COHERENT PION PRODUCTION INDUCED BY PROTONS AND LIGHT IONS

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Abstract

We study coherent pion production by means of the (p,n) and (He,t) reactions on different nuclei and at different energies of the projectile. Energy and angular distributions are calculated. The angular distributions are rather narrow along the direction of the momentum transfer, particularly in heavy nuclei. The reaction provides valuable information on the longitudinal part of the elementary $NN - N\Delta$ interaction. It is also a good tool to obtain information on the pion nuclear interaction, complementary to that offered by reactions with real pions.

1 Introduction.

Coherent pion production in (p,n) or $(^3He,t)$ collisions in nuclei, where the target nucleus is left in its ground state, has emerged as a byproduct of the study of the shift of the Δ peak in charge exchange reactions in nuclei [1, 2]. Although many reaction channels are responsible for the shift of strength in these reactions [3] it was found theoretically that the peak of the coherent channel is shifted by about 60 MeV towards lower excitation energies with respect to the peak in the elementary reaction, (p,n) or $(^3He,t)$ on proton targets [4, 5, 6]. Experimental work on the issue has just begun. There is some preliminary work on the $(^3He,t)$ reaction on ^{12}C target [7] confirming the peak position and the angular dependence found in [6] and some estimates of the coherent channel in the (p,n) reaction on ^{12}C in [8]. Work is in progress in two more experiments [9, 10]. Actually, even if the pion was not detected, the first clear evidence of coherent pion production was shown in ref. [11]. This experiment was aimed at exciting the Roper resonance with an isoscalar probe in the (α,α') reaction on protons. A signal for the Roper excitation was found but a larger peak for 'Δ excitation in the projectile' (the α particle) was found in the reaction. The Δ decays producing pions and the α particle remains in its ground state (emerging α'). This reaction viewed in the frame of reference where the α particle is at rest qualifies as coherent pion production on ^4He with the (p,n) and (p,p') reactions, and a large strength for these channels was found in this reaction. A recent theoretical work on the (α,α') reaction is done in [12] establishing the connection between the mechanism of Δ excitation in the projectile and coherent pion production. The data are well reproduced.

So far experiments looking for coherent pions have only been done in ^{12}C and at very specific energies. Also the calculations have all been done in ^{12}C and the extension of the calculations to heavier nuclei is technically difficult with the approaches of refs. [4, 5] which require the specific treatment of large spaces of Δh states. The work of ref. [6] uses instead a different approach to the Δh model of [13] which was tested with success in pion nucleus scattering around resonance for different nuclei from $^{16}0$ to ^{208}Pb [14] and at low energies, going beyond the Δh approach, in ref. [15] with equally good results. The method consists in the evaluation of a microscopical optical potential with a local term and a non-local one. However some other non localities implicit in the detailed Δh approach [13] are proved to be unessential and are taken into account by means of appropriate local functions. Thus the evaluation of the scattering amplitudes or the pion waves is done in an easy way by means of a numerical solution of the Klein-Gordon equation with the optical potential written in terms of the nuclear density, for which the experimental information is used. The problem becomes then as easy in heavy as in light nuclei and allows us to make predictions of coherent pion production over the periodic table.

In this paper we present the first results for coherent pion production in

nuclei other than ^{12}C. It is important that both experiments and calculations are done in different nuclei in order to gain control on this reaction from where much information concerning the transition amplitude $NN \to N\Delta$ and the interaction of off shell pions with nuclei is expected to come [4, 5, 6, 16].

Additional information should come from the study of the dependence of the cross section on the energy of the incoming beams. Both these aspects, mass dependece and dependence on the beam energy are dealt with in the present work.

Another interesting aspect discussed here is the angular dependence of the pions, which come out in a narrow cone along the direction of the (p,n) momentum transfer. The angular cone becomes narrower in heavy nuclei and the process leads to highly monochromatic and unidirectional pions with analogies to the photons produced in the tagging technique. However, there are substantial dynamical differences with the ordinary Bremsstrahlung and the process of coherent pion production does not qualify for this name, as we shall see.

2 Formalism for coherent pion production.

We study the (p,n) reaction in nuclei producing a π^+ and leaving the nucleus in the ground state

$$p + A(g.s.) \to n + A(g.s.) + \pi^+ \qquad (1)$$

In the first place it is useful to establish from the beginning the difference between this process and a similar one, coherent Bremsstrahlung in e^- nucleus scattering. This latter process is given by

$$e + A(g.s.) \to e + A(g.s.) + \gamma \qquad (2)$$

and is a standard problem in QED [17]. The process proceeds via the mechanisms depicted in fig. 1. The electron interacts with the Coulomb potential of the nucleus and the photon goes out as a free wave. It is thus the fact that the e^- dispersion relation is changed by the interaction with the nucleus what makes it possible for a free photon to emerge. The long range character of the Coulomb interaction ($1/\vec{q}^{\,2}$ dependence of the amplitude) and the zero mass of the photon, which places the e^- propagator near its mass shell, collaborate to make the mechanism of fig. 1 extremely efficient in producing photons in the direction of the electron momentum transfer.

In the case of the pions the situation is different because of the finite mass of the pion and the strong interaction of the nucleons. We can see that the analogous mechanism of fig. 1 does not work in the case of pions, at least for the case of forward propagating neutrons, which makes the production of pions most efficient by means of other mechanisms.Indeed, because of the strong interaction of the nucleons with the nucleus we can no longer use perturbation theory as in fig. 1, but must replace the p and n free waves by their corresponding wave functions in the nucleus. This is depicted in fig. 2 where the pion is still kept as a free wave in analogy to the mechanism of photon emission. For forward propagation of the nucleons, and relatively large energies of the nucleons, as needed to produce pions, we can rely upon Glauber theory. Thus the matrix element for the transition $p \to n\pi$ in fig. 2 would be proportional to

$$A = \int d^3x \phi_n^*(\vec{x}) e^{-i\vec{p}_\pi \vec{x}} \phi_p(\vec{x}) \delta(E_p - E_n - E_\pi) \tag{3}$$

with

$$\phi_p(\vec{x}) = e^{i\vec{p}_p \vec{x}} exp\left(-\frac{1}{2}\int_{-\infty}^{z} \sigma(1-i\eta)\rho(\vec{b}, z')dz'\right)$$

