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ABSTRACT

Experimental data on (d,π^-) reactions at 300 MeV and 600 MeV incident energy are presented. Inclusive spectra on ^6Li, ^9Be and ^{10}B targets near the kinematical limit do not show the usual scaling behaviour. For the two-body reaction $^6Li(d,\pi^-)^8B$ the lowest energy discrete states of the final nucleus were clearly resolved and the cross sections for pion production leading to those states have been determined.

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Even at low incident energies, the two-body reaction A(B,π)C involves large momentum transfers, considerably larger than the Fermi momentum in the nucleus. Consequently one may expect very low cross sections for this type of reaction. However, if such exclusive reactions can be observed, we may hope to obtain information on high momenta in nuclei and to determine to what extent the different nucleons of the projectile and the target are collectively involved in the production of the pion. Only one estimate of cross section, obtained in a poor resolution experiment on the ^{6}Li(^{3}He,π^-)^{9}C reaction at $E_{^3He}$ = 910 MeV has been published until now[1], giving the very low value of ∿10pb/sr. New results on the ^{3}He(^{3}He,π^+)^{6}Li reaction at $E_{^3He}$ = 282 MeV indicate a rather high yield (∿25nb/sr) at low energy[2]. To our knowledge the two-body (d,π) reaction has never been observed. However the inverse reaction ^{12}C(π^+,d)^{10}C has been observed with a cross section of 650nb/sr at 49.3 MeV incident pion energy[3], corresponding to an incident deuteron energy of 195 MeV. It seemed to us important to get data on the (d,π) reaction in order to encourage theoretical studies and to serve as a guide to further experimental work on pion coherent production. We report in this paper final results of the first observation of the reaction ^{6}Li(d,π^-)^{8}B at 300 and 600 MeV deuteron energy[4]. Inclusive cross sections for the reactions ^{6}Li, ^{9}Be, ^{10}B(d,π^-) at 600 MeV incident energy have also been measured near the kinematical limit of the two-body reaction.

The measurements were performed using the deuteron beam from the Saturne synchrotron and the high resolution spectrometer SPES I. The basic detection system consisted of five planes of scintillation hodoscopes and three lucite Čerenkov counters. A 7-fold coincidence between the 3 Čerenkov counters and the first 4 planes of scintillation counters defined the trigger. In addition the time of flight was measured between the first and the fifth plane of scintillators. The particle trajectories were determined with 4 two-fold drift chambers up-stream of the scintillation counters. The counters were calibrated and their efficiencies measured using the $p + p \rightarrow d + \pi^+$ reaction, at 390 MeV and 720 MeV incident energies in order to get pions of the same energy as those detected in the deuteron induced reactions.

The total detection efficiency was found to be (70±6)% and (85±5)%, at 300 and 600 MeV incident energy respectively. The measured counting rates have been corrected for pion losses due to nuclear reactions in the counters and to decay, taking into account a contribution of muon counting. The reaction $p + p \rightarrow d + \pi^+$ was also used to check and calibrate the spectrometer. In the conditions of our experiment the solid angle was $(3.2 \pm 0.03)\,10^{-3}$ sr and the momentum acceptance was (3.29±0.08)%. The beam intensity which was $\sim 10^{11}$ deuteron/burst was monitored by means of a secondary emission chamber (S.E.C.). The absolute normalization was obtained by calibrating the S.E.C. using the carbon activation method ($^{12}C(d,X)^{11}C$ reaction). The absolute cross sections are obtained with an overall uncertainty of 20%. The error bars on fig.1 and in Table 1 include statistical and non systematic uncertainties. The measurements were performed at 15° (lab) which was a compromise to lower the background while keeping the pion rate measurable. For the inclusive cross sections, corrections of about 1% were evaluated by measurements without target.

Measurements were also performed beyond the two-body kinematic limit to ensure that the peaks were physical.

