EXCLUSIVE MEASUREMENTS OF MEAN PION MULTIPLICITIES IN ^{4}He–NUCLEUS REACTIONS FROM 200 TO 800 MeV/NUCLEON

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Mean multiplicities of π^+ and π^- in ^{4}He collisions with C, Cu, and Pb at 200, 600, and 800 MeV/u, and with C and Pb at 400 MeV/u have been measured using the large solid angle detector Diogene. The dependence of pion multiplicity on projectile incident energy, target mass and proton multiplicity is studied in comparison with intra-nuclear cascade predictions. The discrepancy between experimental results and theory is pointed out and discussed.

1. Introduction. One of the major challenges of relativistic heavy ion physics is the determination of the nuclear equation of state for densities up to ~4 times normal density. During the last years, the use of the pion multiplicity (measured in central collisions) as a "nuclear matter thermometer" [1] in order to extract the equation of state from experimental data has raised considerable interest. However, the question whether this observable is mainly sensitive to the equation of state is still not settled [2–10]. It is clear that new experimental data are needed in order to constrain the models and clarify the situation. More generally, the study of the pion production in relativistic heavy ion collisions is a very interesting tool for probing the dynamics of the reaction [11].

We report quasi-exclusive measurements of π^+ and π^- mean multiplicities for ^{4}He+(C, Cu, Pb) at 200, 600 and 800 MeV/u, and ^{4}He+(C, Pb) at 400 MeV/u [12]. They were performed at the Saturne synchrotron in Saclay, using the cylindrical drift chamber of the large solid angle detector "Diogene" [13]. These results contribute to remove the lack of data concerning charged pion production in this energy range and establish a link between proton [14,15] and heavy ion [1,11,15–17] induced reactions. The drift chamber surrounds the target, and is placed inside a magnet. A barrel of scintillators is placed around the chamber for use as a trigger. For each collision one measures simultaneously the angles and momenta of π^+, π^-, p, d, t and He emitted between 20° and 132°, above energy thresholds of ~23 MeV for pions and ~42 MeV for protons, with a momentum resolution $\Delta p/p$ that is typically 10–20% (FWHM). With the aim of selecting non peripheral events, the specific trigger for these ^{4}He experiments required at least one charged particle in the scintillator barrel, emitted between 37° and 119°, with an

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energy above ~43 MeV for pions and ~70 MeV/u for baryons.

We estimated the slight systematic error on the measured pion multiplicities due to the contamination of pions by the electrons and positrons which are created by gamma ray conversion inside the target and the beam pipe [13]. The gamma rays come mainly from the π^0 decay, and also from nuclear (or nucleon–nucleon) bremsstrahlung. The low energy e^+ and e^- (less than ~120 MeV) are correctly identified [13]. Their amount is less than 10% of the charged pions one. But higher energy e^+ and e^- can be misidentified as pions. We estimated their amount by using a Monte Carlo simulation of the $\pi^0 \to \gamma\gamma$ process and subsequent γ conversion. This calculation provided e^+ and e^- spectra that are peaked at low energy (much less than 120 MeV). As the $e^\pm$ spectra from nuclear bremsstrahlung gamma rays are also peaked at low energies, we could estimate that less than 5% of the particles measured as pions are in fact electrons or positrons.

Our data are compared to the predictions of Cugnon's intra-nuclear cascade [18]. This model is a Monte Carlo calculation describing a nucleus–nucleus collision as a succession of binary (N, Δ, and π) free collisions. It neglects the compressional (potential) energy. The following improvements to the original code [18] have been implemented: firstly the charge dependence of elementary cross sections is taken into account; secondly, the spectator nucleons are "frozen" as described in ref. [19]. The results of the calculations are filtered by the experimental cuts for comparison with the measurement [#1].

2. Mean pion multiplicities. The measured and calculated total mean pion multiplicities (i.e. the mean number of positive or negative pions emitted in the detector acceptance, per event triggering the scintillator barrel) $\langle n_{\pi^+} \rangle$ and $\langle n_{\pi^-} \rangle$, for ^{4}He+(C, Cu, or Pb) at 200, 400, 600, and 800 MeV/u, are displayed in figs. 1 and 2. Fig. 1 shows the incident energy (E/A) dependence: the experimental multiplicities increase roughly linearly with E/A except perhaps for

