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Inelastic interactions of 9.38 GeV/c deuteron in emulsion

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Abstract. Characteristics of the inelastic interactions of 9·38 GeV/c deuterons with nuclear emulsion nuclei have been studied. These have been compared with nucleon-nucleus interactions at a corresponding momentum. The probability of nucleon stripping in deuteron-nucleus interactions has been observed to be 0·5. The charged particle multiplicity in deuteron-nucleus interactions exhibit A-dependence of the type A^{α} with $\alpha=0{\cdot}08$. The experimental data disagree with KNO scaling.

Keywords. Particle multiplicity; stripping probability; KNO scaling; deuteron interactions.

1. Introduction

With the availability of high energy ion beams considerable interest has now been invoked in the studies of nucleus-nucleus interactions (Thomas 1971, 1972). The interactions of relativistic heavy ions may exhibit some similarity with hadron-hadron or hadron-nucleus collisions and may provide useful tests for certain models of multiparticle production (Anon 1974; Gurtu *et al* 1974; Aggarwal *et al* 1977; Glauber 1958, 1967, 1970). Deuteron-nucleus interactions can be regarded as the first step towards nucleus-nucleus interactions although weak binding of the deuteron makes such studies nearer to hadron-nucleus interactions. Interactions of deuteron as projectile and as target have been the subject of considerable experimental and theoretical interests. However, most of these studies have been limited to deuteron beams of kinetic energy of a few hundred MeV. Comparatively, the experimental data of interactions of higher energy deuterons with nuclei are rather limited (Vaisemberg *et al* 1973; Galstyan *et al* 1973; Bagachev *et al* 1972; Silesh *et al* 1972).

In the present work, in addition to the conventional multiplicity studies done by Galstyan *et al* (1973), a critical study of the inelastic interactions of 9·38 GeV/c deuteron with emulsion nuclei is made. The stress is on the detailed studies of the multiplicity distributions leading to a better estimate of the stripping probability, dependence of shower particle multiplicity on the mass number of the target nucleus and the scaling behaviour in deuteron-nucleus interactions. The results are compared with proton-nucleus inelastic interactions.

2. Experimental details

A stack of BR-2 emulsion consisting of pellicles of the size $20\times10\times0{\cdot}04$ cm^3 is exposed at the JINR synchrophasotron to a deuteron beam of 9·38 GeV/c (i.e. 4·7

GeV/c per nucleon). The average intensity of the beam in the pellicle is $\approx 2\times10^4$ particles/cm^2. The pellicles were aligned to the beam at the time of exposure and the angular divergence of the beam is $< 0{\cdot}3°$ at $\sim 1{\cdot}5$ cm from the entry in the pellicles. The proton contamination in the beam is $\lesssim 5\%$.

The data have been obtained through line scanning along the beam tracks under a magnification of 2250× (100×objective). All the interactions except (d—p) scatterings of $\leqslant 5°$ were picked up in the scanning. The plates have been double-scanned by atleast two independent observers and the average efficiency of the double scan has been >94%.

In view of the fact that the (d—p) scatterings of angle $\leqslant 5°$ have not been recorded, we exclude all $N_h=0$, $N_s=1$ events from the data*. Thus all elastic scatterings and some one-prong inelastic events are excluded from the data. A total of 316·9 m of track length has been scanned in which 1178 such interactions are picked up. This leads to a mean free path, $\gamma=26{\cdot}9\pm0{\cdot}8$ cm. The corresponding cross-section is 473 ±14 mb.

Each interaction is scrutinised by atleast two independent observers and each track is classified as N_s or N_h according to ionisation**.

3. Experimental results and discussion

3.1. *General features of the charged particles multiplicities*

The mean values of shower, grey and black tracks for all interactions except with $N_h=0$ and $N_s=1$ are summarised in table 1. The experimental data are corrected for the elastic scatterings***. These results are consistent with those of Galstyan *et al* 1973. Slight difference in the values of $\langle N_g\rangle$ and $\langle N_b\rangle$ in the two experiments can be easily understood in terms of the difference in the selection criteria

Table 1. Mean multiplicities of charged secondaries of d-nucleus interactions and p-nucleus interactions.

