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PION PRODUCTION IN HEAVY ION REACTIONS NEAR ABSOLUTE THRESHOLDS

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1. Introduction

Pion production in heavy ion collisions at energies below the free nucleon-nucleon threshold, i.e. at energies, where the pion mass exceeds the kinetic energy of a projectile nucleon in the zero momentum frame, has been discussed for a long time in terms of probing the intrinsic Fermi motion in the projectile and target nuclei. However, as the beam energy is lowered this process gets more and more unlikely and below a certain energy it should not be observed anymore. In a sharp cut-off Fermi gas model this occurs[1] at E_{lab}=50 MeV/u. However, as long as the total center of mass energy exceeds the pion mass, pions still can be produced by a cooperative sharing of the beam energy of several (or all) projectile nucleons. The experiments presented here are meant to extend the experimental information into that kinematic domain and represent the up to now lowest beam energy, where pion production has been identified unambigiously[2]. The production of a pion of 100 MeV kinetic energy with a 35 MeV/u ^{14}N beam requires Fermi momenta as high as ~350 MeV/c or alternatively 60% of the total beam energy. The information from the present experiments together with the results of previous experiments at higher beam energies of 44 MeV/u and 60-84 MeV/u (Refs. 3 and 4) allows to distinguish between the alternative production mechanisms.

2. Experiments

In the experiments presented here neutral pions have been detected through their predominant fast decay into two high-energy γ-rays. These two γ-rays were observed in coincidence in an annular array (coplanar with the beam axis) of lead glass Cerenkov detector telescopes; each telescope consists of a converter and an absorber section with respective depths of 2 and 15 radiation lengths (for details see ref. 2). The measurement of the two γ-energies and angles (within the opening angles of the separate telescopes) allows for a reconstruction of the pion invariant mass, its kinetic energy and emission angle.

In a first experiment[2], ten of these telescopes were combined together to cover a solid angle of about 2% of 4π and a 35 MeV/u ^{14}N beam of the K=500 superconducting cyclotron at MSU was used to bombard targets of natural Al, Ni and W. In a second experiment using the same beam and the Ni target we aimed at obtaining very detailed information on one particular target and combined twenty Cerenkov telescopes; by the finer granularity of this set-up the γ-ray angular resolution, improved from 24 to 17 degrees, thus providing a significantly better pion angle and kinetic energy resolution (see Figs. 1 and 2). The solid angle covered by this set-up was somewhat smaller (about 1% of 4π).

The probability that the 2 decay γ-rays of a pion actually hit the set-up is obtained from Monte-Carlo simulations taking into account the pion decay kinematics. The response of the converter sections to 125 MeV electrons has been measured to be 75% and this provides an upper limit for the according response to γ-rays. The energy dependence of this response is obtained from Monte Carlo simulations[5] that include the conversion of a γ-ray into an electromagnetic shower, the subsequent Cerenkov light emission and collection probability, as well as the photomultiplier response. The resulting detection probability increases monotonically with increasing γ-energy and levels off at ~150 MeV at 68% in good agreement with our measured value.

The very intense background of beam-correlated γ-radiation, neutrons and cosmic rays is efficiently reduced by (i) our coincidence technique, which requires a 4-fold trigger of 2 absorber signals together with the according two converter signals, (ii) the ~2 ns time resolution of the set-up, that allows the application of narrow gates on the various detector-detector and detector-beam time differences, (iii) a soft-ware threshold on low γ-energies (30-40 MeV) and small opening angles ϕ between the two γ-rays (a minimum ϕ is kinematically determined by the pion kinetic energy) and (iv) a gate on the pion invariant mass. The effects of the different cuts on the data were investigated by Monte-Carlo simulations and, if necessary, respective corrections were applied to the deduced quantities.

Figure 1 shows the experimental invariant mass spectrum. It exhibits a clear peak around the π^0 invariant mass of 135 MeV; approximately 900 pions have been detected in a beam time of one week. Also displayed in Fig. 1 is the result of a Monte-Carlo simulation and its good agreement with the data proves a proper treatment of the geometry, the γ-ray energy and angular resolution and the various cuts on the data as well as an effective background suppression.