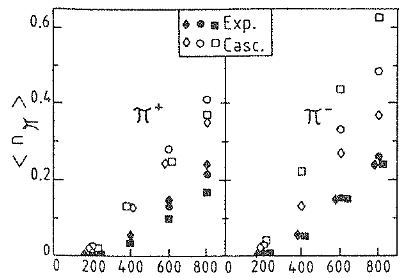

Fig. 1. Mean π^+ (left) and π^- (right) total multiplicities measured in Diogene for the ^{4}He+(C, Cu, Pb) reactions from 200 to 800 MeV/u, as a function of the ^{4}He incident energy, for the three targets. The experimental results (closed symbols) are compared to the cascade predictions (open symbols). The lozenges, circles and squares correspond to the C, Cu and Pb targets, respectively. The statistical error bars are smaller than the symbols. Overlapping symbols have been slightly shifted for sake of readability.

the 200 MeV/u points (which are below the nucleon–nucleon pion production threshold). The slope depends on the target, mainly for the π^+. The cascade predictions are larger than our experimental results, but they also have a linear dependence on the projectile energy, including the 200 MeV/u points; and the theoretical slopes are steeper than the experimental ones.

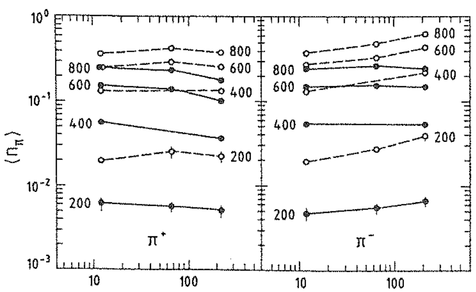

Fig. 2. Mean π^+ (left) and π^- (right) total multiplicities measured in Diogene for the ^{4}He+(C, Cu, Pb) reactions from 200 to 800 MeV/u, as a function of the target mass A_T, for the four given incident energies. The experimental results (closed symbols joined by solid lines) are compared to the cascade predictions (open symbols joined by dashed lines). Each curve is labelled at its left end (experiment) or right end (theory) by the incident energy value.

[#1] The precise description of the chamber and trigger acceptances is necessary for theoretical models to be compared to our results. It is available upon request from the authors.

Fig. 2 shows the same results, but as a function of the target mass: for a given incident energy, the measured multiplicities either decrease (π^+) or stay roughly constant (π^-) when the target mass increases. The model does not account for this target mass dependence. The ratio between the theoretical and the experimental results increases when the target mass increases or when the incident energy decreases. It is worthwhile to notice that this ratio is roughly the same for π^- and π^+: the π^- values are only 5–20% larger than the π^+ ones.

The fact that the pion yield does not increase with the target mass may seem surprising, since for heavy ion collisions it generally increases with the mass of the system [1,11,15,16]. But in our case, the projectile is much smaller than the target, and this has two consequences. Firstly, at a given incident energy, the energy per participant nucleon (in the participants center of mass) significantly decreases when the target mass increases, implying an important decrease of the pion yield per participant nucleon. Secondly, it is likely that the interactions between the ejected particles and the target spectators are more significant in our case than in heavy ion collisions, specially for heavy targets. In fact, one expects the ^{4}He+A reactions to be intermediate between p+A and A+A reactions. For the p+A reactions, it can be stated that the π multiplicities do not increase when the target mass A increases. As a matter of fact, the data [14] show that the π^+ (respectively π^-) production cross sections are proportional to $Z^{1/3}$ (respectively $N^{2/3}$), Z and N being the target proton and neutron numbers. As the mean pion multiplicities are equal to the ratio between the production and the reaction cross sections, if we assume the latter to be proportional to $A^{2/3}$, we find that for the p+A reactions, $\langle n_{\pi^+} \rangle$ decreases and $\langle n_{\pi^-} \rangle$ stays roughly constant when the target mass increases.

We also studied the dependence of the mean pion multiplicity on the proton-like multiplicity $n_{\text{"p"}}$. $n_{\text{"p"}}$ is defined as the total number of measured protons, no matter they are free or bound in a light nucleus. The results are presented in fig. 3 for the incident energy 800 MeV/u. Similar experimental trends are observed at 400 and 600 MeV/u. The cascade shows that, even for such a small projectile, some correlation exists between $n_{\text{"p"}}$ and the impact parameter b. For instance, in the ^{4}He+Cu reaction at 800 MeV/u,