	9·38 GeV/c Deuteron-nucleus (present study)	7·1 GeV/c proton-nucleus Winzeler (1960, 1965)
Number of events	1178	1769
$\langle N_b\rangle$	6·5 ± 0·2	—
$\langle N_g\rangle$	2·0 ± 0·1	—
$\langle N_s\rangle$	3·1 ± 0·1	2·8 ± 0·1
$\langle N_h\rangle$	8·5 ± 0·3	8·8 ± 0·2
$\langle N_c\rangle$	11·6 ± 0·3	11·6 ± 0·3

*N_s indicates the number of shower particles in the emulsion i.e. the tracks of the particles which register ionisation $\leqslant 1{\cdot}4\, g_{\min}$. All tracks with ionisation $> 1{\cdot}4\, g_{\min}$ are included in N_h. (Tracks with ionisation $\geqslant 3{\cdot}5\, g_{\min}$ are called black and those with ionisation, $1{\cdot}4\, g_{\min} <$ ionisation $< 3{\cdot}5\, g_{\min}$ are called grey).

**The ionisation measurements are based on the grain count over $\sim 350\ \mu$m of track length. The $g_{\min}$ is measured for each event from the grain density of the beam track. The average $g_{\min}$ is $33{\cdot}2 \pm 0{\cdot}4$ per 100 μm.

***The correction for elastic scatterings are 3% of the total deuteron-nucleus interactions as described by Silesh *et al* (1972).

used for the separation of grey and black tracks. Similar results for 7·1 GeV/c p-nucleus interactions from Winzeler (1960, 1965) are also summarised in table 1. The detailed distributions are presented in figures 1 and 2. It is observed that the distributions for the deuteron-nucleus interactions compare well with those for proton-nucleus interactions. This indicates that the stripping of nucleons before the deuteron interacts is rather significant, though it may not be 100%.

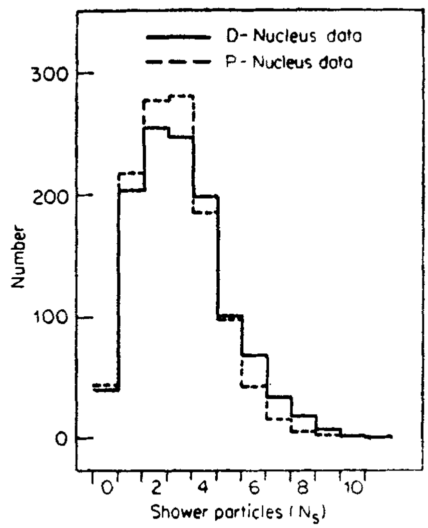

Figure 1. N_s distribution for all interactions (excluding one prong events). The data for 7·1 GeV/c p-nucleus interactions is also shown for comparison.