$$\phi_n^*(\vec{x}) = e^{-i\vec{p}_n \vec{x}} exp\left(-\frac{1}{2}\int_{z}^{\infty} \sigma(1-i\eta)\rho(\vec{b}, z')dz'\right) \tag{4}$$

where σ is the spin-isospin averaged NN cross section, η the ratio of real to imaginary part in the forward NN amplitude (we take $\eta = 0.275$ in our calculations), $\vec{b}$ the impact parameter and $\rho(\vec{r})$ the nuclear density. The two exponentials in eq. (4), accounting for the distortion of the nucleon waves, combine to provide a function which depends on $\vec{b}$ but not on z. Hence the matrix element of eq. (3) becomes

$$A = \int d^3x e^{i(\vec{p}_p - \vec{p}_n - \vec{p}_\pi)\vec{x}} C(\vec{b}) \delta(E_p - E_n - E_\pi)$$

with

$$C(\vec{b}) = exp\left(-\frac{1}{2}\int_{-\infty}^{\infty} \sigma(1-i\eta)\rho(\vec{b}, z')dz'\right) \tag{5}$$

and thus

$$A = 2\pi\delta(p_{pz} - p_{nz} - p_{\pi z}) \int d^2b e^{i(\vec{p}_p - \vec{p}_n - \vec{p}_\pi)\vec{b}} C(\vec{b}) \delta(E_p - E_n - E_\pi) \tag{6}$$

The large mass of the nucleon and finite mass of the pion do not allow the two arguments of the δ functions to be simultaneously zero, and the mismatch in energy and longitudinal momentum is quite large for momenta of the nucleons and pions of the order of their respective masses. Only in the limit of forward propagation of the particles and ultrarelativistic nucleons and pions the two arguments can approach zero simultaneously. We are concerned here about the production of intermediate energy pions, around the Δ region and below and there the energy and momentum mismatch in eq. (6) is very large and the Bremsstrahlung-like mechanism of fig. 2 does not proceed.

In order to have coherent pion production we must then look at the interaction of the pion with the nucleus. This is depicted diagrammatically in fig. 3 for the particular case when the pion interaction with the nucleus proceeds via Δh excitation.

The diagrammatic expansion is selfexplanatory. The pion selfenergy contains Δh excitation plus the iteration of Δh excitations with the ingredients of the Δh interaction additional to one pion exchange. After the diagrams which are included in the pion selfenergy we find either one pion alone or a pion line followed by Δh excitations and their iteration by the whole spin isospin interaction. The whole sum of the free pion line and the iterative excitation of Δh states is nothing but a renormalized pion in the medium. This is depicted diagrammatically in the second member of the equation in fig. 3, which already accounts for the fact that the first term (fig. 3a) does not contribute, as we have seen. According to refs. [14, 15] the pion selfenergy can be written as

$$\Pi(\vec{r}) = \Pi^{(s)}(\vec{r}) + \vec{\nabla}\Pi^{(p)}(\vec{r})\vec{\nabla} \tag{7}$$

where the first term is associated to the s-wave πN interaction and the second one to the p-wave one, but the potential contains the lowest order in density and higher order corrections.

The cross section for the reaction of eq. 1 is given in the lab system by

$$\frac{d\sigma}{d\Omega_n dE_n d\Omega_\pi} = \frac{1}{(2\pi)^5} \frac{M_p M_n p_n p_\pi}{2p_p} |\vec{T}|^2 \tag{8}$$

where the matrix element $\vec{T}$ is given by [6]

$$-iT_i = -\sqrt{2}\frac{f}{\mu}\sqrt{\frac{-q^2}{\vec{q}^2}} \int d^3x \phi_n^*(\vec{x})\phi_p(\vec{x})$$

$$\left(\frac{q_i F^2(q)}{q^{02} - \vec{q}^2 - \mu^2}\Pi^{(s)}(\vec{x}) - [V_L' \hat{q}_i \hat{q}_j + V_T'(\delta_{ij} - \hat{q}_i \hat{q}_j)]\Pi^{(p)}(\vec{r}) i\nabla_j\right)\phi_{out}^*(\vec{p}_\pi, \vec{x}) \tag{9}$$

Where the longitudinal and transverse parts of the spin-isospin interaction are given by

$$V_L'(q) = \frac{\vec{q}^2}{q^{02} - \vec{q}^2 - \mu^2}F^2(q) + g'$$

$$V_T'(q) = \frac{\vec{q}^2}{q^{02} - \vec{q}^2 - m_\rho^2}C_\rho F_\rho^2(q) + g' \tag{10}$$

The factor $(-q^2/\vec{q}^2)^{1/2}$ in eq. (9) is included to make invariant the πNN coupling, $\frac{f}{\mu}\vec{\sigma}\vec{q}$, assumed implicitly in eqs. (9,10). $F(q), F_\rho(q)$ are the π, ρ form factors taken of the monopole type with $\Lambda = 1.3 GeV$ and $\Lambda_\rho = 1.4 GeV$ and $C_\rho = 3.96$ [18] and $\vec{q}$ in eqs. (10) is evaluated in the Δ rest frame. We take $g' = 0.6$ as used in the study of pionic reactions [14, 15]. The pion wave function $\phi^*_{out}(\vec{p}_\pi, \vec{r})$ is obtained by solving numerically the Klein Gordon equation with the potential of eq. (7) and imposing to it the proper boundary conditions. This is done in the following way: first we use the property [19]

$$\phi^*_{out}(\vec{p}_\pi, \vec{r}) = \phi_{in}(-\vec{p}_\pi, \vec{r}) \tag{11}$$

and

$$\phi_{in}(\vec{q}, \vec{r}) = 4\pi \sum_l i^l \sum_l Y^*_{lm}(\hat{q}) Y_{lm}(\hat{r}) \tilde{j}_l(q;r) \tag{12}$$

with $\tilde{j}_l(q;r)$ solutions of the radial differential equation with the asymptotic properties

$$\tilde{j}_l(q;r)|_{r\to\infty} \simeq e^{i\delta_l} \frac{1}{qr} sin(qr - l\frac{\pi}{2} + \delta_l) \;\; for\; \pi^0$$

$$\tilde{j}_l(q;r)|_{r\to\infty} \simeq e^{i(\delta_l + \sigma_l)} \frac{1}{qr} sin(qr - l\frac{\pi}{2} + \sigma_l + \delta_l - \eta ln2qr) \;\; for\; \pi^\pm \tag{13}$$

with η and σ_l defined in [19] and δ_l the complex phase shifts obtained from the numerical solution of the Klein Gordon equation.

