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Charged-Particle Multiplicity Distribution in pd Interactions at 300 GeV/c.*

by

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ABSTRACT

Charged-particle multiplicity distributions from 300 GeV/c pd interactions have been determined from an exposure of the Fermilab 30-in. bubble chamber. The data show clear evidence for double scattering inside the deuterium nucleus. We have been able to correct for the effects of the second scatters using a simple semi-empirical model. The resulting pp multiplicity distribution is in excellent agreement with the pp data obtained from a p-H_2 experiment at the same energy. The pn multiplicity distribution appears to be shifted from the pp distribution with $\langle n_c \rangle_{pn} = 7.84 \pm 0.17$.

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Experiments at Fermilab, CERN and Serpukov have revealed interesting systematic trends in the charged-particle multiplicity distributions above 50 GeV/c[1]. In studies thus far, the multiplicity distributions in the momentum range 50 - 1500 GeV/c display very little dependence on the initial hadrons in the interactions, and the shape of the distribution is relatively independent of the incident momentum. These studies have been restricted to interactions containing two charged hadrons in the initial state, from which only the even-prong charged-particle multiplicities are populated. In this letter we present data on the charged-particle multiplicity distribution obtained from one of the first Fermilab bubble chamber experiments using deuterium as the target.

The data of this analysis come from a 52500 picture exposure of the 30-inch Fermilab deuterium filled bubble chamber to a 300 GeV/c proton beam. All the pictures were double scanned at approximately life size magnification. A second scan was carried out independently of the first scan at a second institution. The following criteria were used for accepting a frame during the two scans: (1) There had to be at least two good views out of the three taken. (2) There had to be no more than six beam tracks entering through the window as projected in view 2. All beam tracks were required to be parallel to within 1.5 mrad. (3) There had to be no more than three non-beam tracks entering the chamber. With these criteria, 29,900 frames were accepted; most of the rejected frames contained evidence of a hadron shower upstream of the visible deuterium. The information recorded for each accepted frame was the number of beam tracks, and, when there was an interaction, the event topology, the number of positive tracks, secondaries, V's and neutron stars. No fiducial restriction was used in recording this information.

events without a stopping track and events with three or more prongs was 94.6 ± 2.1% inside a fiducial length of 53 cm[2]. The efficiency for detecting one prong events and two prong events with a stopping track was found to be less than 50%. This exceptionally low scanning efficiency was principally due to the difficulty in finding small angle pn elastic interactions with a short or invisible spectator proton. However, in this analysis of the charged-particle multiplicity distribution it is not crucial to determine the exact number of one and two prong events.

In approximately 30% of all the events there were discrepancies between the two scans due to disagreements in prong counts. About 1/4 of these discrepancies were re-examined by physicists on a high magnification table with an image ten times life size. There was no indication of any systematic error in the prong counts of the single scans. However the errors on the multiplicity distribution due to the random errors in prong counting were found to increase linearly from (0.2 ± 0.2)% at $n_c = 2$ to (7.0 ± 1.0)% for $n_c = 20$ or more.

Column 2 of Table 1 lists the raw multiplicity distribution as determined from a single scan. The errors shown include the contributions due to the uncertainties in the prong count. The 1-prong events were not included due to the poor detection efficiency. This distribution was further corrected for scanning biases such as missed close-in V's, missed secondaries, and missed Dalitz pairs[3]. This corrected distribution and the corrected distribution of events with a positive stopping track in the bubble chamber are listed in columns 3 and 4 of Table 1.

In order to separate the data into pp and pn interactions we have divided the events into three classes: (1) All odd prong events, (2) even prong events without a positive track which stops in the visible region of the bubble chamber, and (3) even prong events with a positive stopping track. We then assume that no spectator proton leaves the visible region of the bubble chamber[4]. Therefore we assume that all class 1 events are pn interactions and all class 2 events are pp interactions. The events in class 3 can arise from either pp interactions with a visible stopper or from pn interactions with a visible spectator proton. We have divided this class into pp and pn interactions by assuming that the fraction of pp events with a stopper in pd collisions is the same as we have observed experimentally in a p-H_2 experiment in the same chamber at the same energy[3] (colum

The resulting pp and pn multiplicities are listed in the last two columns of Table 1 where the errors also include the errors involved in separating the class 3 events. Fig. 1 shows this multiplicity distribution. It is evident that there are far more pp interactions with $n_c \geq 4$ (6396 ± 196) than pn interactions with $n_c \geq 3$ (5029 ± 111). Furthermore there is evidence for an excess of higher multiplicity pp interactions when compared with the corresponding hydrogen data as indicated by the average multiplicity of $\langle n_c \rangle_{pp} = 9.07 \pm 0.17$ in deuterium[5] versus $\langle n_c \rangle_{pp} = 8.50 \pm 0.12$ in hydrogen[3]. A process that can produce both of these effects is double scattering inside the deuterium nucleus. We have analyzed the data using an empirical model to correct for the effects of double scattering and obtained excellent agreement between the number of pp interactions with $n_c \geq 4$ and the number of pn interactions with $n_c \geq 3$.