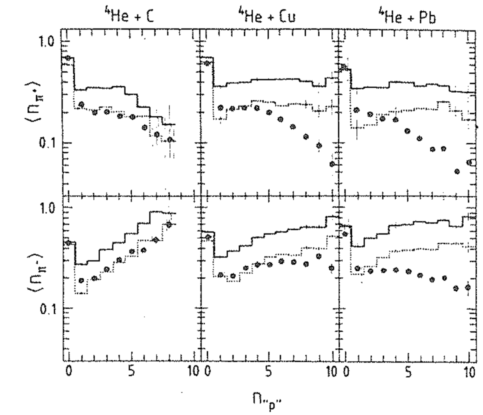

Fig. 3. Mean π^+ (upper plots) and π^- (lower plots) multiplicities as functions of the proton-like multiplicity $n_{\text{"p"}}$, for the ^{4}He+(C, Cu, Pb) reactions at 800 MeV/u incident energy. The plots from left to right correspond to the C, Cu and Pb targets. The experimental results measured in Diogene (black circles) are compared to the cascade predictions (histograms represented by a solid line). The histograms represented by a dotted line correspond to the "new" version of the cascade, which includes the binding energy and Pauli blocking prescriptions (see text).

the mean impact parameter selected by $n_{\text{"p"}}=6$ is ~2.2 fm, while it is ~4.4 fm for $n_{\text{"p"}}=1$, the standard deviation of the b distribution being ~1 fm for those two cases. One can see in fig. 3 that the largest $\langle n_\pi \rangle$ values are reached for $n_{\text{"p"}}=0$, due to the triggering by charged particles. Except those points, fig. 3 shows that experimentally, $\langle n_{\pi^+} \rangle$ decreases with increasing $n_{\text{"p"}}$, while $\langle n_{\pi^-} \rangle$ increases, stays constant, or decreases, respectively for the C, Cu, and Pb targets. The ratio between the theoretical prediction (solid line in fig. 3) and the experimental result (black circles in fig. 3) increases with $n_{\text{"p"}}$, mainly for the Cu and Pb targets. The model does not predict the decreases of $\langle n_\pi \rangle$ observed for the Cu and Pb targets. No $\langle n_\pi \rangle$ decrease (when $n_{\text{"p"}}$ increases) has ever been observed in the A+A collisions [1,17]. But the fact that our systems are highly asymmetrical probably plays an important role, as already noticed in our discussion on the target mass dependence of the total mean multiplicity. The charge conservation has also to be considered. For instance, for the C target, when $n_{\text{"p"}}$ approaches 8, $\langle n_{\pi^+} \rangle$ should decrease and $\langle n_{\pi^-} \rangle$ increase, as they do.

3. The cascade pion excess. An important result at this point is that the cascade strongly overpredicts our data. In summary, the ratio $[\langle n_\pi \rangle(\text{cascade})]/[\langle n_\pi \rangle(\text{experiment})]$ increases when the target mass or the proton-like multiplicity increases, or when the incident energy decreases. Similar trends had been obtained for symmetric systems [1,17]. It has been proposed that the high densities reached during the collisions induce a high compressional energy which lowers the kinetic energy for pion production, and therefore the pion yield [1]. The cascade shows that in ^{4}He+A collisions at 800 MeV/u, densities larger than $3\rho_0$ can be reached, in a small zone of about 2 fm diameter. Consequently, the compressional energy effects cannot be completely neglected. On the other hand, the fact that the cascade/experiment ratio of pion yields increases with increasing target mass or $n_{\text{"p"}}$ multiplicity suggests that pion absorption in nuclear matter is underestimated in the cascade code. However one has to keep in mind that in standard Cugnon's cascade used here, the binding energies of the two nuclei are not included. Therefore, we recalculated the cascade pion yields, with the binding energy prescription introduced in ref. [2]. In this approach, the nucleons suddenly loose 40 MeV just before their first collision. We found that this prescription strongly reduces the discrepancy between the cascade and the experimental total pion multiplicities. The Pauli blocking effect has also been tested, using a prescription similar to what is used in the VUU [5] or BUU [3,20] codes. At 800 MeV/u, its influence on the total pion multiplicities is smaller than the statistical uncertainties. If we include these two prescriptions in a "new" cascade, we find that at 800 MeV/u, the ratio (casc./exp.) of the total mean $\pi^\pm$ multiplicities becomes 0.94, 1.1, and 1.4 for the targets C, Cu, and Pb respectively; while it was 1.5, 1.9, and 2.4 with the "old" version. But it has to be stressed that a large discrepancy remains for "high" $n_{\text{"p"}}$ and heavy targets as it can be seen in fig. 3 (dotted line).

In conclusion, first quasi-exclusive data measured with the Diogene detector are presented. Target mass, incident energy, and $n_{\text{"p"}}$ dependences of the mean pion multiplicities measured in ^{4}He–nuclei collisions are studied. Comparisons to the cascade calculations clearly establish that, even for such a light projectile, the theory overestimates the experimental data. The discrepancy is reduced if the binding energy is taken into account in the model, but it remains large for heavy targets and high $n_{\text{"p"}}$.

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