The results obtained can be immediately generalized to the $({}^3He, t)$ or $(t, {}^3He)$ reactions. For instance the cross section for the $({}^3He, t)$ reaction would be obtained by changing the p variables to those of the ${}^3He$ and the n variables to those of the t and one must multiply the matrix element of eq. (9) by the (He, t) transition form factor [20].

$$F_{He,t}(q) = e^{-\alpha q^2}(1 + \epsilon q^4);\; \alpha = 16\,GeV^{-2};\; \epsilon = 20\,GeV^{-4} \tag{14}$$

Furthermore σ in eq. (4) becomes now the cross section ${}^3He\,N$ or tN averaged over spin-isospin, which are about the same, and the ${}^{12}C$ density is changed to the convoluted density with the finite size of the ${}^3He$.

Similarly we can also use the formulas of of eqs. (8), (9) to evaluate coherent π^0 production with the (p, p') reaction. This is simple: one removes the factor $\sqrt{2}$ in eq. (9) and substitutes the outgoing n by the p'. Also the optical pion potential becomes now the one of a π^0. For spin-isospin saturated nucleus, and neglecting the small effect of the Coulomb interaction on the pion wave function, the cross section is the same as for (p, n) divided by two.

3 Results and discussion.

We look first at the energy distribution of pions. We choose a particular energy of the incoming nucleon, $T_p = 800 MeV$, and integrate eq. (8) over the pion angles. Thus we obtain $d\sigma/d\Omega_n dE_n$ as a function of the outgoing n kinetic energy T_n. In fig. 4 we show this energy distribution for ${}^{12}C$, ${}^{40}Ca$ and ${}^{208}Pb$

for neutrons in the forward direction. The cross sections have similar strength in the different nuclei and show a peak around the Δ excitation region. We should also note that the peak of the distribution appears at $T_n \simeq 525 MeV$, or equivalently $T_\pi = 135 MeV$, while in the πN system with the nucleon at rest the Δ peak appears at $T_\pi = 190 MeV$. Thus there is a shift of the peak by about 55 MeV toward lower excitation energies. This shift appears in all sort of phenomena where the pion is produced coherently in the delta region. Two examples are coherent π^0 photoproduction [21, 22] and coherent π^0 electroproduction [23], also shows up clearly in the simplest coherent process: pion nucleus elastic scattering [24]. Although one can justify this shift technically in different languages, there are intuitive physical arguments which can be used to explain the shift: the nuclear form factor and the distortion of the pion wave. The nuclear form factor acts like a reducing factor as the energy increases, because for the same angle the momentum transfer increases with the energy and the form factor is reduced (in the region of the first maximum from where the angular integrated cross section gets most of its strength). On the other hand, as we approach the Δ resonance energy in the process of elastic pion nucleus scattering there is an increasing loss of pion flux because of quasielastic collisions or pion absorption whose strength increases as we approach the Δ peak. Thus, the nuclear process involves a combination of the $\pi N \to \pi N$ strength mediated by the Δ, which has its strength at the free Δ peak, the distortion factor which has a minimum at that energy and the form factor effect which is a decreasing function of the energy. The consequence of all these effects is a shift of the Δ peak at lower excitation energies.

The coherent pion production process, as shown in fig. 3, qualifies as virtual pion production followed by elastic scattering of the pion. The qualification is appropriate even if in the production step we have the whole spin-isospin interaction V'_L, V'_T of eqs. (10) and not only pion exchange, because this is also the case in intermediate steps of multiple scattering in pion nucleus collisions. Furthermore, as we shall see, the longitudinal part of the interaction in the case of the p-wave part, and the one pion exchange in the case of the s-wave part (see eq. (9)) dominate the cross section. The longitudinal part V'_L is also dominated by one pion exchange in this process, particularly as the energy of the nucleons and the pion increases.

In figures 5, 6, 7 we show differential cross sections in different nuclei for the (p, n) reaction. The cross sections are rather forward peaked and show a difraction structure like in pion scattering. The cross section for the case of ${}^{208}Pb$ is rather narrow peaked. One can envisage the (p, n) or (p, p') reaction in heavy nuclei as a source of highly monochromatic and unidirectional pions, in analogy with the production of photons with these properties with the tagging technique in (e, e') scattering on nuclei.

In fig. 5 we have also separated the contributions from the transverse part by omitting V'_L and the s-wave part in eq. (9). As we can see the contribution is rather small and does not contribute at zero angle. This is because the combination of the transverse part projected into the longitudinal channel of the final pion state induces a factor $sin^2\theta$ like in pion photoproduction [21, 22]. Thus, coherent pion production in the forward direction around the resonance region is giving us information on the longitudinal part of the $NN \rightarrow N\Delta$ transition. Combined studies of coherent pion production, inclusive pion production, where V_L', V_T' appear with different weights, and the elementary reaction [25, 26], should put more constrains on the different models which exist for this amplitude [4, 5, 6, 27].

Next we discuss the dependence of the cross section as a function of the energy beam. This is shown in fig. 8. We observe that the cross section increases as the energy increases and the peak of the pion energy distribution is shifted towards higher pion energies.

Obviously, at low p energies, the phase space factor p_n/p_p of eq. (8) reduces drastically the cross section, as we can see for $E_p = 400 MeV$. Also the nuclear form factor (implicity contained in the pion nucleus optical potential, acts as a reduction factor, particularly at low p energies. At higher energies when the p_n/p_p is of the order of unity the changes must be found elsewhere. One of the the reasons for this behaviour must be seen in the fact that as we go to higher energies the virtual pion produced in the (p, n) vertex becomes progressively more real. To envisage this let us assume the nucleons and the pions relativistic, such that their momenta are bigger than the mass. If we stick to the forward direction for nucleons and the pion we have

$$p_\pi = p_p - p_n \equiv q$$

$$E_p - E_n = \sqrt{p_p^2 + M^2} - \sqrt{p_n^2 + M^2} \simeq p_p - p_n + \frac{M^2}{2p_p} - \frac{M^2}{2p_n}$$

$$= (p_p - p_n)(1 - \frac{M^2}{2p_p p_n})$$

$$\omega_\pi = \sqrt{(p_p - p_n)^2 + m_\pi^2} \simeq (p_p - p_n)(1 - \frac{m_\pi^2}{2(p_p - p_n)^2}) \qquad (15)$$

The one pion exchange part of V_L' in eq. (10) becomes

$$V_\pi(q) \simeq \frac{q^2}{-\frac{M^2 q^2}{p_p p_n} - \mu^2}; \quad (q \equiv |\vec{q}|) \qquad (16)$$

Assuming q fixed $|V_\pi|$ increases when p_p increases. Assuming $M^2/p_p p_n << 1$ and fixed, $|V_\pi(q)|$ increases with q. These are the features which show up in fig. 8 and which tell us that by looking at the reaction at different beam energies one is placing different weight into the components of V_L' and one can investigate the structure of this interaction.