The following assumptions were used in the double scattering model. 1) The distance separating the two nucleons in the deuterium nucleus is large enough such th all second scatters are incoherent, and that there is an equal and independent probability for each particle produced in the first interaction to scatter from the second nucleon. 2) The multiplicity distribution of the second scatter is the same as that of the secondary interactions observed experimentally in the bubble chamber, and is independent of the multiplicity of the first interaction. 3) The average number of neutral particles, n_o, produced in the first interaction is $n_o = n_-$ for pp interactions, and $n_o = n_- + 1$ for pn interactions where n_- is the number of negative particles produced. The final results, however, are quite insensitive to the actual values used for n_o. Using these assumptions the numbers of observed events are given by:

$$M_n = N_n \beta_n (1 - \alpha \sum_{i=2}^{\text{even}} p_i)^n \; (1 - \alpha \sum_{i=1}^{\text{odd}} p_i)^{n_o(n)} \tag{1}$$

for odd multiplicity n, and

$$M_n = \sum_{k=1}^{n-1} [1 - (1 - \alpha p_{n-k+1})^k \; (1 - \alpha p_{n-k})^{n_o(n)}] \tag{2a}$$

$$+ N_{n-1}(1 - \beta_{n-1}) \; (1 - \alpha \sum_{i=2}^{\text{even}} p_i)^{n-1} (1 - \alpha \sum_{i=1}^{\text{odd}} p_i)^{n_o(n-1)} \tag{2b}$$

$$+ N_n \; (1 - \alpha \sum_{i=3}^{\text{odd}} p_i)^n \; (1 - \alpha \sum_{i=2}^{\text{even}} p_i)^{n_o(n)} \tag{2c}$$

for n even. The definitions for the notations used are:

M_n = the number of observed n-prong events.

N_n = the number of n-prong events produced in the first interaction.

β_n = the fraction of odd n-prong pn events without an observed spectator. The value for β_n is dependent upon the multiplicity and was obtained by dividing column 3 by column 7 in Table 1.

p_i = the normalized probability for a second scatter with i charged prongs. The values of the p_i's were obtained from the observed secondary interactions and $\sum_{i=1}^{20} p_i = 1$.

$n_o(n)$ = the average number of neutral particles associated with an n-prong event.

α = the overall probability for each outgoing particle to second scatter. The value for α is to be determined in the analysis.

The RHS of (1) is the number of n-prong pn events that neither double scatter nor have an observed spectator proton. The three terms in (2) are: (a) the number of lower multiplicity events that are observed as an n-prong through double scattering, (b) the number of (n - 1) odd-prong pn events that are observed as an n-prong due to the presence of an observed spectator proton, and (c) the number of n-prong pp events that do not double scatter.

In order to do the model calculation we need the number of 1 prong pn and 2 prong pp events since these can also double scatter and populate the higher multiplicities. We have assumed that the number of 1 prong pn events is equal to the number of 2 prong pp events.

These equations are easily solved for each N_n with α being the only free parameter. The value of α was determined by fitting the pp (even) multiplicity calculated from this model to the pp distribution of Ref. 3. The best χ^2 obtained is 5.3 for 8 degrees of freedom ($4 \le n_c \le 20$) with $\alpha = 0.021 \pm 0.004$[6]. Fig. 2 shows the pp and pn multiplicity distributions determined from this fit. The numbers of pp events with $n_c \ge 4$ and pn events with $n_c \ge 3$ are 5620 ± 204 and 5750 ± 165, respectively, which are in excellent agreement. Table 2 lists some of the moments and the Mueller correlation parameters $f_2^{+-} = \langle n_c(n_c - 1)\rangle - \langle n_c\rangle^2$ for both the pp and pn multiplicities together with the values for pp interaction from Ref. 3 for comparison.