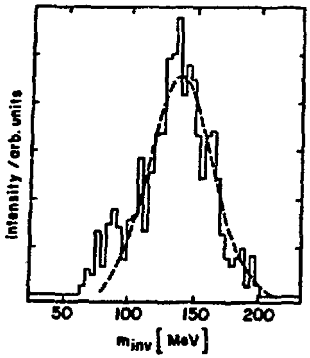

Fig. 1 Experimental invariant mass spectrum for 35/u ^{14}N on Ni together with the result of a Monte-Carlo simulation (dashed line).

3. Results and Discussion

The angle integrated pion kinetic energy spectrum for the Ni target is shown in Fig. 2 together with respective spectra gated on different regions of pion emission angles θ in the laboratory. Also shown as the dashed lines are the according spectra assuming a γ-energy independent response of 70% for the set-up. This is, of course, unrealistically high and is shown to demonstrate the maximum systematic uncertainty introduced by the calculated response. The conclusion is that even in that extreme case our findings persist: The spectra are peaked at $T_\pi \sim 10$ MeV and exhibit an exponential fall-off towards higher kinetic energies with a remarkably large decay

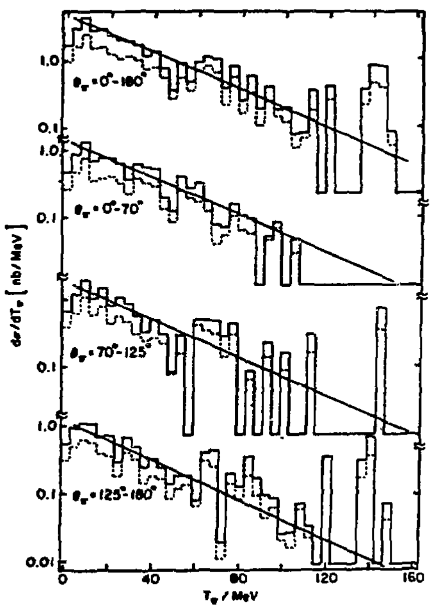

Fig. 2 Experimental pion kinetic energy spectra obtained for 35 MeV/u ^{14}N on Ni. For the meaning of the dashed spectra see text. The experimental resolution was calculated to be $\Delta T_\pi = 6$ MeV (30 MeV) at $T_\pi = 10$ MeV (100 MeV). The straight lines represents and exponential with a slope constant $E_0 = -23$ MeV.

constant of E_0=23(3) MeV (representd by the solid lines in Fig. 2). This does evidently not continue the trend established at higher beam energies[6,4] where a steady decrease of the inverse slope factors from 50 over 27 to 22 MeV has been observed for beam energies of 180, 84 and 60 MeV. The overall slope of the spectra is independent on the pion angle θ; the very high energy pions (T_π>100 MeV), however, seem to be observed predominantly under backward angles in the laboratory (see the lowest panel of Fig. 2).

The energy integrated pion angular distributions in the laboratory are forward-backward symmetric with a minimum at 90° and a 0°: 90° ratio of ~1.5 as displayed in Fig. 3 again for the Ni target. The same observation - only statistically less significant - was made in the first experiment[2] for both the Al and Ni targets and similar angular distributions are observed[4,7] at higher beam energies (60-84 MeV/u). For the highest pion kinetic energies, however, the present data show a significant pion excess at backward angles.

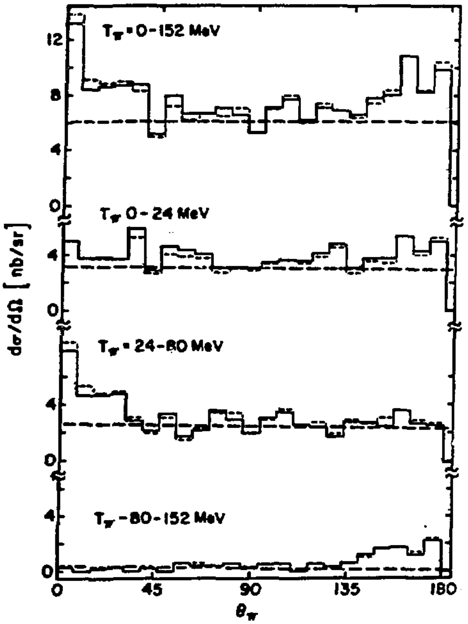

Fig. 3 Pion angular distributions in the laboratory (dashed spectra see text); the experimental resolution is $\Delta\theta_\pi$=15°. The thick dashed line is adapted to the experimental cross section around 90° and is shown to visualize on occasional asymmetry of the data.