As discussed in section 2, the formalism serves equally to study coherent π^0 production with the (p, p') reaction, and the cross sections are approximately one half of those of the (p, n) reaction. Coherent π^0 production through the

(p, p') reaction would provide the first opportunity to study elastic scattering of π^0 with nuclei for near on shell π^0. Comparison with coherent π^+ production in the same nucleus through the (p, n) reaction (dividing by two this cross section) would provide the ratio of elastic scattering for the two pions. Eventually, with sufficient intensities of the p beam, the secondary beam of real $\pi^{0'}s$, whose energy and direction is kown, would have enough intensity to induce other collisions in other elements of the target, in spite of its short lifetime, and allow us to have direct measurements of π^0 scattering with protons for instance.

At the present moment there are no experimental data on the coherent π production with the (p, n) reaction. The closest experiment which can serve as a test of our results is the one of [28] channels where several exclusive were measured in the (p, n) reaction on ^{12}C. One of the channels measured in [28] is one where a π^+ alone is detected in the final state. This is not all coherent pion production since events where no other charged particles are emitted are also included . Hence incoherent $\pi^+ n$ emission is also included. But all the coherent channel is contained there. The authors of [28] mention that some of the events correspond to cases where the π^+ carries the maximum possible energy (i.e., coherent π^+ since no energy is used to excite nucleons). The other interesting feature is that the peak for 'π^+ alone' is shifted considerably towards lower excitation energies with respect to the elementary peak of the Δ excitation, as it corresponds to the findings for the coherent channel.

In fig. 9 we compare our results with the channel 'π^+ alone' of [28] adopting the same experimental cuts and folding with their resolution. We obtain a cross section (note that now we plot $d\sigma/d\Omega dp$) with a peak at around $p_n = 1175 MeV/c$, or equivalently a π^+ with $T_p = 125\ MeV$. The strength of the cross section at the peak is about $0.02\ mb/sr MeV$, which is about 1/3 of the strength of the experimental peak. The rest we would expect to come from the inclusive process $pn \rightarrow nn\pi^+$, which as we know from [20] collects its strength in roughly equal parts from Δ excitation in the target and in the projectile.

We would like to compare our results with those of of ref. [29]. The features for the coherent cross section are similar, however by comparison of fig. 19 of ref. [29] with the present result we observe that the peak in [29] appears at $T_\pi \simeq 85 MeV$ while here it appears at about $T_\pi \simeq 125 MeV$ and the strength in [29] is about twice as big as here. The authors of [29] also evaluate the incoherent cross section coming from $pn \rightarrow nn\pi^+$, but only Δ excitation in the target is included while from ref. [20] one knows that this channel contains a large fraction of strength coming from Δ excitation in the projectile.

It is clear that devoted experiments are needed to help unravel the details of the $NN \rightarrow N\Delta$ interaction as well as those of virtual pion interaction in nuclei, the two basic elements coming ino the theoretical interpretation of these reactions.

4 Coherent π^+ production with the $(^3He, t)$ reaction.

This channel was studied explicitly in [6]. The cross section is increased with respect to the (p,n) one because of the factor $M_{He}M_t$, instead of M_pM_n, in the numerator of the cross section in eq. (8). On the other hand the transition (He,t) form factor and the distortion in ^{12}C by the ^3He or t instead of the p or n, decrease the cross section. As a result we find cross sections of similar strength as in (p,n), still bigger in the $(^3He,t)$ reaction. However, we find a faster decrease of the cross section as the mass number increases.

In the present calculations there is a small correction with respect to ref. [20]. $V_L(q)$ and $V_T(q)$ are calculated with q in the rest frame of the Δ instead of the rest frame of the nucleus, as was done in ref. [20]. This is consistent with the fact that te $\Delta N\pi$ coupling $\vec{S}\vec{q}$ is taken in the Δ rest frame. The elementary $NN \to N\Delta$ interaction was well reproduced with this interaction [12].

At the same time we have taken advantage to take into account the finite range of the ^3He, by using convoluted densities of the target nucleus with the size of ^3He. The combined affect of these corrections results in a reduction of the cross sections of [20] by about 20%. With this in mind one can obtain cross sections on ^{12}C from the results of [20] and we do not duplicate the information here.

We have also performed calculations of the $(^3He,t)$ cross sections for other nuclei. At $T_{He} = GeV$ we find at $T_t = 1.755GeV$, close to the peak, the following cross sections : 0.062, 0.036, 0.018 $mb/srMeV$ for ^{12}C, ^{40}Ca and ^{208}Pb respectively. The cross section in ^{208}Pb has fallen down by a factor 3.7 with respect to ^{12}C, while in the (p,n) case it only falls by a factor 1.5. This is due to the effect of the increased distortion in the $(^3He,t)$ case.

At present there is very little experimental information available. In ref. [7] there are some data for the $(^3He,t)$ reaction. The data are extracted from the inclusive data since the experiment was not aimed at searching for the coherent channel. Devoted experiments at SATURNE with the same reaction are under way [9].

As noted in [6] the qualitative features of our results agree with those of [7]. The peak position is at the same place, the angular distribution is also about the same and the total strength is also consistent with the estimations of [7]. However it will be very interesting to do detailed comparisons with the data when the experiments are completed.

Our theoretical results have some features in common with the results of ref. [5], like the peak position of the energy distribution. However, the strength at the peal is in our case about a factor 2.5 smaller than in the case of [5]. As in the case of the (p,n) reaction the experimental results are much needed to help us gain control on details of the $NN \to \Delta N$ transition and the propagation of virtual pions in the nuclear medium.