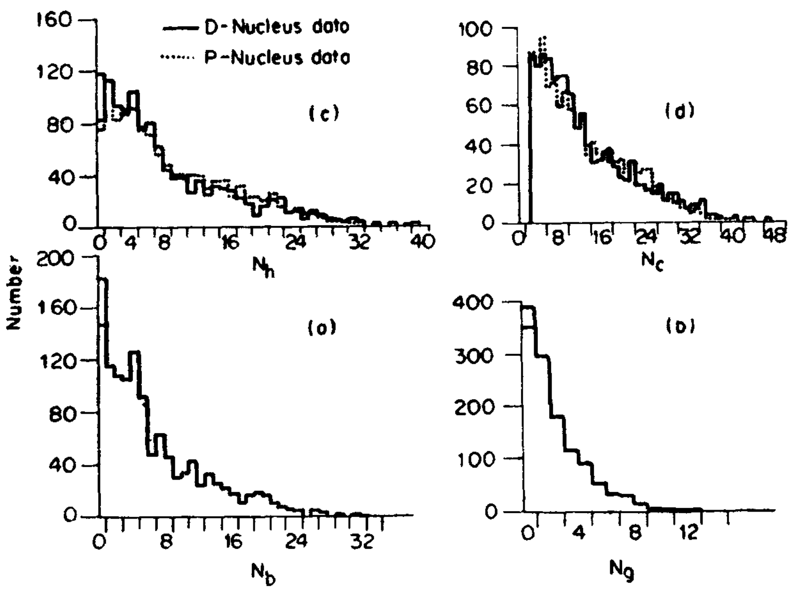

Figure 2. Multiplicity distribution of N_b, N_g, N_h and N_c in deuteron nucleus interactions at 9·38 GeV/c (figures 2a, 2b, 2c, 2d). In figures 2c and 2d, data for 7·1 GeV/c p-nucleus interactions are also superimposed for comparison.

3.2. *Stripping probability*

Considering P as the probability that deuteron as a whole interacts with the target nucleus, one can easily find,

$$P = [\langle N_s \rangle_d - \langle N_s \rangle_p] / [\langle N_s \rangle_p - 1]. \tag{1}$$

$\langle N_s \rangle_d$ and $\langle N_s \rangle_p$ respectively denote the experimentally observed mean multiplicities for shower particles for the d-nucleus and p-nucleus interactions where the momentum of proton is equal to the average momentum of nucleons in the deuteron. In obtaining this relation, one considers that the interactions of deuteron as a whole with nucleus are equivalent to simultaneous independent interactions of the proton and neutron. In the present experiment $\langle N_s \rangle_d = 3{\cdot}1 \pm 0{\cdot}1$. The $\langle N_s \rangle_p$ can be obtained through extrapolation of the p-nucleus shower particle multiplicities at other energies. It is observed by Kaul *et al* (1979) that between 6·2 GeV to 8 TeV the $\langle N_s \rangle$ in p-nucleus interactions is best represented by the relation $\langle N_s \rangle = A + B \ln (\nu_{em} S) + C \ln (\nu_{em} S)/(\nu_{em} S)^{a}$*. This gives $\langle N_s \rangle_p = 2{\cdot}40 \pm 0{\cdot}05$ for 4·7 GeV/c p-nucleus interactions. This yields $P = 0{\cdot}50 \pm 0{\cdot}08$. The probability that only one nucleon of deuteron interacts with nucleus (stripping probability) is $(1-P)$ which is also 0·5. This value of stripping probability is slightly lower than that obtained by Galstyan *et al* (1973) which is $(1-P) = (1-0{\cdot}42) = 0{\cdot}58$.

The stripping probability of 0·5 gives a stripping cross-section of 236 mb on the consideration that the total d-nucleus cross-section observed in the present experiment is 473 ± 14 mb. This value agrees with the theoretical calculations of Serber (1947) but is higher than that given by Glauber (1955).

3.3. *Separation of interactions with heavy and light emulsion nuclei*

Much more useful inferences can be drawn if charged particle multiplicities for deuteron interactions with fixed mass targets are obtained. It is well known that the emulsion experiments have limited scope in this direction. Various statistical methods have been used for the separation of emulsion data into interactions with AgBr ($\langle A \rangle = 94$) and with H, CNO ($\langle A \rangle = 7$) (e.g. see Areti *et al* 1977; Barashenkov *et al* 1959/60; Anon 1976; Lohrmann and Teucher 1962 and Florian *et al* 1973). The method followed by us is similar to that of Babecki (1975) where a linear fit $(a + bN_h)$ is obtained to the N_h distribution (figure 2c) for points with $N_h \geqslant 9$ which are exclusively for d-AgBr interactions**. The fitted line is extrapolated to the region with $N_h \leqslant 8$ and events under the line are taken as the contribution of d-AgBr interactions having $N_h \leqslant 8$. Thus one obtains the total number of interactions with AgBr and H, CNO separately in the sample. These numbers are 824 and 354 respectively, giving the ratio, d-AgBr/d-H, CNO=2·3***. This is consistent with the ratio that one expects on the basis of the composition of the nuclear emulsion.