The data for the inclusive reactions are presented on fig.1 in the form of Lorentz invariant cross sections versus the scaling variable x. Previous data from Papp et al.[5] at relativistic energies are also presented. Several features may be noticed :

i) The shape of the spectra is independent of the target. This is in agreement with previous observations at smaller x[5], implying that the projectile structure dominates the light particle spectra observed at forward angles, usually called projectile fragmentation region.

ii) For $x \approx 0.75$ the data by Papp et al. at 1.05 and 2.1 GeV/nucleon, are lower than ours by about one order of magnitude. The transverse momentum dependence, due to non zero experimental angles, which should be taken into account before comparing the experiments[7,8], cannot explain such a difference. In fact, in our experiment $k_\perp = k\sin\theta$ has a value 103MeV/c, being between those corresponding to the Berkeley data ($k_\perp \approx 65$, 130 MeV/c)[7]. Hence, the scaling behaviour against incident energy, which was one of the most striking features of pion inclusive spectra at energies above 1 GeV/nucleon[6,7,8], does not persist down to 300 MeV/nucleon.

iii) Our experimental data in the interval $0.7 < x < 1$ are much less steep than those obtained at 1 GeV/nucleon for $x < 0.7$. In the frame of recent theoretical models[9,12], the invariant cross sections can be parametrized as $(1-x)^n$, where the exponent n is related to the number of constituents and to the basic interactions of the model, and, at forward angles, depends only on the projectile structure. At relativistic deuteron energies an exponent $n = 9$ was obtained in agreement with the theory[9]. Fitting such an expression to our data leads to $n \approx 3$. A similar decrease in the exponent beyond $x = 0.7$ has also been observed in the ($^3He,\pi^-$) reaction at 300 MeV/nucleon[1], where a value of $n \sim 4$ is required in the region close to $x = 1$. A lower exponent would correspond to a smaller number of constituents participating in the reaction, and such a decrease in the exponent has been seen and explained in the target fragmentation region[10]. However, the exponent behaviour near the kinematical limit is not yet clearly understood. In addition, it must be noted that the hard collision model which leads to an $(1-x)^n$ law is expected to be valid only in appropriate kinematical conditions[12] and these conditions are not satisfied when the incident momentum per nucleon is not high compared to the nucleon mass.

Measurements of the π^+ cross section were also carried out although they were made difficult by the high proton background. Nevertheless, we find that π^+ and π^- cross sections are equal within the limits of our experimental uncertainty which was about 10% for these measurements.

Typical spectra for the two-body reaction $^6Li(d,\pi^-)^8B$ are shown on fig.2. The first three levels are excited at both 600 and 300 MeV incident energies. In figures 2a (Ed = 600 MeV) and 2b (Ed = 300 MeV) the ground and first excited state are not well separated due to the target thickness, but the second excited state is clearly seen. The spectrum in fig.2c was obtained with a thinner target (140mg/cm^2) at 300 MeV and the experimental f.w.h.m. of 0.3 MeV permits a clear separation of the three levels. The expected positions of the peaks were calculated knowing, to an accuracy of $\sim 10^{-3}$, the energy of the incident beam and the calibration of the spectrometer and taking into account the energy losses in the targets. Least square fits to thick target spectra have been performed assuming linear and parabolic shapes for the background and gaussian shapes for the peaks. This analysis confirmed the peak positions previously calculated and allowed us to extract cross sections for the ground state and for the two first excited states at 600 MeV. At 300 MeV, the two first levels were not resolved by this method and the thin target spectrum (fig.2c) was used to calculate the relative intensities of the two peaks.

The resulting absolute differential cross sections are shown in Table 1. The first observation is that these cross sections are very small. The most striking feature however is that they are significantly higher (by a factor of 5.5 to 8.5 depending on the level) at the lower energy of 150 MeV/nucleon. This shows that the momentum transfer (4.6 and 5.8fm^{-1} at 300 and 600 MeV respectively) dominates the cross section, eventhough the energy/nucleon is far below the $NN \rightarrow NN\pi$ threshold, and suggests possible collective or cooperative interactions. The inverse reaction $^{12}C(\pi^{+},d)^{10}C$, leading to the ground and first excited states has been observed at $E_{\pi} = 50$ MeV and at an angle of 30°[3]. This is equivalent to the (d,π^{+}) reaction at $E_{d} = 195$ MeV with a momentum transfer of $\sim$[illegible].3fm^{-1}. A detailed balance calculation yields $(\frac{d\sigma}{d\Omega}) \approx 3$nb/sr. Although a direct comparison of this result to ours is rather questionable due to the different initial and final nuclei involved, the trend of increased cross section at low energy is confirmed. Another experimental comparison between the CERN $^{6}Li(^{3}He,\pi^{-})$ results[1] ($\sim$10pb/sr at

910 MeV) and Orsay preliminary results for the same reaction (~50pb/sr at 282 MeV) shows a similar behaviour : the cross sections are larger at the lower energy. DWBA calculations on the $^{12}C(\pi^+,d)^{10}C$ reaction at E_π = 50 MeV[14] yield the right order of magnitude for the observed (π,d) cross sections[3]. For the (d,π) reaction, there is a DWBA prediction at 185 MeV[15], but none in the range of our experiment.