The results indicate that at low multiplicities the pn distribution tends to be shifted from the pp distribution. However, at higher multiplicities this shift is somewhat reduced and there the overall multiplicity distribution tends toward being interleaved. The χ^2 values calculated by comparing the pn distribution with a shifted pp distribution $\left((\sigma_{pn}(n_c) = \sigma_{pp}(n_c + 1)\right)$ are 2.58 (6 d.f.) for $3 \le n_c \le 13$, and 3.09 (3 d.f.) for $15 \le n_c \le 19$. The corresponding values for a linearly interleaved pn distribution $\left((\sigma_{pp}(n_c - 1) + \sigma_{pp}(n_c + 1))/2\right)$ are 13.38 (6 d.f.) and 1.42 (3 d.f.) respectively.

We thank the staffs of the accelerator, Neutrino Laboratory and 30-in. Bubble Chamber of the Fermi National Accelerator Laboratory for their help during the course of the experiment. We also thank the scanning staffs at our institutions for their careful and painstaking work in scanning the difficult and sometimes impossible events.

Table 1: Multiplicity Distribution from pd Interactions at 300 GeV/c.

Charged Prongs	Scanned Events[a]	Corrected Events[a]	Corrected Events with Stoppers[a]	Fraction of pp Interactions without Stopper[3]	pp Events[b]	pn Events[b]
2	1945 ± 47	1960 ± 47	1076 ± 33	0.52 ± .02	1700 ± 112	
3	529 ± 24	546 ± 24	50 ± 7			822 ± 44
4	1194 ± 39	1224 ± 40	442 ± 23	0.83 ± .03	948 ± 68	
5	639 ± 28	653 ± 29	43 ± 10			919 ± 40
6	1290 ± 47	1307 ± 48	346 ± 22	0.93 ± .03	1041 ± 69	
7	628 ± 31	646 ± 33	58 ± 10			953 ± 43
8	1479 ± 61	1521 ± 64	359 ± 22	0.96 ± .04	1214 ± 84	
9	576 ± 32	582 ± 35	40 ± 10			820 ± 43
10	1281 ± 63	1305 ± 65	270 ± 21	0.97 ± .04	1067 ± 82	
11	482 ± 31	483 ± 36	39 ± 9			662 ± 42
12	988 ± 57	1025 ± 62	196 ± 18	0.98 ± .05	846 ± 77	
13	295 ± 23	268 ± 29	31 ± 9			403 ± 34
14	683 ± 46	705 ± 51	135 ± 16	1.00 ± .05	570 ± 61	
15	224 ± 20	192 ± 25	15 ± 7			259 ± 29
16	420 ± 34	433 ± 44	67 ± 14	1.00 ± .08	366 ± 55	
17	112 ± 13	77 ± 25	10 ± 7			105 ± 26
18	215 ± 22	187 ± 29	28 ± 8	1.00 ± .11	159 ± 35	
19	61 ± 9	26 ± 15	15 ± 10			33 ± 17
20	130 ± 15	119 ± 21	7 ± 7	1.00 ± .16	112 ± 28	
21	50 ± 8	31 ± 13	2^{+4}_{-2}			36 ± 14
22	62 ± 10	44 ± 14	5^{+5}_{-4}	1.00 ± .22	39 ± 17	
23	21 ± 7	9 ± 9	4^{+5}_{-4}			10 ± 10
24	29 ± 6	26 ± 9	1^{+5}_{-1}	1.00 ± .37	25 ± 14	
25	14 ± 4	3^{+7}_{-3}	1^{+3}_{-1}			5^{+8}_{-5}
26	13 ± 4	6^{+7}_{-6}	2^{+4}_{-2}	1.00 ± .45	4^{+8}_{-4}	
27	5 ± 3	1^{+5}_{-1}	0 + 3			1^{+6}_{-1}
28	7 ± 3	3^{+5}_{-3}	0 + 3	1.00 ± 1.00	3^{+6}_{-3}	
29	3 ± 2	1^{+4}_{-1}	1^{+3}_{-1}			1^{+5}_{-1}
30	4 ± 2	2^{+5}_{-2}	0 ± 3	1.00 ± 1.00	2^{+6}_{-2}	
Total	13379 ± 116	13385 ± 116	3243 ± 57		8096 ± 226	5029 ± 111

(a) All errors include the statistical errors combined with the errors involved in the corrections.

(b) pp and pn multiplicities before correcting for the effects of double scattering. See text for discussion on separating the data into pp and pn interactions.

Table 2: Moments and Correlation Parameters[5].