The resulting angle and energy integrated cross sections for the various targets and the 35 MeV/u ^{14}N beam are displayed in Fig.4 as a function of the target mass number. The errors displayed cover statistical uncertainties and contributions from the various cuts on the data. The observed cross sections increase certainly more slowly than linearly with A_T and also than an $A_T^{2/3}$ dependence (full line in Fig. 4) as it was proposed[4] for higher beam energies

(60-84 MeV/u). Rather they are reproduced by an $(A_T^{1/3}+A_p^{1/3})^2$ dependence or, even better, by $(A_T^{1/3}A_p^{2/3}+A_T^{2/3}A_p^{1/3})$ as indicated by the dashed and dashed-dotted lines in Fig. 4.

The observed A_T dependence of the integrated cross sections could indicate that, as the projectile nucleus is increasing, only part of it, namely the part overlapping with the smaller projectile nucleus, is active

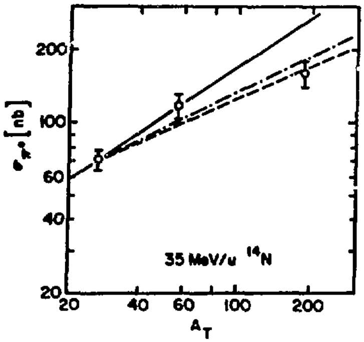

Fig. 4 Angle and energy integrated cross sections for the production of neutral pions as a function of the target mass number. The lines given represent the different parameterizations in A_T and A_P as explained in the text.

for pion production. However, a flattening of the observed pion yields with increasing target mass could also be indicative for an increasing effect of pion reabsorption. Here we can give only a brief discussion of the conceivable influence of this effect on the experimentally observed and deduced quantities. Experimental information[8,9] for (charged) pion absorption cross sections exists only for pion kinetic energies $T_\pi \geq 37$ MeV, i.e., the bulk part of our present data is not covered by these experiments.

We performed schematic Monte-Carlo simulations assuming a pion kinetic energy spectrum as observed in the present experiment and pion mean free paths $\lambda_{abs}(T_\pi)$ as resulting from the optical model calculation of Hüfner and Thies[10] that reproduces the experimental absorption cross sections at higher energies. The results are the following:

(i) the average mean free path for $0 \leq T_\pi \leq 150$ MeV is $\lambda_{abs} \sim 3$ fm with a maximum around $T_\pi=25$ MeV. For a pion source located in the center of the combined (N+Ni)-system 80% of the produced pions are reabsorbed. This number reduces to 55% for a pion source located at the surface of the combined (N+Ni)-system. An off-centered pion source is well conceivable, e.g.,this would occur if the projectile is stopped before traveling through the whole target nucleus. Such an off-center location of the pion source would of course entail an distortion of the observed angular distribution and since the mean free path for pion absorption is energy dependent also the distortion of the angular distributions would vary with T_π; in particular the effect is expected to increase with increasing T_π.

(ii) The influence of reabsorption on the pion kinetic energy spectra is two fold: the maximum is shifted towards higher T_π and simultaneously the decay constant E_o is reduced significantly (up to 30% for our schematic simulation).

Finally it should be noted that for the highest pion kinetic energies observed also rescattering is not negligible; according to Ref. 10 at T_π>100 MeV the mean free path for rescattering become comparable to the size of the system (~5 fm). This will affect the higher energy part of the energy spectrum and also the according angular distribution. However, since these events contribute less than 10% to the total pion production cross section, our conclusions on the rapidity y of the pion source should not be hampered.