*The best fit is obtained for $A = 38{\cdot}49 \pm 1{\cdot}53$, $B = -0{\cdot}34 \pm 0{\cdot}12$, $C = -31{\cdot}49 \pm 0{\cdot}98$ and $a = 0{\cdot}33$.

**Data points with $N_h > 30$ are not considered for the fit because of their small statistical weight. The values of the constants a and b of the linear fit are $49{\cdot}6 \pm 3{\cdot}0$ and $-1{\cdot}6 \pm 0{\cdot}1$ respectively.

***The errors (statistical and extrapolation) on the number are 824 ± 38 and 354 ± 28 respectively. Therefore error on the ratio d-AgBr/d-H, CNO$=2{\cdot}3 \pm 0{\cdot}2$.

The N_h distribution for the d-interactions with AgBr and H, CNO can be separately obtained from the matrix of total number of events assuming that for a given N_h, the N_s distribution does not depend on the target mass and events of each N_h are divided into AgBr and H, CNO in the ratio of the inferred numbers. Thus one can obtain both the N_s distributions and the mean values of charged particles multiplicities. These distributions are shown in figure 3. The $\langle N_s \rangle$ and $\langle N_h \rangle$ for these interactions are given in table 2. It is observed that $\langle N_h \rangle$ for the two groups of target nuclei is significantly different but $\langle N_s \rangle$ does not change appreciably. However, the difference in the N_s distribution is reflected in the value of dispersion

$$D = [\langle N_s^2 \rangle - \langle N_s \rangle^2]^{1/2}$$

3.4. *Nature of N_s distribution*

Many models of p-nucleus interactions assume that the N_s distributions should be Poisson. This can be easily determined by studying various multiplicity moments (μ_i). These are shown in table 3, for the present data and for the p-nucleus interactions at 7·1 GeV/c. For a true Poisson distribution, $\lambda = \langle N_s \rangle$, $\mu_2 = \mu_3 = \lambda$, $\mu_4 = \lambda\ (3\lambda + 1)$ where λ is given by $(PN) = e^{-\lambda}\ \lambda^N/N!$*. The comparison of the experimental data with the Poisson distribution curves for the p-nucleus data at 7·1 GeV/c ($\lambda = 2·8$) and for d-nucleus interactions ($\lambda = 3·1$) are shown in figures 4(a) and 4(b) respectively. It is clearly observed that for the d-nucleus interactions, the Poisson curve does not fit the data points whereas for the p-nucleus interactions the

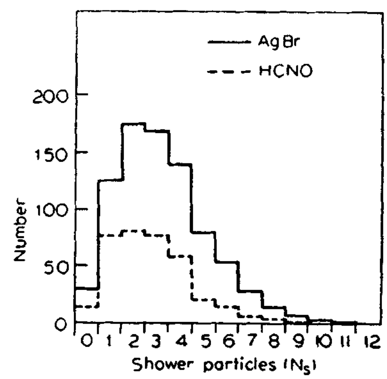

Figure 3. N_s distribution for interactions with AgBr and H, CNO.

Table 2. Average value of N_h and N_s for the interactions of deuteron with light (H, CNO) and heavy (AgBr) emulsion nuclei. The errors are statistical.

Target	H, CNO	AgBr
$\langle N_h \rangle$	3·3 ± 0·2	10·6 ± 0·4
$\langle N_s \rangle$	2·7 ± 0·1	3·3 ± 0·1
D^2	2·7 ± 0·2	3·8 ± 0·2

*For Poisson distribution, the cumulants $K_{2,3} = \mu_{2,3}$ and $K_4 = (\mu_4 - 3\mu_2^2)$.