	$\langle n_c \rangle$	$\langle n_c^2 \rangle$	f_2^{+-}	f_2^{cc}
pn	7.84 ± 0.17	80.9 ± 3.2	4.86 ± 0.33	11.59 ± 1.29
pp	8.45 ± 0.19	87.8 ± 4.0	4.11 ± 0.36	8.00 ± 1.38
pp from Ref. 3	8.50 ± 0.12	90.2 ± 1.6	4.49 ± 0.28	9.45 ± 0.51

References

1. See review by J. Whitmore, Phys. Reports <u>10C</u>, 274 (1974).

2. A fiducial length cut was imposed along the beam direction to provide at least 6 cm of visible outgoing tracks.

3. A. Firestone et al., Phys. Rev. <u>D10</u>, 2080 (1974).

4. Inside the chosen fiducial region the percentage of spectator protons that do not stop in the visible deuterium varies from 0 to 3% depending on the vertex position. This gives an overall average of less than 1/2% of the spectator protons leaving the visible region.

5. The number of inelastic 1 prong and 2 prong events were each estimated to be 450 ± 110. These numbers were used in calculating the averages and correlation parameters. This estimate was obtained by extrapolating the pp multiplicity distribution of Ref. 3 to the pd data.

6. The cross section for interacting with the second nucleon may be estimated by using the simple formula $\alpha = \sigma/4\pi R_D^2$ where R_D is the radius of the deuteron. This gives $\sigma \simeq 42 \pm 8$ mb which is of the correct order of magnitude for πN and NN interactions.

Figure Captions

Figure 1. pp and pn multiplicity distributions[5)] before correcting for the effects of double scattering. Solid circles represent pp interactions and crosses represent pn interactions.

Figure 2. pp and pn multiplicity distributions[5)] after correcting for the effects of double scattering. Solid circles represent pp interactions and crosses represent pn interactions.