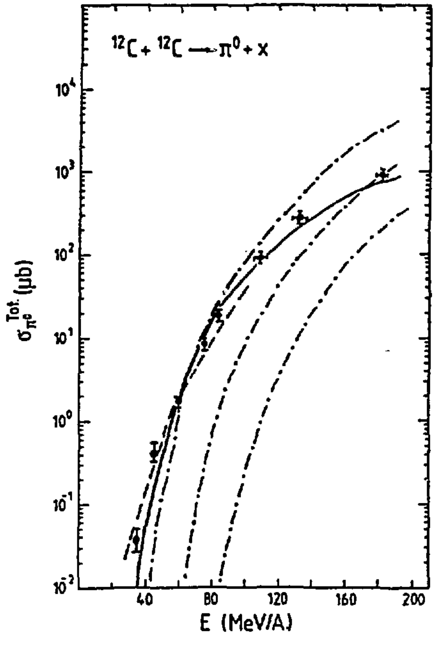

Fig. 5 Inclusive neutral pion production cross sections as a function of the bombarding energy in the laboratory. The experimental points have been taken from Ref.3,4,11,6 and the present experiment and if necessary, they have been transformed into the C+C system (see text). The solid line corresponds to a calculation within the extended phase space model[12]. The dashed line is the result of the pionic bremsstrahlung model[13] and the dashed dotted lines result from the single nucleon-nucleon collision knock-out model[14] for U=0,-100,-200 MeV from the bottom to the top curve.

Figure 5 shows our integral cross section for neutral pion production at 35 MeV/u together with a systematics of according cross section measured at higher beam energies. For this systematics the datapoints (if necessary) have been translated into the $^{12}C+^{12}C$ system by using the relation $\sigma(12,12)=(12\cdot 12/A_T\cdot A_P)^{2/3}\cdot\sigma(A_TA_P)$. For all data points shown the beam energy is below the free nucleon-nucleon threshold for pion production and between E_{lab}=184 MeV/u and 35 MeV/u the experimental cross sections drop 6 orders of magnitude. Yet our data point at the lowest beam energy is unexpectedly high and the production mechanism discussed for the higher energies ($E_{lab} \geq 100$ MeV/u), i.e, single nucleon-nucleon collisions with an extra boost from the intrinsic Fermi motion of the bound nucleons either in a Fermi-gas model or better shell model description fails completely. Already at 85 MeV/u the experimental yields are underpredicted by a factor 100 by a realistic shell model calculation[15] and at 35 MeV/u this discrepancy is more than three order of magnitude[15] (an inclusion of Pauli blocking in the final state would even further reduce the theoretical cross sections). A special nucleon-nucleon collision production mechanism is discussed by Guet and Prakash[14]. They consider only collisions between a projectile and the target nucleon, where the two nucleons are left unbound after pion production. This approximation avoids complications by the Pauli blocking and is expected to hold at higher beam energies. The results are shown as the dashed dotted lines in Fig. 5 and they also display the effect of the attractive part of the ion-ion optical potential (the three curves correspond to U=0,-100,-200 MeV) that indeed enhances the pion production cross section considerably. This production mechanism certainly can account for the cross sections at the higher beam energies. However, even for a strongly attractive optical potential, invariably the experimental cross sections below E_{lab}~50 MeV/u are underpredicted by orders of magnitudes and furthermore the pion kinetic energy spectra resulting from these calculations decrease much to fast towards high pion kinetic energies[14] (this is also true for other shell model calculations[15]).

The conclusion is that, below a certain beam energy, nucleon-nucleon single collision mechanisms cannot account for the experimental 'subthreshold' pion production cross sections and spectra and that demands the cooperative sharing of the beam energy of several projectile nucleons. Several mechanisms have been proposed, which we will discuss briefly in the following.

The formation of secondary particles in hadronic collisions by a collective bremsstrahlung-type mechanism[16] has been applied by Vasak et al[13] to the production of neutral pions in the beam energy regime of interest and for colliding systems of equal mass. In this model the cross section is determined by the time scale of the deceleration and a slowing down length of 1.5-2 fm has been adjusted to the experimental data. Figure 5 shows that this calculation can account for the experimental inclusive cross sections between 35 and 84 MeV/u. Also the experimental pion kinetic energy spectra and angular distribution for beam energies of E_{lab}=60-84 MeV are reproduced. The present data at the lowest beam energy call for an extension of this model to asymmetric projectile-target systems.

Another collective description also making use of the dynamics of heavy ion collisions is the mean field approach to pion production [17] Applied for higher beam energies (164 MeV/u) the version that produces pions via the decay of a Δ can account for the experimental data; again an extension of the calculations is needed to allow comparison to the present data.

