lower beam energies. At 600 MeV and above, DCX is totally dominated by π production, except for the small region of phase space where π production is kinematically forbidden.

There are some interesting results in the literature concerning exclusive DCX processes at high energies. In particular, the cross sections of the $^{18}O(\pi^+,\pi^-)^{18}Ne$ and $^{14}C(\pi^+,\pi^-)^{14}O$ reactions have been calculated in ref.[14] at energies up to 1400 MeV. Their resulting cross sections present two deep minima at energies around 700 and 1300 MeV. That result does not depend on nuclear structure or the specific nuclei chosen. It simply reflects the energy dependence of the πN SCX amplitude. Thus one expect to get a similar result for the inclusive DCX process and, possibly, gaining in yield and requiring a less precise energy measurement of the final pion, because there is no need to separate clearly a given final state of the target nucleus.

We have selected as observable the integrated DCX cross section, putting as a cut that the energy of the final pion is, at most, 150 MeV below the beam energy. This eliminates practically all cases in which there is a pion production. The results, in Calcium, and as a function of the beam kinetic energy, are presented in fig. 4. Very similar results are obtained putting an additional cut in angles, given that most pions fulfilling the previous energy condition go forward.

We do not considered this a prediction of a extremely low DCX cross section at high energies. We do not expect that. The curve in the figure corresponds only to the ingredients of the code. namely, to two consecutive quasifree single charge exchange πN collisions. Let us them state our result in a meaningful way: The contribution to inclusive DCX processes of the conventional mechanism, with two (or more) quasielastic SCX steps decreases very fast as a function of the energy and reaches very low values, compared with the quasielastic channel, at energies above 600 MeV.

This result, and the high energy DCX data presented by A. Krutenkova in this conference,[16] clearly call for further investigation of this topic, and in particular, the study of alternative mechanisms contributing to DCX.

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