A rough comparison can also be made of the exclusive pion production by p[16], d and ^3He[1] on the same ^6Li target nucleus, although the energy per nucleon is higher in the proton case. The cross sections are in the ratio $1 : 10^{-3} : 2.5\ 10^{-5}$ at 600 MeV proton energy, 600 MeV deuteron energy and 900 MeV ^3He energy respectively. The cross section shows a strong decrease with the mass of the projectile.

In conclusion, several points have been clearly established. Inclusive pion spectra have been measured near x = 1 for ^6Li, ^9Be and ^{10}B target nuclei; the scaling behaviour observed at relativistic energies does not persist at energies near threshold. The present experiment establishes the existence of the two-body pion production induced by deuterons. Cross sections for the reaction $^6Li(d,\pi^-)^8B$ leading to the three first levels of the final nucleus were obtained at 600 and 300 MeV incident energies. These cross sections are found to be higher at the subthreshold pion production energy. The present data will be useful as a starting point for theoretical work. Future studies of this type of reaction should be carried out at energies below and around the free $NN \rightarrow NN\pi$ threshold. Because the cross sections are low, further experimental work will require high beam intensities, good resolution and large

solid angle spectrometers.

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FIGURE CAPTIONS

Fig.1 Inclusive pion spectra induced by 600 MeV deuterons. The scaling variable x is defined as the ratio of the longitudinal momentum along the beam direction in the center of mass frame $k^*_{//}$, over the maximum value kinematically allowed $k^*_{//max}$. Results of ref.[11] are also partially presented. The curves are the theoretical binomial shapes $(1 - x)^n$ normalized to both sets of data for n = 9 and to our data for n = 3.

Fig.2 Pion spectra of the reaction $^6Li(d,\pi^-)^8B$ at 15°(LAB). Spectra (a) and (b) : each of them has been obtained with two different settings of the magnetic field, in order to cover the momentum range of the three first states; as a consequence, only the central parts between the dashed lines correspond to the full deuteron amount and the counts on the sides have been normalized; the solid lines are typical fits to the data. Spectrum (c) : due to the limited momentum acceptance, the second excited state is partially truncated.

TABLE 1

Values of $^6Li(d,\pi^-)$ differential cross sections (LAB) measured at 300 MeV and 600 MeV incident energy, leading to the ground state (2^+), and the two first excited states (0.780 MeV), (2.32 MeV, 3^+) of ^8B.

	Incident energy E_d	
Levels	300 MeV	600 MeV
0	520±120pb/sr	75±30pb/sr
0.78 MeV	710±140pb/sr	85±30pb/sr
2.32 MeV	1330±160pb/sr	240±40pb/sr

