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CASCADES OF NUCLEAR INTERACTIONS IN LIQUID HYDROGEN

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1. Introduction

Getting detailed information on interaction of nuclei with protons, apart from shedding light on the interaction mechanism, is called for answering several astrophysical questions, in particular those on the origin of the nuclear component in cosmic radiation, its nature, distance of the source etc.

Difference between the composition of nuclei in cosmic radiation and those in celestial bodies of the solar system, especially for the lithium-beryllium group of nuclei, led to the conclusion that light nuclei of cosmic radiation originate from the fragmentation of heavier nuclei on interstellar matter consisting mainly of hydrogen [1, 2]. This experiment, performed in a 1 m hydrogen bubble chamber exposed to a 50 GeV/c oxygen beam, could be viewed as a model for testing the development of cascading interactions in the interstellar gas. Note, that one meter of liquid hydrogen with density 0.584 g/cm^3 is equivalent to the distance of 3.7 10^6 light-years in the interstellar space.

In this paper we are mainly concerned with topologies and charge distributions in chains of successive interactions of light nuclei with hydrogen. Another objective is to find explanation of already reported excessive emission of doubly charged fragments in interactions of the oxygen and carbon nuclei with protons. Both,oxygen and carbon nuclei are isotopic singlets with mass-number divisible by 4. To understand the mechanism of a copious emission of Z=2 fragments, it is intructive to compare the fragmentation of neighboring by charge and mass-number nuclei by studying the chains of successive interactions of fragments in the same experiment. The hydrogen bubble chamber, being a visual detector, offers unique opportunity for such a study.

2. The experiment

One meter hydrogen bubble chamber has been exposed to the low intensity oxygen beam with 3.1 A GeV/c momentum at the Dubna synchrofasotron [3]. The typical number of the beam nuclei per photograph was about four. The fiducial volume for primary interactions was 33 cm long. The tracks of all secondary fragments were followed in the scanning and all secondary, tertiary etc. interaction were recorded and the distances between them measured. The magnetic field of the bubble chamber allowed to determine a sign of the particle charge. A visual ionizations check provided the separation between Z=1 and multicharged fragments. A charge of the multicharged fragment was determined by analyzing a chain of successive interactions the fragment initiated. A sample collected consisted of 17448 events. 6855 of them exhibited one or more successive interactions. Their distribution and the distribution of interactions as a function of the fragment charge are listed in table 1 and 2, respectively. The maximum number of recorded successive interactions was five. Figure 1 shows one rare example of five-fold cascade. It is:

$O + p \rightarrow B + p + p + p + \pi$

$B + p \rightarrow Be + p + p$

$Be + p \rightarrow He + He + p + \pi + \pi$

$He + p \rightarrow He + p$

$He + p \rightarrow He + p$

Table 1

Number of interactions	2	3	4	5
Number of events	5648	1059	138	10

Table 2

Charge of the fragment	2	3	4	5	6	7	8
Number of interactions	2207	564	390	489	1200	1370	8851

3. The results

In table 3 we present yields of the observed charge configurations for interactions of fragments with charge from 2 to 8 with protons. The yields are listed in order of decreasing probability. The relative probability for each configuration normalized to unity for every Z is also presented. Table 4 is derived from table 3 and is organized as follows: the probabilities of charged configuration of fragments (Z equal 2 or more) are listed by analogy with smaller charge of projectile, and new topologies are added in order decreasing their probabilities; it was another words a natural joint of sequence.