5 Conclusions.

We have studied coherent pion production induced by protons or light ions. We have carried out calculations in different nuclei in order to study the mass dependence of the cross section and have also studied the dependence on the energy of the beam.

The process qualifies as virtual pion production followed by elastic scattering of the virtual pion with the nucleus till it becomes real, hence it allows to investigate properties of π^0 elastic scattering on nuclei, providing a quite novel information. It also allows one to study elastic scattering of pions, charged or neutral, for off shell situations of the pion, which can be varied at will. This would provide extra constraints on theories and should help us increase our microscopic understanding of the pion nucleus interaction.

The energy dependence of this reaction and its comparison with incoherent and elementary processes should also provide information on the elementary $NN \to N\Delta$ transition.

We observed that the process was mostly sensititive to the longitudinal part of the $NN \to N\Delta$ amplitude and that by changing the energy of the beam the weight of the different components of V_L' changed. Hence a systematic study of this process as a function of the energy, together with information from the elementary $NN \to N\Delta$ reaction and inclusive pion production experiments should ultimately give us precise answers for the elementary $NN \to N\Delta$ amplitude which at present seems to be reproduced by a large variety of different models.

Another feature worth mentioning is the analogy of the process with the production of monochromatic and unidirectional photons with the tagging technique. The possibility of making some practical applications of the similar properties in the coherent pions is worth receiving some thoughts.

Comparison with the first experimental analysis supports the basic features which we have stressed about the reaction. However, devoted experiments in different nuclei and a broad range of energies are necessary to push forward this novel and interesting field.

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Figure captions:

fig. 1: Diagrams for coherent Bremsstrahlung in (e,e') reactions on nuclei.

fig. 2: Bremstrahlung like mechanism for coherent π^+ production on nuclei with the (p,n) reaction. The crossed circle indicates the p or n distorted wave in the nucleus.

fig. 3: Diagrammatic representation of coherent pion production. The dashed lines indicate the pion, the wavy lines the spin-isospin interation and the dotted line with a cross the ingredients in the Δh interaction additional to one pion exchange. The dashed lines with a dashed circle in the middle represent a renormalized pion. The crossed circle indicates the pion selfenergy.

fig. 4: Double differential cross section for coherent π^+ production with the (p,n) reaction on ^{12}C, ^{40}Ca and ^{208}Pb at $T_p = 0.8\ GeV$ and $\Theta_n = 0^0$, as a function of the n kinetic energy.

fig. 5: Angular distribution of the pion for π^+ coherent production on ^{12}C at $T_p = 800 MeV, T_n = 525 MeV$ and $\Theta_n = 0^0$. The dashed line represents the contribution of the transverse part of the $NN \to N\Delta$ interaction.

fig. 6: Same as fig. 5 for ^{40}Ca.

fig. 7: Same as fig. 5 for ^{208}Pb.

fig. 8: Coherent π^+ production cross sections for the (p,n) reaction on ^{12}C at several energies of the incoming proton, as a function of the pion kinetic energy for $\Theta_n = 0^0$.

fig. 9: Experimental results for the "π^+ alone" channel in the (p,n) reaction on ^{12}C from ref. [28] which accounts for coherent π^+ production plus the incoherent $pn \to nn\pi^+$ channel. The dots on the continuous line indicate our results for coherent π^+ production with the same cuts as done in the experiment ($12^0 \leq \Theta_\pi \leq 141^0$, and Θ_n measured between 0^0 and 6^0).

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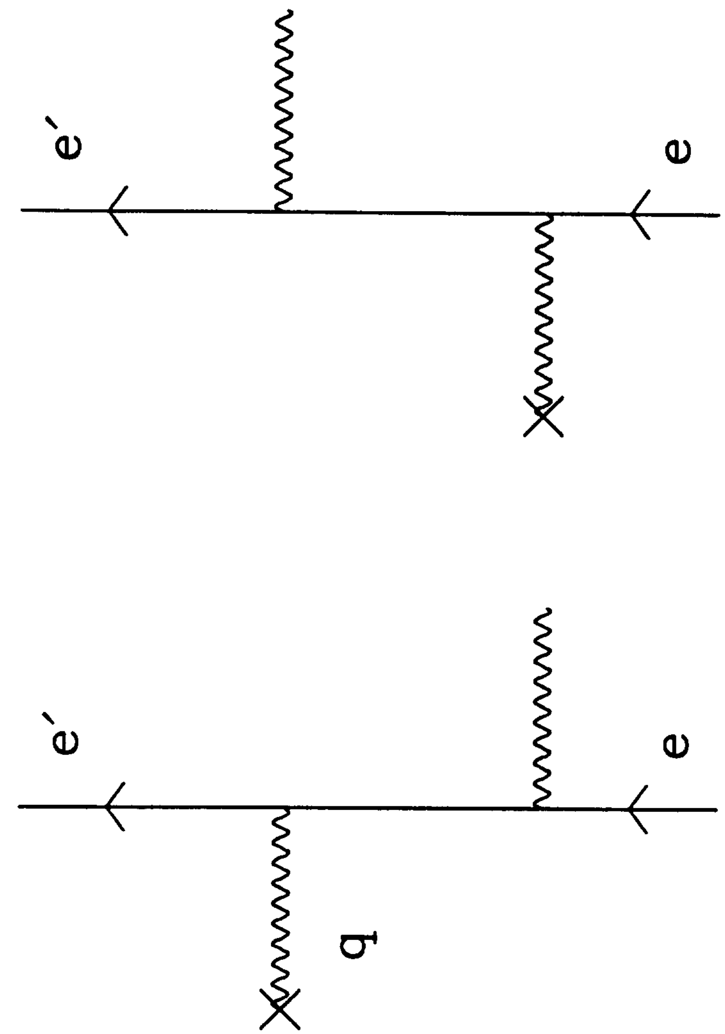