Shyam and Knoll[12] apply a statistical model to produce 'subthreshold' pions by the cooperative action of several projectile and target nucleons. The whole collision process is described by multiple quantum mechanical off-shell collisions, where the participating projectile and target nucleons dynamically form a cluster that shares the available beam energy. The decay of such a cluster is governed by the statistical phase space limit and a further cooperative effect, i.e., the formation of fragments of various masses in the exit channel, determines the slopes of the pion kinetic energy spectra. The essential free parameter, the effective nucleon-nucleon cross section, was σ^{eff}=120 mb for all beam energies. The solid line in Fig. 5 represents this calculation. At higher beam energies it is in good agreement with the experimental data. At lower beam energies this model yields cross sections that are drastically enhanced as compared to models based on single nucleon-nucleon collisions and it is in much better agreement with the data; still below 50 MeV/u increasing discrepancies are observed (about a factor 4 at 35 MeV/u). The experimental A dependence for 60-84 MeV/u ^{12}C+A inclusive pion production is very well reproduced and the agreement with the pion kinetic energy spectra is good for $T_\pi \geq 74$ MeV[12]; however, with decreasing beam energy the calculated spectra are increasingly too steep ($E_o \sim 16$ MeV at E_{lab}=35 MeV/u as compared to the experimental value of 23 MeV). These remaining discrepancies to the experimental data at the lowest beam energies are attributed to mean field effects not considered in that model, which are expected to increasingly dominate pion production as the beam energy is lowered.

The statistical sequential decay of an equilibrated hot spot has been proposed by Aichelin[18] to describe 'subthreshold' pion production data. However, these calculations involve several ad hoc assumptions, so that their predictive power is small. A more detailed investigation of such an approach is underway.[19]

Finally, there is one more piece of experimental information, that can provide information on the velocity of the source that emits the pions. Figure 6 shows a plot of the double differential cross section versus the rapidity y and the momentum perpendicular to the beam direction $p_\perp$ for the present experiment at 35 MeV/u. It can be seen that the experimental cross sections are symmetric around y=0.01(5), which indicates that the pions source is moving very slowly. This again is a strong hint that single nucleon nucleon collisions are not the origin of the presently observed pion cross sections; for this process a source velocity of half the beam rapidity (labelled by 1/2 p in Fig. 6) is expected in clear contradiction to the

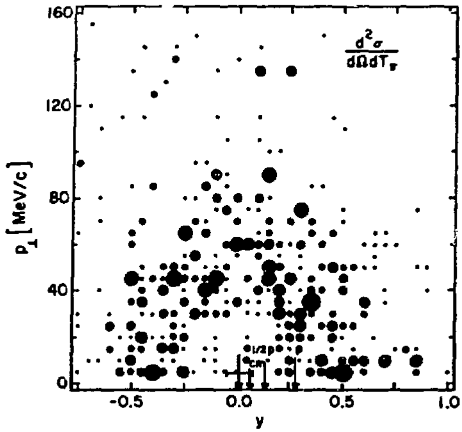

Fig. 6 Double differential cross sections $d^2\delta/d\Omega dT_\pi$ versus rapidity $y=1/2\log[(E+p_{||})/(E-p_{||})]$ and momentum perpendicular to the beam axis $p_\perp$ for 35 MeV/u $^{14}N+Ni$. The arrows indicate the projectile rapidity, half the projectile rapidity, the rapidity of the $^{14}N+Ni$ center-of-mass system and the centroid of the experimental cross sections <y>=0.01±0.05.

experiment. On the other hand, pion emission from the N+Ni composite system is compatible with the data. This is in accordance with similar information[4] for the asymmetric systems $^{12}C+^{238}U$ and $^{12}C+^{56}Ni$ at E_{lab}=60-84 MeV/u, where also the pion source was found to move significantly slower than the nucleon-nucleon center of mass system. This source velocity can be interpreted to reflect the size of the system emitting the pions and at 60-84 MeV/u it has been concluded[4,7] that if the whole projectile nucleus is active, it involves 14-15% of the U nucleus and 34-41% of the Ni.

The present experiment extends the experimental information on 'subthreshold' pion production to the so far lowest beam energy, where pion have been observed. The experimental data collected so far can be interpreted to display a transition in the pion production mechanism from nucleon-nucleon collisions at high beam energies, with increasing importance of high Fermi momenta as the energy is lowered, to a cooperative sharing of the beam energy of several projectile nucleons, e.g., via multiple quantum mechanical off-shell collisions, and finally towards a collective production mechanism dominated by the mean field.

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