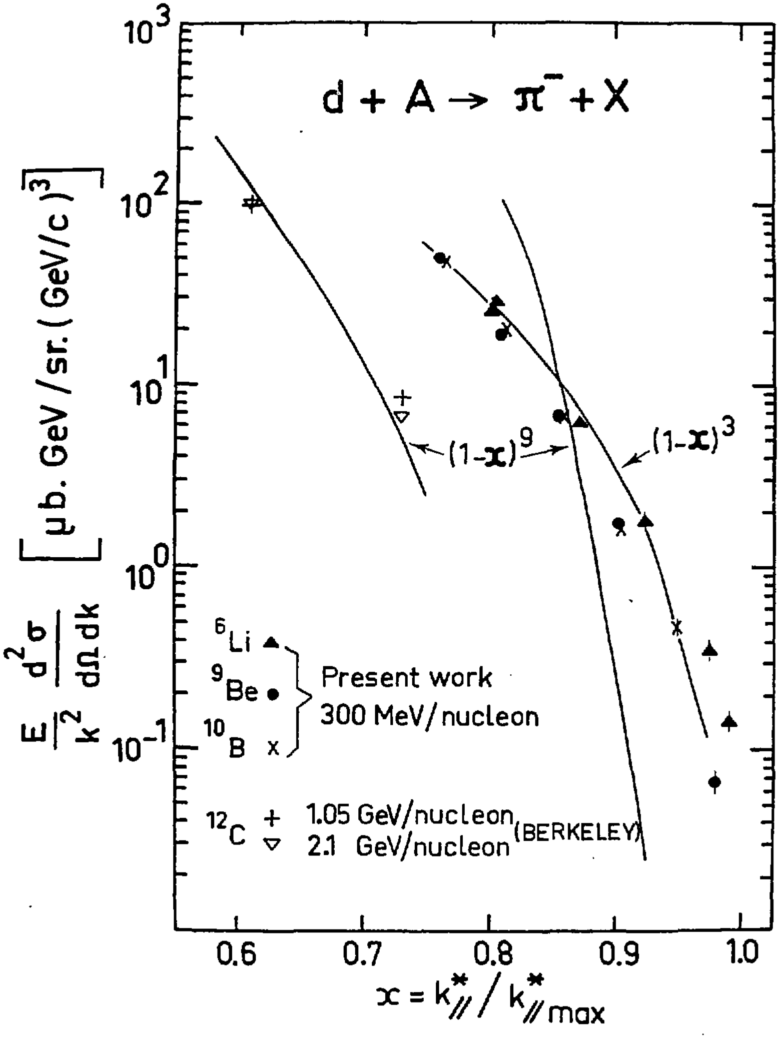
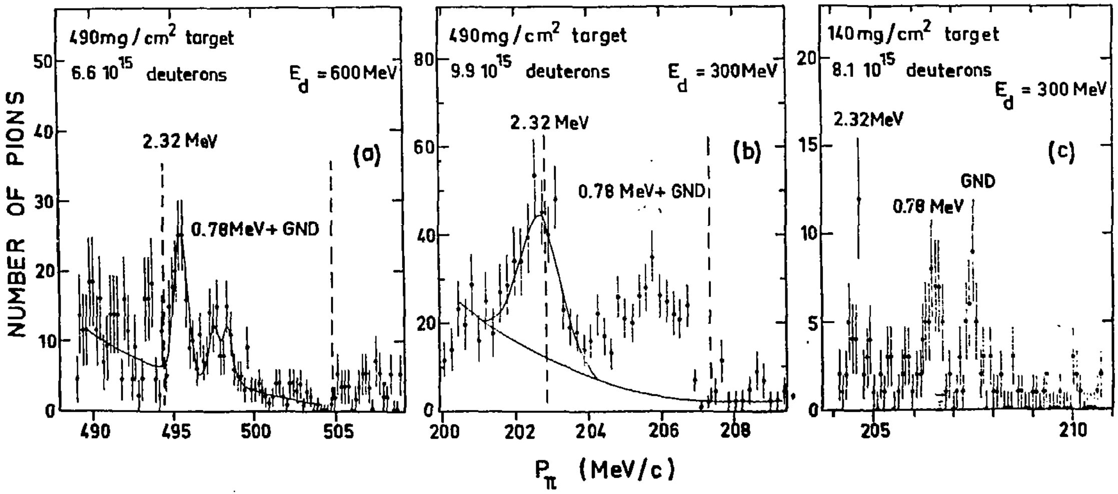

d + A → π⁻ + X
E/k² d²σ/dΩdk [μb. GeV/sr. (GeV/c)³]
10³
10²
10¹
10⁰
10⁻¹
(1-x)⁹
(1-x)³
⁶Li ▲
⁹Be ●
¹⁰B x
Present work
300 MeV/nucleon
¹²C + 1.05 GeV/nucleon (BERKELEY)
▽ 2.1 GeV/nucleon
0.6
0.7
0.8
0.9
1.0
x = k*// / k*// max

Fig. 1



490mg / cm² target
6.6 10^15 deuterons
E_d = 600 MeV
2.32 MeV
0.78MeV+ GND
(a)
490mg / cm² target
9.9 10^15 deuterons
E_d = 300MeV
2.32 MeV
0.78 MeV+ GND
(b)
140 mg / cm² target
8.1 10^15 deuterons
E_d = 300 MeV
2.32MeV
0.78 MeV
GND
(c)
NUMBER OF PIONS
P_π (MeV/c)

Fig. 2

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