To visualize the data presented in table 4, we show them in Fig.2 where the channel numbers of table 4 are plotted on horizontal axis. The lines are drown by hand guide the eye. Inspection of Fig.2 reveals a similarity of the probability distributions, especially those with one- two- and three Z=2 fragments (channels 2,4 and 10) in the final state. One also observers some suppression in the yield of the doubly charged fragments for Z=4 and Z=5 projectiles. The suppression of Z=4 events is less pronounced, if any, if one

Table 3. Charge distributions in collisions of the secondary fragments with protons.

number of channel	charge of secondary fragment	configuration of charges after interaction	number of events	normalized probability
1	2	111	1029	0.4662
2	2	12	729	0.3303
3	2	1111-1	285	0.1291
4	2	112-1	145	0.0657
5	2	1111-1-1	15	0.0068
6	2	1112-1-1	3	0.0014
7	2	111111-1-1-1	1	0.0004
1	3	112	182	0.3250
2	3	13	145	0.2589
3	3	1111	117	0.2089
4	3	1112-1	51	0.0911
5	3	11111-1	38	0.0679
6	3	113-1	17	0.0304
7	3	111111-1-1	5	0.0089
8	3	11112-1-1	3	0.0054
9	3	1122-1-1	2	0.0036
1	4	1112	107	0.2709
2	4	14	64	0.1620
3	4	113	54	0.1367
4	4	122	46	0.1165
5	4	11111	37	0.0937
6	4	11112-1	25	0.0633
7	4	111111-1	14	0.0354
8	4	1122-1	13	0.0329
9	4	1113-1	12	0.0304
10	4	111112-1-1	6	0.0152
11	4	114-1	6	0.0152
12	4	11122-1-1	3	0.0008
13	4	1111111-1-1	1	0.0002
14	4	23	1	0.0002
1	5	15	105	0.2160
2	5	11112	71	0.1461
3	5	114	60	0.1227

Table 3. Charge distributions in collisions of the secondary fragments with protons. (Continue.)

number of channel	charge of secondary fragment	configuration of charges after interaction	number of events	normalized probability
4	5	1122	58	0.1193
5	5	1113	46	0.9441
6	5	111111	26	0.0535
7	5	1111111-1	25	0.0511
8	5	111112-1	24	0.0494
9	5	11113-1	17	0.0350
10	5	11122-1	14	0.0288
11	5	1114-1	10	0.0206
12	5	123	10	0.0206
13	5	115-1	7	0.0144
14	5	1111112-1-1	4	0.0082
15	5	1123-1	3	0.0062
16	5	11111111-1-1	1	0.0021
17	5	16-1	1	0.0021
18	5	111123-1-1-1	1	0.0021
19	5	111113-1-1	1	0.0021
20	5	133-1	1	0.0021
21	5	111122-1-1	1	0.0021
1	6	16	293	0.2462
2	6	115	142	0.1193
3	6	11122	116	0.0975
4	6	111112	97	0.0815
5	6	1114	79	0.0664
6	6	11113	58	0.0487
7	6	111122-1	53	0.0445
8	6	1111111	47	0.0395
9	6	1111112-1	46	0.0386
10	6	1123	35	0.0294
11	6	1222	35	0.0294
12	6	116-1	28	0.0235
13	6	1115-1	26	0.0218
14	6	11111111-1	23	0.0193
15	6	111113-1	22	0.0185
16	6	11114-1	19	0.0160
17	6	11222-1	12	0.0101
18	6	133	9	0.0076

Table 3. Charge distributions in collisions of the secondary fragments with protons. (Continue.)

number of channel	charge of secondary fragment	configuration of charges after interaction	number of events	normalized probability
19	6	124	9	0.0076
20	6	11123-1	8	0.0067
21	6	11111112-1-1	7	0.0059
22	6	1133-1	4	0.0034
23	6	1124-1	3	0.0025
24	6	1111122-1-1	3	0.0025
25	6	111111111-1-1	3	0.0025
26	6	1111113-1-1	2	0.0017
27	6	11115-1-1	2	0.0017
28	6	17-1	2	0.0017
29	6	26-1	1	0.0008
30	6	111114-1-1	1	0.0008
31	6	1116-1-1	1	0.0008
32	6	125-1	1	0.0008
33	6	1111111111-1-1-1	1	0.0008
34	6	25	1	0.0008
1	7	17	299	0.2192
2	7	116	214	0.1569
3	7	111122	104	0.0762
4	7	1115	83	0.0609
5	7	1111112	69	0.0506
6	7	11114	59	0.0432
7	7	11222	57	0.0418
8	7	11123	45	0.0330
9	7	111113	40	0.0293
10	7	1116-1	39	0.0286
11	7	1111122-1	36	0.0264
12	7	11111111	30	0.0220
13	7	11111112-1	29	0.0213
14	7	1124	22	0.0161
15	7	117-1	22	0.0161
16	7	11115-1	21	0.0154
17	7	1111113-1	21	0.0154
18	7	111123-1	20	0.0147
19	7	111222-1	19	0.0139
20	7	1223	19	0.0139