fig. 1

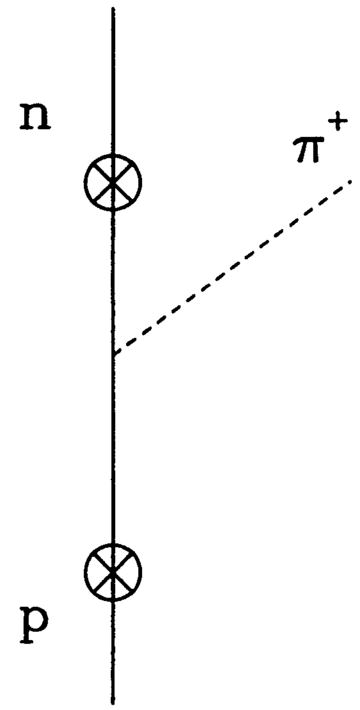


fig. 2

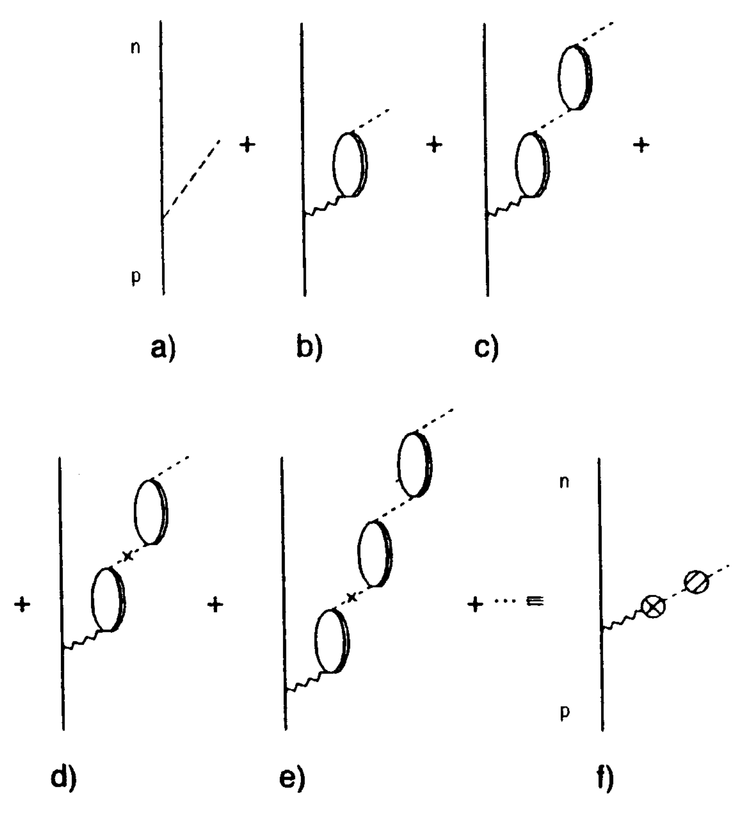