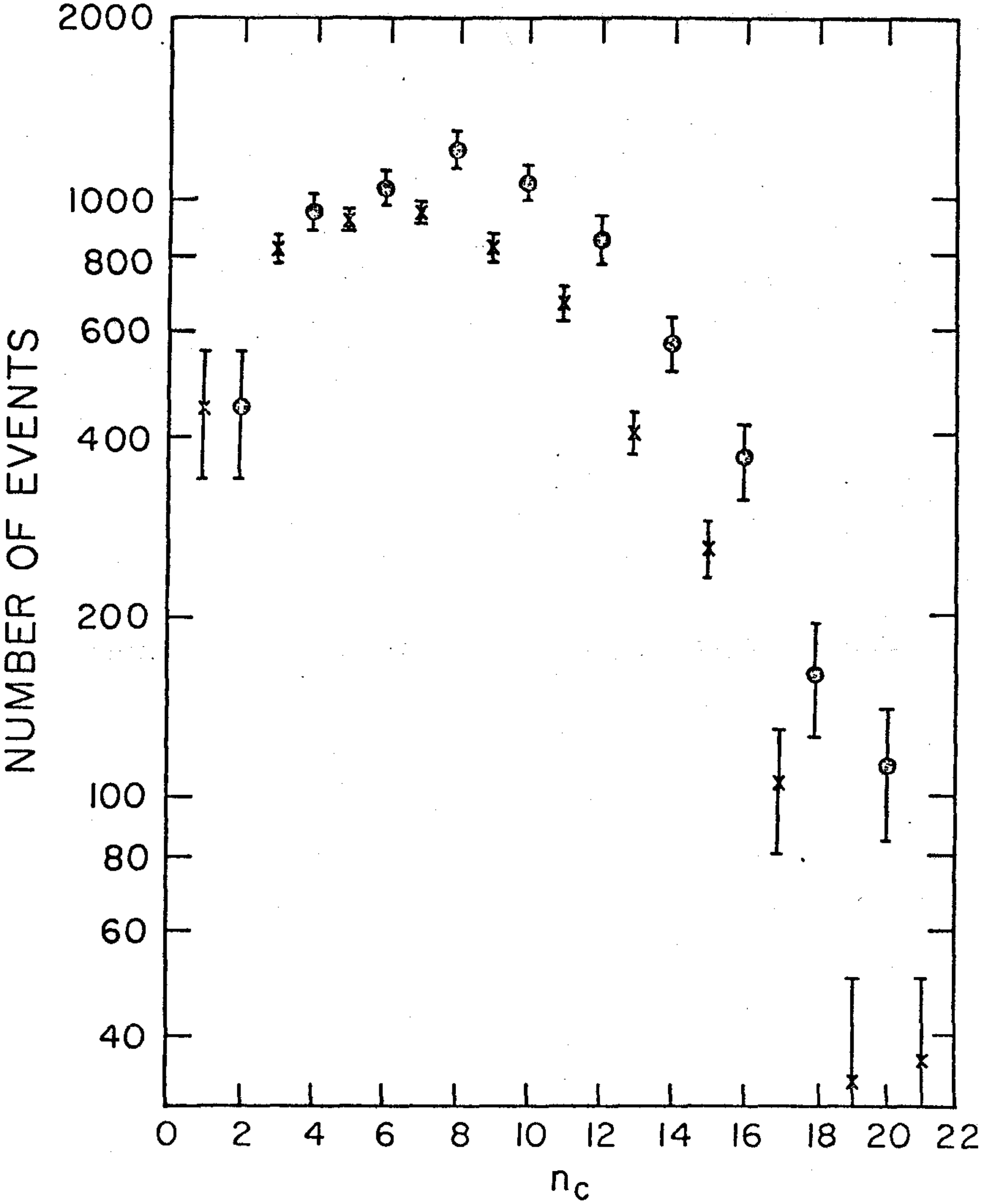

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Fig. 1

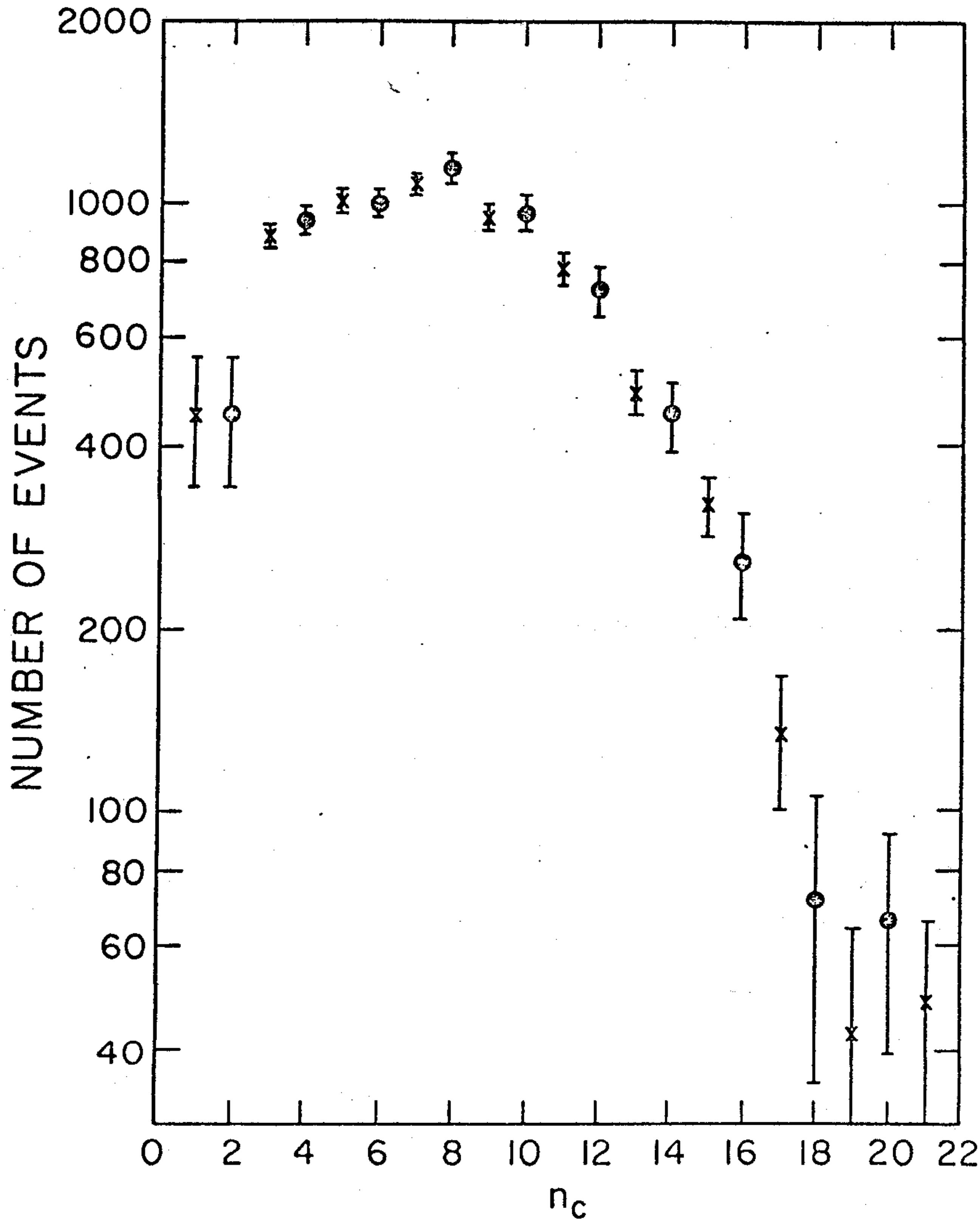
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Fig. 2