Table 3. Charge distributions in collisions of the secondary fragments with protons. (Continue.)

number of channel	charge of secondary fragment	configuration of charges after interaction	number of events	normalized probability
21	7	1133	17	0.0125
22	7	111114-1	14	0.0103
23	7	125	12	0.0088
24	7	111111111-1	10	0.0073
25	7	11111122-1-1	9	0.0066
26	7	1125-1	8	0.0059
27	7	111111112-1-1	6	0.0044
28	7	11133-1	6	0.0044
29	7	134	5	0.0037
30	7	1111222-1-1	4	0.0029
31	7	11111113-1-1	3	0.0022
32	7	11124-1	3	0.0022
33	7	111115-1-1	3	0.0022
34	7	1111114-1-1	3	0.0022
35	7	1111123-1-1	2	0.0015
36	7	1134-1	2	0.0015
37	7	1111111111-1-1	1	0.0007
38	7	18-1	1	0.0007
39	7	11116-1-1	1	0.0007
40	7	26	1	0.0007
41	7	12222-1	1	0.0007
42	7	111133-1-1	1	0.0007
43	7	144-1	1	0.0007
44	7	1224-1	1	0.0007
45	7	1111111112-1-1-1	1	0.0007
1	8	18	2033	0.2284
2	8	117	1249	0.1410
3	8	1116	786	0.0883
4	8	111222	495	0.0556
5	8	1111122	392	0.0440
6	8	11116-1	276	0.0310
7	8	11115	272	0.0306
8	8	1117-1	253	0.0284
9	8	111123	250	0.0281
10	8	118-1	239	0.0269
11	8	1111222-1	230	0.0258

Table 3. Charge distributions in collisions of the secondary fragments with protons. (Continue.)

number of channel	charge of secondary fragment	configuration of charges after interaction	number of events	normalized probability
12	8	11111122-1	226	0.0254
13	8	126	200	0.0225
14	8	11111112	180	0.0202
15	8	11124	144	0.0162
16	8	1125	131	0.0147
17	8	1111123-1	111	0.0125
18	8	111114	109	0.0122
19	8	11223	101	0.0113
20	8	12222	96	0.0108
21	8	1111113	95	0.0107
22	8	111111112-1	91	0.0102
23	8	111115-1	79	0.0089
24	8	111124-1	70	0.0079
25	8	11133	68	0.0076
26	8	1134	59	0.0066
27	8	1111114-1	58	0.0065
28	8	11125-1	41	0.0046
29	8	11111113-1	39	0.0044
30	8	111223-1	36	0.0040
31	8	135	35	0.0039
32	8	111133-1	33	0.0037
33	8	1126-1	31	0.0035
34	8	1224	27	0.0030
35	8	11134-1	26	0.0029
36	8	111111122-1-1	26	0.0029
37	8	111116-1-1	22	0.0025
38	8	111111111	21	0.0024
39	8	11111123-1-1	19	0.0021
40	8	112222-1	17	0.0019
41	8	1111111112-1-1	15	0.0017
42	8	11111111111-1	14	0.0016
43	8	1233	14	0.0016
44	8	144	13	0.0015
45	8	11111222-1-1	12	0.0013
46	8	1111133-1-1	9	0.0010
47	8	111111113-1-1	7	0.0008
48	8	11117-1-1	7	0.0008