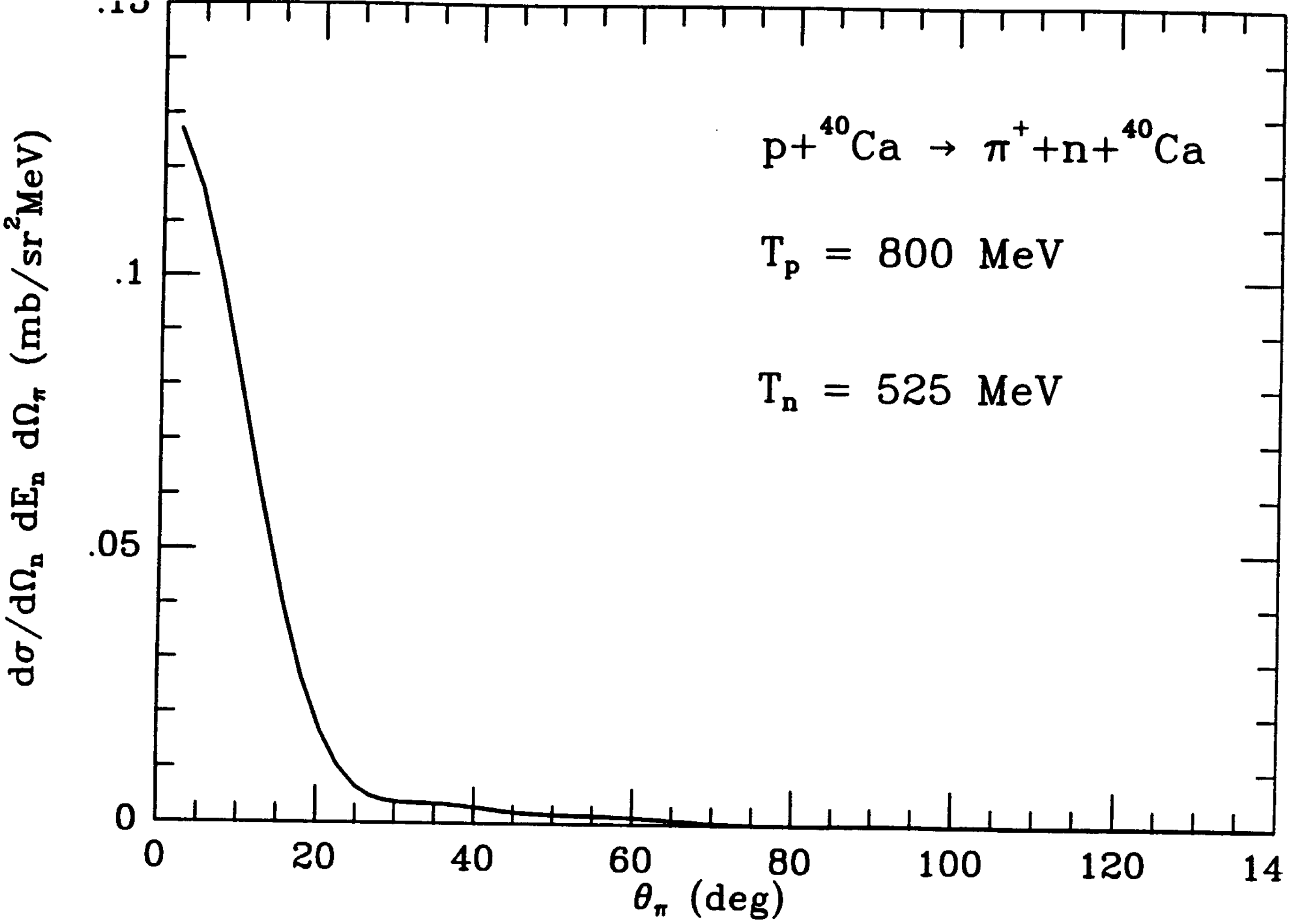
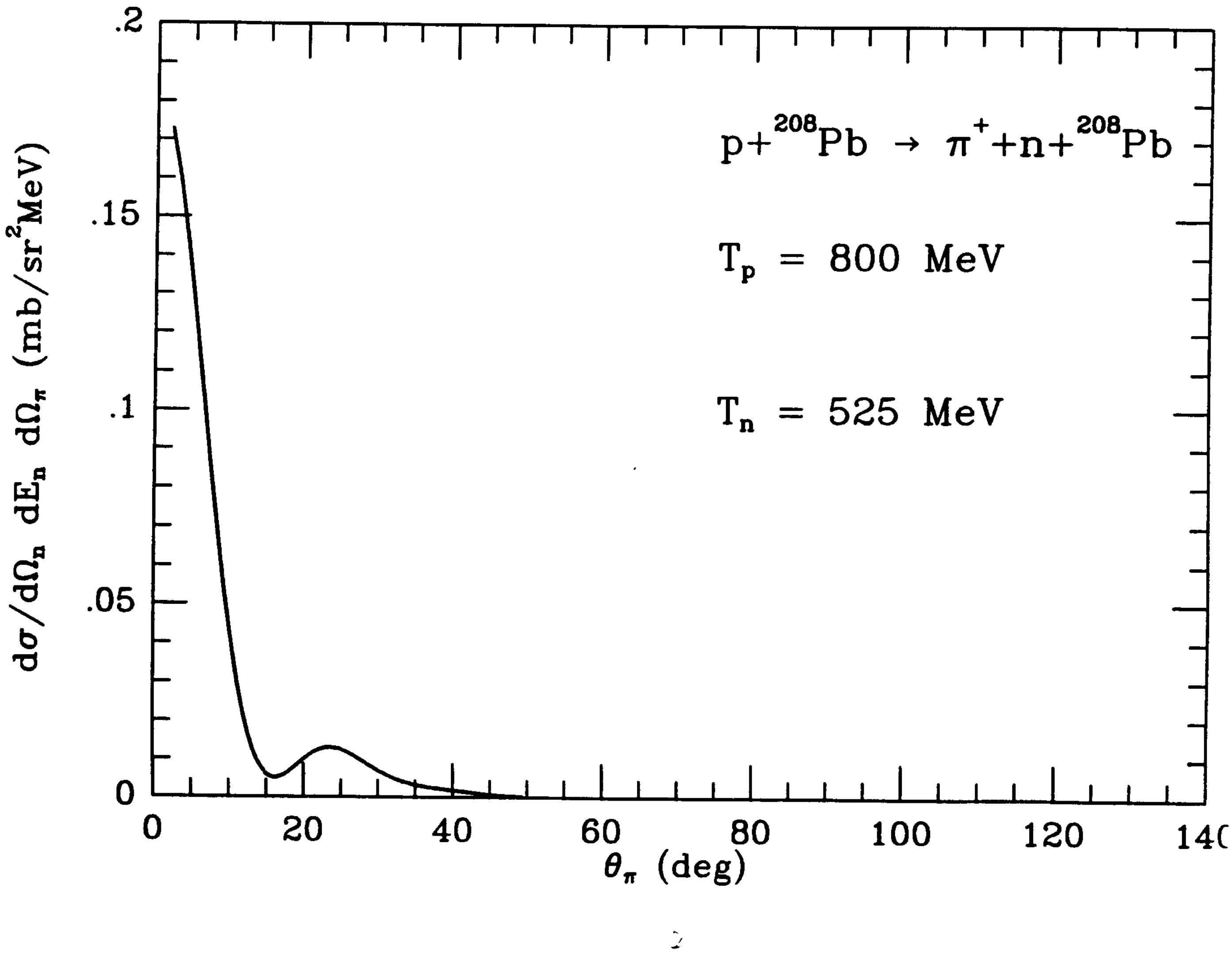