Table 3. The multiplicity moments (μ_i) about the mean and fourth cumulant (K_4) for 9·38 GeV/c d-nucleus interactions and 7·1 GeV/c p-nucleus interactions

Moments	9·38 GeV/c deuteron-nucleus interactions (present study)	7·1 GeV/c proton-nucleus interactions Winzeler (1960, 1965)
$\langle N_s \rangle$	3·1 ± 0·1	2·8 ± 0·1
μ_2	3·5 ± 0·2	2·6 ± 0·1
μ_3	5·4 ± 1·0	2·5 ± 0·5
μ_4	45·3 ± 6·0	22·0 ± 2·3
K_4	8·6	1·7

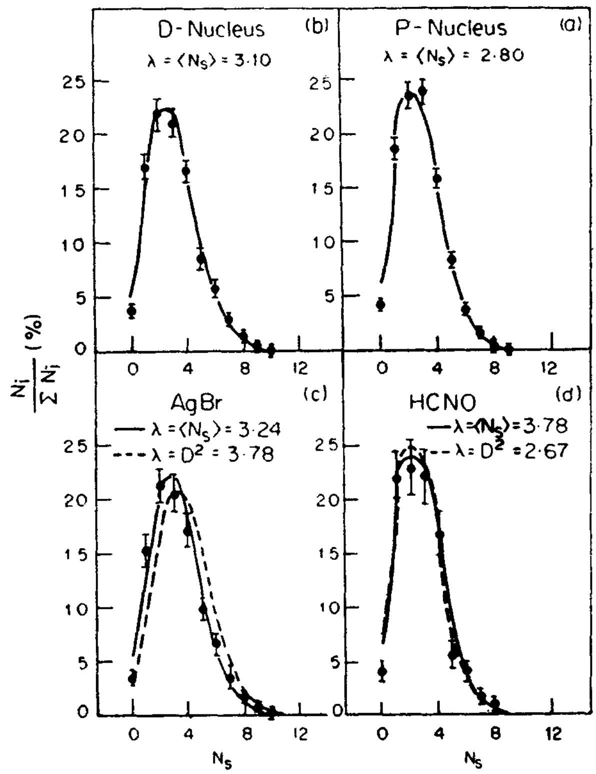

Figure 4. N_s distribution for all inelastic proton-nucleus and deuteron-nucleus interactions fitted with Poisson distribution (figures 4a and 4b). In figures 4c and 4d, the N_s distribution for two groups of target nuclei AgBr and H,CNO is shown. The fits for different values of Poisson distribution parameter are indicated.

fit is reasonably good. The χ^2 for the d-nucleus interactions data is 2·9/DOF whereas for p-nucleus interactions data it is 0·8/DOF.

Figures 4(c, d) present the N_s distribution for the d-interactions with AgBr and H, CNO fitted with Poisson curves for $\lambda = \langle N_s \rangle$. It is observed that for the AgBr interactions there is a good agreement with the Poisson distribution but for the H, CNO interactions there is deviation particularly at the low values of N_s. This result is not in agreement with the observations of Galstyan *et al* (1973). If one takes $\lambda = \mu_2 = (\text{dispersion})^2$ as given in table 2, one observes that the fit with Poisson for H, CNO interactions does not change but for AgBr interactions the change is appreciable and fit with Poisson completely smears out.

The observation that the N_s distribution of p-nucleus (or nucleon-nucleus) interactions around 5–7 GeV/c exhibit good agreement with the Poisson distribution can be used to calculate the value of the stripping probability. It is already argued in § 3.2 that the d-nucleus interactions can be divided into two classes, the single nucleon-nucleus interactions (where stripping has taken place) and the two-nucleon interactions (where no stripping takes place). It is also shown that the $\langle N_s \rangle$ for the two classes of events are respectively $\langle N_s \rangle_p$ and $[2\langle N_s \rangle_p - 1]$. It is further shown that the inferred value of $\langle N_s \rangle_p$ for protons of momentum 4·7 GeV/c (equal to the average momentum of the nucleons in the deuteron) is 2·4. Thus the N_s distribution of d-interactions should be a superposition of two Poisson distributions, one with $\lambda = 2{\cdot}4$ and the other with $\lambda = 3{\cdot}8$*. These two distributions are shown respectively by curves A and B of figure 5. If the two distributions are mixed equally, the resultant is shown by curve C. It is observed that curve C (figure 5) excellently fits the data, thereby confirming that the stripping probability is 50%.**