Table 3. Charge distributions in collisions of the secondary fragments with protons. (Continue.)

number of channel	charge of secondary fragment	configuration of charges after interaction	number of events	normalized probability
49	8	1118-1-1	7	0.0008
50	8	111125-1-1	7	0.0008
51	8	11233-1	7	0.0008
52	8	1111124-1-1	6	0.0006
53	8	11111114-1-1	5	0.0006
54	8	1111223-1-1	5	0.0006
55	8	1111115-1-1	5	0.0006
56	8	11126-1-1	4	0.0004
57	8	19-1	4	0.0004
58	8	11224-1	3	0.0003
59	8	127-1	3	0.0003
60	8	1144-1	3	0.0003
61	8	1135-1	2	0.0002
62	8	11111111111-1-1	2	0.0002
63	8	11111111112-1-1-1	2	0.0002
64	8	111111123-1-1-1	2	0.0002
65	8	1111233-1-1-1	2	0.0002
66	8	11144-1-1	2	0.0002
67	8	1136-1-1	2	0.0002
68	8	27	2	0.0002
69	8	136-1	1	0.0001
70	8	28-1	1	0.0001
71	8	1225-1	1	0.0001
72	8	45	1	0.0001
73	8	111233-1-1	1	0.0001
74	8	111134-1-1	1	0.0001
75	8	11111111122-1-1-1	1	0.0001

Table 4. Charge distributions in collisions of the secondary fragments with proton.

number of channel	charge of secondary fragment	configuration of charges with $Z \geq 2$	number of events	normalized probability
1	2	11	1330	0.6026
2	2	2	877	0.3974
1	3	111	160	0.2857
2	3	2	236	0.4214
3	3	3	162	0.2893
4	3	22	2	0.0036
1	4	1111	52	0.1337
2	4	2	138	0.3548
3	4	3	66	0.1697
4	4	22	62	0.1594
5	4	4	70	0.1799
6	4	23	1	0.0026
1	5	11111	52	0.1092
2	5	2	99	0.2080
3	5	3	64	0.1344
4	5	22	73	0.1534
5	5	4	70	0.1471
6	5	23	14	0.0295
7	5	5	112	0.2353
8	5	6	1	0.0021
9	5	33	1	0.0021
1	6	111111	74	0.0622
2	6	2	150	0.1262
3	6	3	82	0.0690
4	6	22	172	0.1447
5	6	4	99	0.0833
6	6	23	43	0.0362
7	6	5	170	0.1430
8	6	6	322	0.2708

Table 4. Charge distributions in collisions of the secondary fragments with proton.(Continue.)

number of channel	charge of secondary fragment	configuration of charges with $Z \geq 2$	number of events	normalized probability
9	6	33	13	0.0109
10	6	222	47	0.0395
11	6	24	12	0.0101
12	6	7	2	0.0017
13	6	25	2	0.0017
14	6	26	1	0.0008
1	7	1111111	41	0.0301
2	7	2	105	0.0770
3	7	3	64	0.0469
4	7	22	149	0.1092
5	7	4	76	0.0056
6	7	23	67	0.0491
7	7	5	107	0.0784
8	7	6	254	0.1862
9	7	33	24	0.0178
10	7	222	80	0.0586
11	7	24	25	0.0183
12	7	7	321	0.2353
13	7	25	20	0.0147
14	7	26	1	0.0007
15	7	223	19	0.0139
16	7	34	7	0.0051
17	7	8	1	0.0007
18	7	44	1	0.0007
19	7	224	1	0.0007
20	7	2222	1	0.0007
1	8	11111111	37	0.0042
2	8	2	288	0.0327
3	8	3	102	0.0116
4	8	22	645	0.0733
5	8	4	172	0.0195
6	8	23	383	0.0435

Table 4. Charge distributions in collisions of the secondary fragments with proton.(Continue.)