Fig. 3



p+^{40}Ca → π^++n+^{40}Ca
T_p = 800 MeV
T_n = 525 MeV
$d\sigma/d\Omega_n\ dE_n\ d\Omega_\pi$ (mb/sr^{2}MeV)
θ_π (deg)

Fig 6



p+^{208}Pb → π^++n+^{208}Pb
T_p = 800 MeV
T_n = 525 MeV
$d\sigma/d\Omega_n\ dE_n\ d\Omega_\pi$ (mb/sr^{2}MeV)
θ_π (deg)

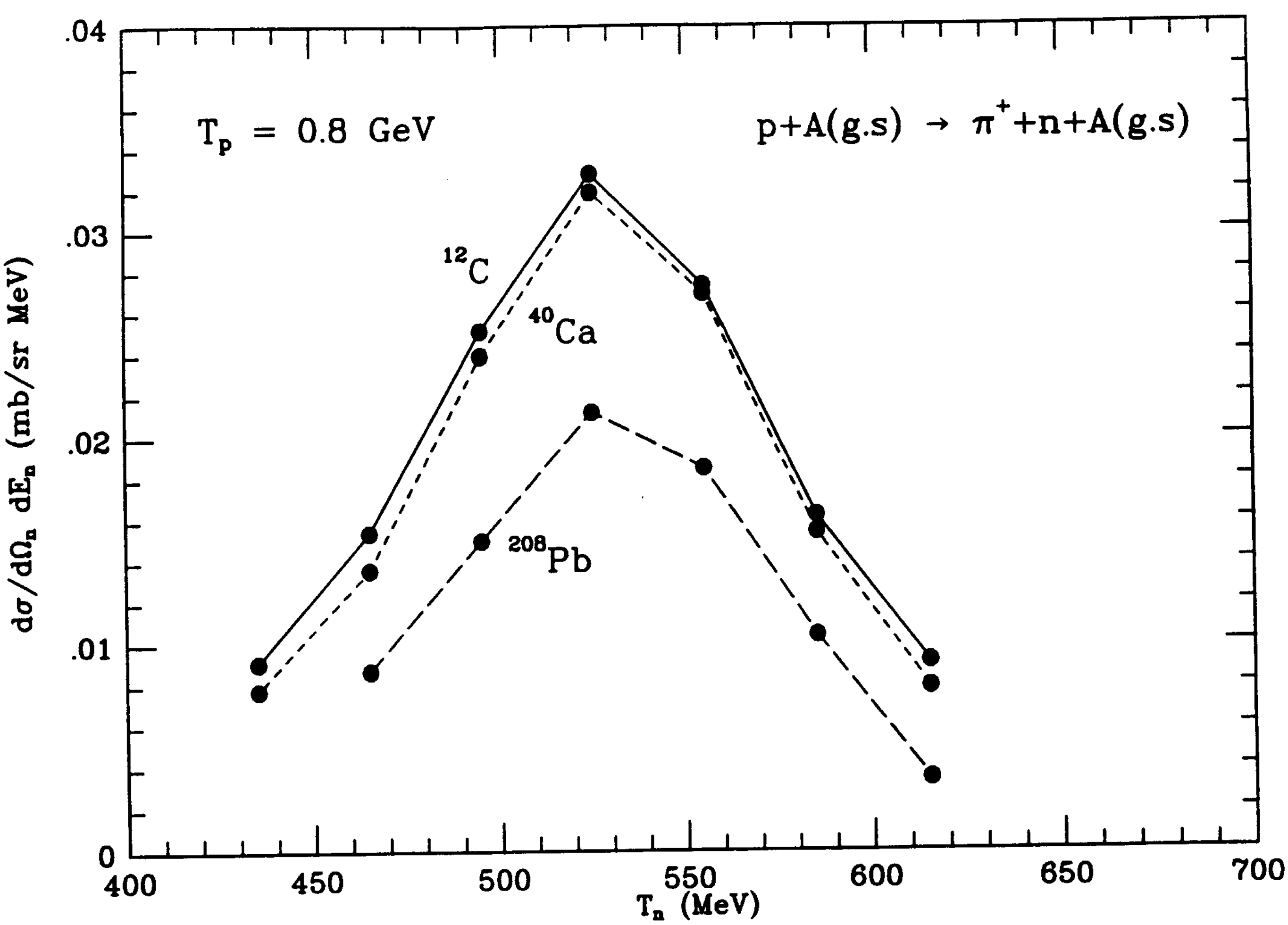
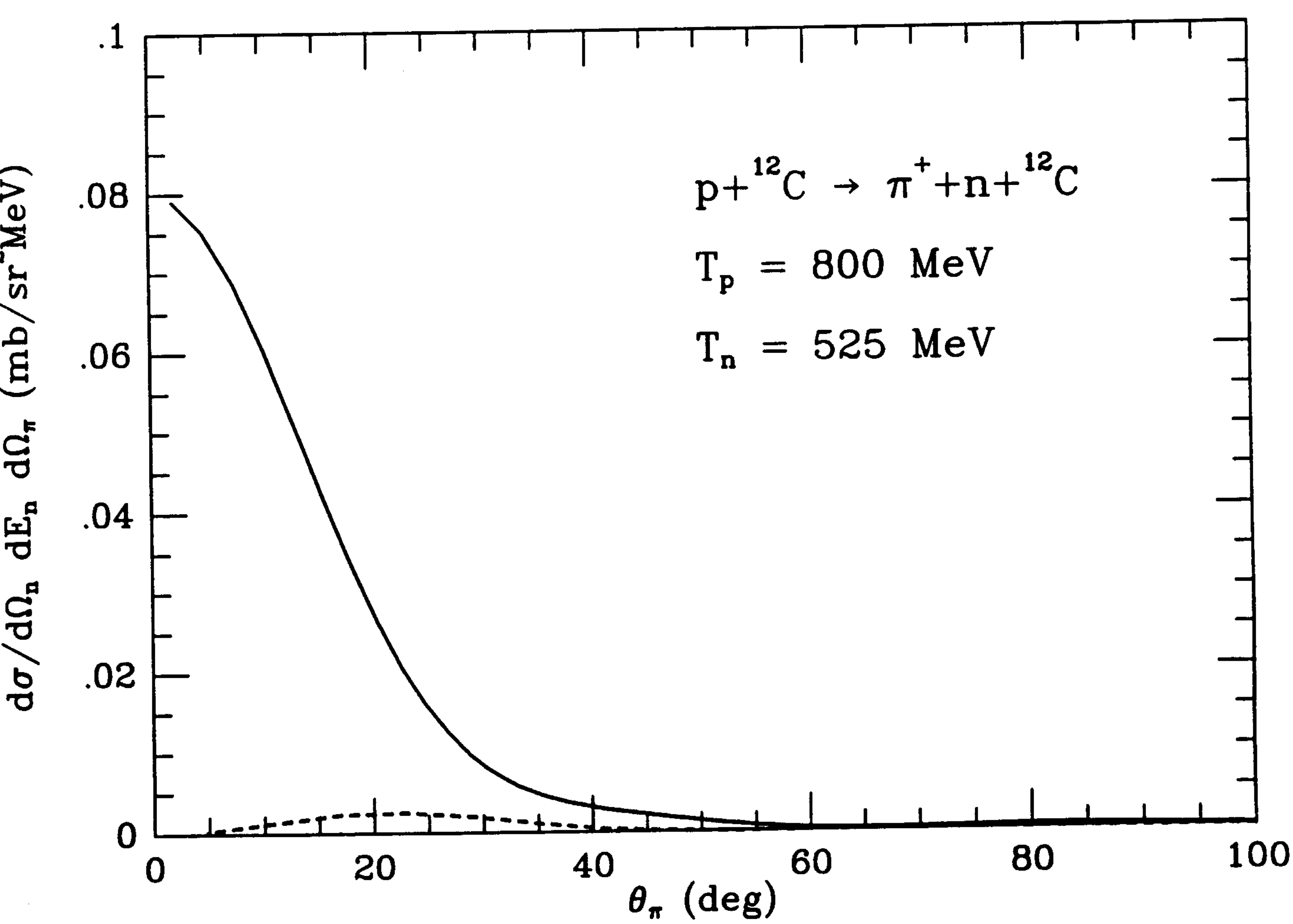

T_p = 0.8 GeV
p+A(g.s) → π^++n+A(g.s)
^{12}C
^{40}Ca
^{208}Pb
dσ/dΩ$_n$ dE$_n$ (mb/sr MeV)
T_n (MeV)
0
.01
.02
.03
.04
400
450
500
550
600
650
700

Fig 4


p+^{12}C → π^++n+^{12}C
T_p = 800 MeV
T_n = 525 MeV
dσ/dΩ$_n$ dE$_n$ dΩ$_\pi$ (mb/sr^{2}MeV)
θ_π (deg)
0
.02
.04
.06
.08
.1
0
20
40
60
80
100