3.5. *Variation of N_s with A and N_h*

The results obtained in the present study allow us to examine the variation of N_s with the target mass number A. The results from p-nucleus interactions indicate that this variation is rather slow and has the form, A^{α} with $\alpha = 0{\cdot}09$ at 7·1 GeV/c. From the data presented in table 2 and assuming that $\langle N_s \rangle \propto A^{\alpha}$, we get $\alpha = 0{\cdot}08 \pm 0{\cdot}04$. This indicates that the variation is similar to that observed in the p-nucleus interactions thereby again confirming that the d-nucleus interactions are similar to p-nucleus interactions.

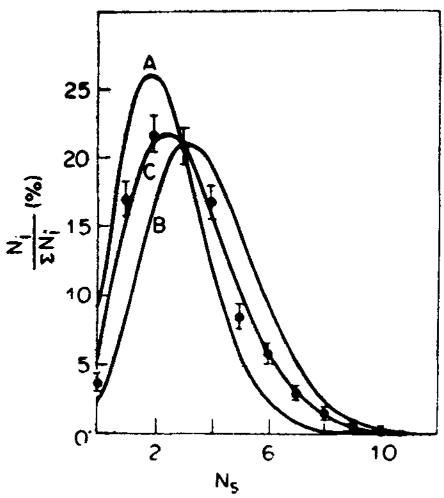

Figure 5. N_s distribution for all inelastic interactions (excluding $N_h = 0$, $N_s = 1$). The three Poisson curves are fitted (for details see text).

*With same argument one can consider the Poisson distribution with $\langle N_s \rangle = 3{\cdot}8$ as superposition of two Poissons, one with $\langle N_s \rangle = 2{\cdot}4$ (corresponding to p-nucleus interactions) and the other with $\langle N_s \rangle = 1{\cdot}4$ (corresponding to n-nucleus interactions). It is observed that the results of the two calculations are similar.

**The χ^2 of the fit for stripping probability 50% is 2/DOF. If the stripping probability is assumed 40% or 60% the χ^2 becomes 2·8/DOF.

The variation of $\langle N_s \rangle$ with N_h is shown in figure 6 along with a linear fit $\langle N_s \rangle = a+b\ N_h$ for the points with $N_h = 1$ to 20. Data point for $N_s = 0$ is excluded because of the loss of one prong ($N_h = 0$) inelastic interactions. The points for $N_h > 20$ are excluded because of the poor statistics and because the fragmentation may start in this region. The best fit gives $a = 1{\cdot}32 \pm 0{\cdot}08$ and $b = 0{\cdot}10 \pm 0{\cdot}01$. The χ^2 for the fit is 29 for 18 DOF. The line corresponding to a similar fit for the proton nucleus interactions at 7·1 GeV/c is also shown in figure 6. The corresponding values of a and b are $a = 2{\cdot}10 \pm 0{\cdot}06$ and $b = 0{\cdot}08 \pm 0{\cdot}01$. The χ^2 for the fit is 48 for 18 DOF. The similarity between the two linear fits again confirms that the processes responsible for the growth of the created particles in the two cases are same.

3.6. *Scaling behaviour of deuteron interactions*

The results of *p-p* interactions indicate that the data fits the predictions of the KNO scaling (Koba *et al* 1972.) It is shown by Koba *et al* (1972) that the *p-p* data from ~4–28 GeV/c indicate that $\langle N \rangle / D$ is approximately constant. It is further shown that if one defines the normalised cross-sections $P_N(s)$ as $\sigma_N(s)/\sigma_{tot}(s)$ and two variables x and y as, $x = (N - \langle N \rangle / D$ and $y = DP_N$ then all the data of πp collisions for $\lesssim$ GeV/c lies nearly on a single universal curve represented by a generalised Poisson distribution of the type:

$$y = 2\, de^{-d^2} \frac{d^2\,(xd+d^2)}{\Gamma(xd+d^2+1)}, \qquad (2)$$

where $d = 1{\cdot}8$. It is surprising that for $\bar{\pi} p$ interactions the scaling sets in at such low projectile momenta. For the *p-p* data Slattery (1973) indicates that the scaling sets in only at momenta $\gtrsim 20$ GeV/c. For the *p*-nucleus interactions, it is not clear whether the scaling sets in at much higher momenta (~ few hundred GeV/c) or at medium momenta (~20–30 GeV/c).