number of channel	charge of secondary fragment	configuration of charges with $Z \geq 2$	number of events	normalized probability
7	8	5	356	0.0405
8	8	6	1084	0.1232
9	8	33	110	0.0125
10	8	222	737	0.0838
11	8	24	220	0.0250
12	8	7	1509	0.1715
13	8	25	179	0.0203
14	8	26	235	0.0267
15	8	223	143	0.0162
16	8	34	85	0.0097
17	8	8	2279	0.2590
18	8	44	18	0.0020
19	8	224	30	0.0035
20	8	2222	113	0.0013
21	8	35	37	0.0042
22	8	233	24	0.0027
23	8	27	5	0.0006
24	8	9	4	0.0004
25	8	36	3	0.0003
26	8	28	1	0.0001
27	8	225	1	0.0001
28	8	45	1	0.0001

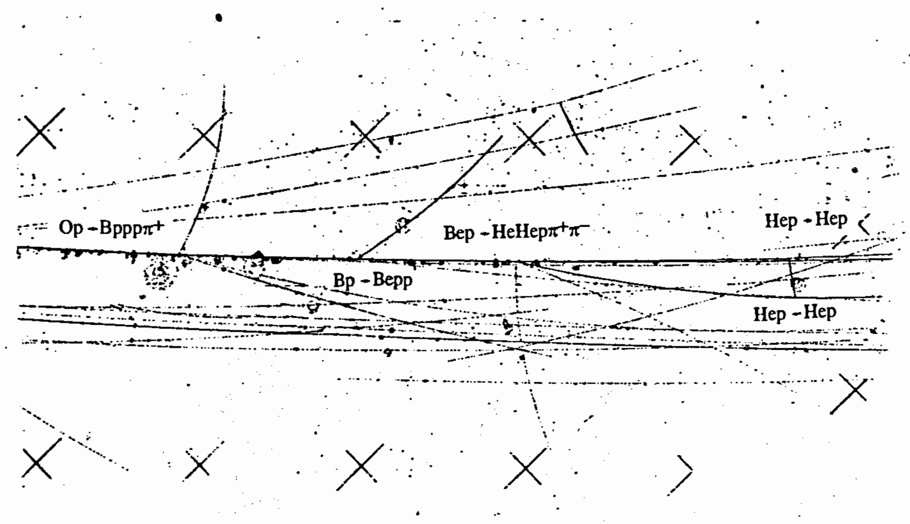

Fig. 1. Example of O+p→B+...→Be+...→He+...→He+...→He+...
five-fold secondary cascade interaction.

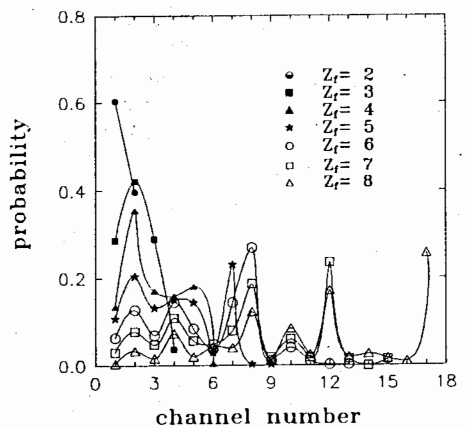

Fig. 2. Probability distribution of various charge configurations
presented as function of the channel number defined in table 4.

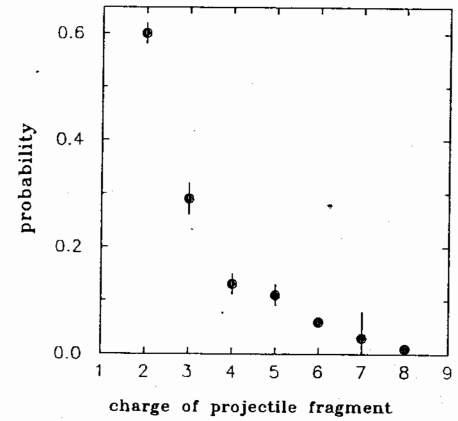

Fig. 3. Probability distribution of the total destruction of the
projectile as a function of its charge.