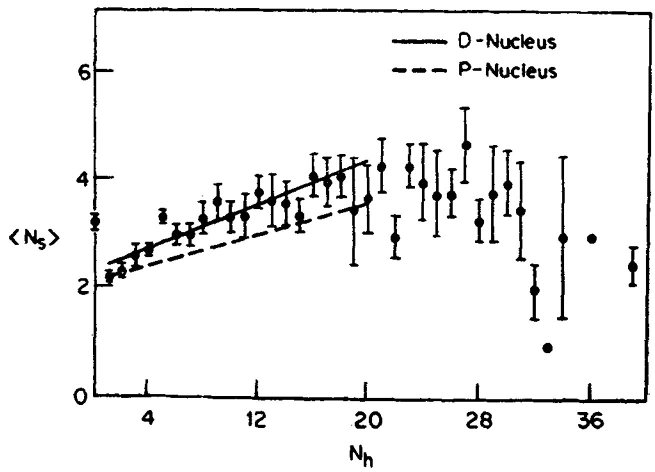

Figure 6. Dependence on N_h of $\langle N_s \rangle$. Linear fit is shown upto $1 \leqslant N_h \leqslant 20$ for the present data and for *p*-nucleus interactions at 7·1 GeV/c.

The variable similar to $\langle N\rangle/D$ for the p-nucleus interactions is $R_{em}=\langle N_s\rangle/\langle N_{ch}\rangle$ where N_{ch} is the multiplicity in p-p interactions. It is expected that this ratio should be ≈ 2 if KNO scaling is obeyed. It is shown by Aggarwal *et al* (1977) that R_{em} becomes approximately constant from $\sim$20 GeV/c onwards.

If d-nucleus interactions at 9·38 GeV/c are identical in all respects to p-nucleus interactions, it would be interesting to study the variation of scaling parameters. The first parameter which we evaluate is $\langle N_s\rangle_{d\text{-nucleus}}/\langle N_{ch}\rangle_{p\text{-}p}$ which is similar to the ratio R_{em} defined for p-nucleus interactions†. Considering the stripping probability to be $\sim$ 50% and the interaction proceeds as discussed in § 3.2, one can easily get

$$\langle N_s\rangle_{d\text{-nucleus}}/\langle N_{ch}\rangle_{p\text{-}p} = 1{\cdot}5\ R_{em} - \frac{0{\cdot}5}{\langle N_{ch}\rangle_{p\text{-}p}}. \qquad (3)$$

Following the relation given by Whitmore (1976) the $\langle N_{ch}\rangle_{p\text{-}p}$ at 4·7 GeV/c is 2·6. The corresponding value of $R_{em}=0{\cdot}92$. These values satisfy equation (3) with $\langle N_s\rangle_{d\text{-nucleus}}/\langle N_{ch}\rangle_{p\text{-}p} = 1{\cdot}2$. However, one may find that the simple model of interaction particularly when deuteron interacts as a whole in the nucleus may change at higher energies.

As no other data for d-nucleus interactions are currently available, we cannot study the variation of scaling parameter, the ratio $\langle N\rangle/D$ where $\langle N\rangle$ is the mean multiplicity and D is the dispersion. We can compare this ratio with that for hadron-nucleon and hadron-nucleus interactions at similar momenta which are presented in table 4. It is observed that the ratio for d-nucleus interactions is different from those for hadron-nucleon interactions but similar to that for the p-nucleus interactions as expected. Thus the scaling does not seem to set in at such low energies.