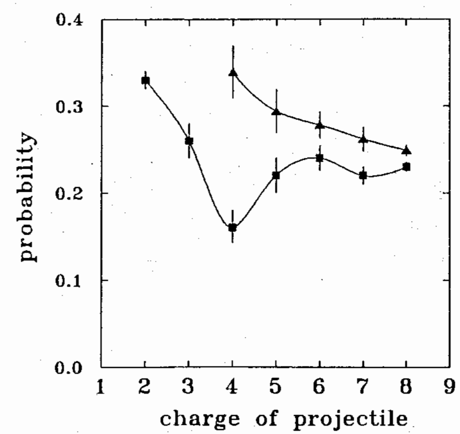

Fig. 4. Probability distribution of secondary fragment interaction:
lower curve - Z+1 - Z+1 events; upper one - a sum of the relative probabilities of yields for the fragments with Z=4 and events with two or more doubly charged fragments.

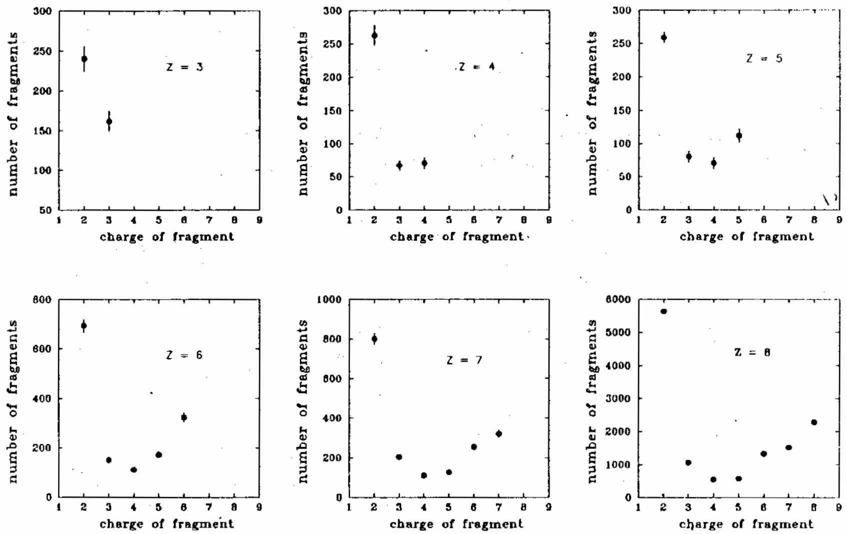

Fig. 5. Charge distributions of secondary fragments produced by the projectile with Z from 3 up to 8.

selects events with total destruction of the projectile (Fig.3), whereas it is fairly strong (Fig.4, lower curve) if the events of $Z+1 \rightarrow Z+1$ (the charges of the fragments in initial and final state are the same) are listed. There are two possible reactions:

$$^9Be + p \rightarrow ^9 Be + p \quad (1)$$

and

$$^9Be + p \rightarrow ^8 Be + p + n \rightarrow ^4 He + ^4 He + p + n \quad (2)$$

Obviously, while reaction (1) contributes to topology 41, reaction (2) enriches topology 221. Assuming that all events with two or more Z=2 fragments in the final state originate from the decay of ^{8}Be and summing up the corresponding probabilities with those for the events with Z=4 fragments, one gets a smooth upper curve shown in Fig.4. The plausible explanation of the dip at Z=4 can be therefore a substantial yield of ^{8}Be isotope with a life time of 10^{-16} sec. and its subsequent decay into two α -particles. The ^{8}Be is the only so short-lived isotope among nuclei from helium to oxygen. All other with overwhelming probability decay outside the bubble chamber. Fig.5 displays the fragment charge distributions for $2 < Z < 8$ projectiles. They exhibit quite similar qualitative behavior for Z from 4 to 8.

To conclude, we presented detailed yields of various charge configurations produced in chains of cascading interactions of light nuclei with protons.

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