Figure 7(a) shows the distribution of the KNO scaling function ($\langle N_s\rangle\cdot P_N(s)$) with the normalised multiplicities ($N_s/\langle N_s\rangle$). This distribution is similar to that given by Slattery (1973). It is again clear that the data do not agree with the predictions of KNO scaling. Figure 7 (b) shows the variation of the function $y(x)$ with x, defined above. The data points are fitted to the generalised Poisson distribution (equation (2)). It is observed that the most probable value of d is $\simeq$ 0·25

Table 4. $\langle N\rangle/D$ for hadron-nucleon, hadron-nucleus and deuteron-nucleus interactions

Reaction	P_{lab} GeV/c	$\langle N\rangle$	D	$\langle N\rangle/D$	References
π^-p	6·8*	3·15 ± 0·09	1·38 ± 0·06	2·29 ± 0·12	Czyzewski *et al* (1970)
π^+p	7·0	3·62 ± 0·04	1·40 ± 0·02	2·58 ± 0·05	Stone *et al* (1971)
pp	5·5	2·71 ± 0·01	1·03 ± 0·01	2·64 ± 0·02	Czyzewski *et al* (1970)
p-nucleus	7·1**	2·80 ± 0·04	1·60 ± 0·03	1·75 ± 0·04	Winzeler (1960, 1965)
d-nucleus	9·38** (4·7 GeV/c per nucleon)	3·09 ± 0·09	1·88 ± 0·04	1·65 ± 0·05	Present study

*Propane bubble chamber data; **Emulsion data.

†One can also define the ratio $\langle N_s\rangle_{d\text{-nucleus}}/\langle N_{ch}\rangle_{d\text{-}p}$ and probably this will indicate the projectile effect in a much better way. At present there are no data to evaluate this parameter.

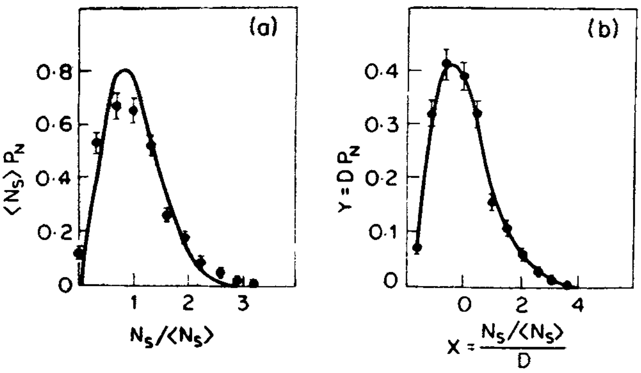

Figure 7. (7a) shows the variation of scaling function ($\langle N_s \rangle$ $P_N(s)$ with normalised multiplicities ($N_s/\langle N_s \rangle$). The variation of the function $y(x)$ with x (defined in text) is shown in (7b).

although the fit is not perfect, particularly for the low and high values of x. Clearly more data at different energies are required to study the behaviour of the scaling parameters.

4. Conclusions

The comparison of charged particle multiplicity parameters of d-nucleus interactions at 9·38 GeV/c with those for p-nucleus interactions at approximately the same momentum as of nucleons in the deuteron indicate striking similarity. The probability of stripping of nucleons in d-interactions is $0{\cdot}50 \pm 0{\cdot}08$. The corresponding stripping cross-sections agree with the predictions of Glauber and Serber. The N_s distribution for the d-nucleus interactions is observed to be non-Poisson in character but can be explained in terms of the superposition of the distribution functions of single nucleon and two nucleon interactions in d-nucleus interactions. It is observed that the A-dependence of d-nucleus interactions follow a simple form, like A^{α} where $\alpha = 0{\cdot}08 \pm 0{\cdot}04$. The behaviour of the scaling parameters is also examined. It is observed that as expected the scaling does not seem to set in at such low momenta (unlike the $\pi^- p$ interactions) but definite conclusions can be drawn only when further data are available.

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