Light nucleus clustering in fragmentation above 1 A GeV

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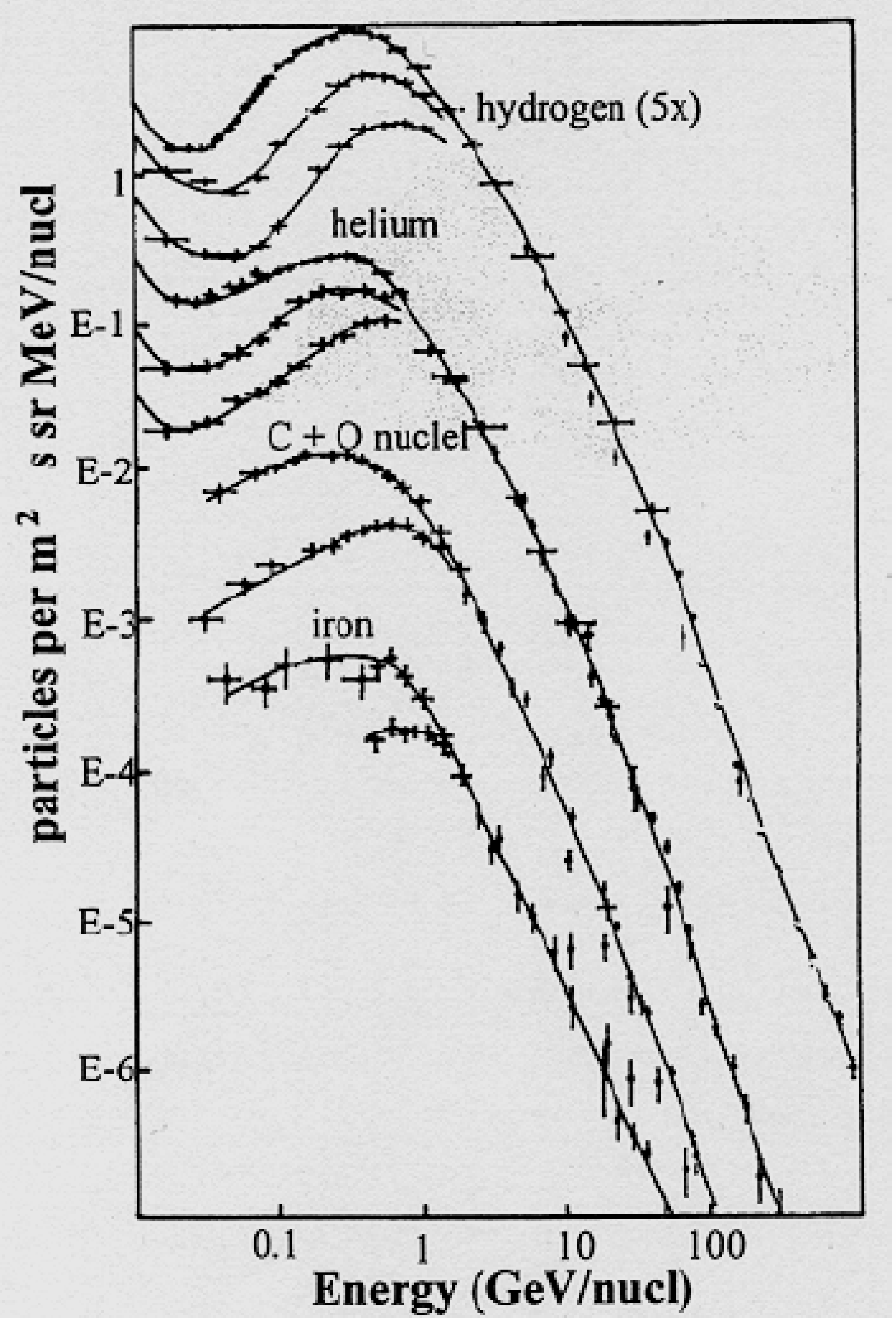
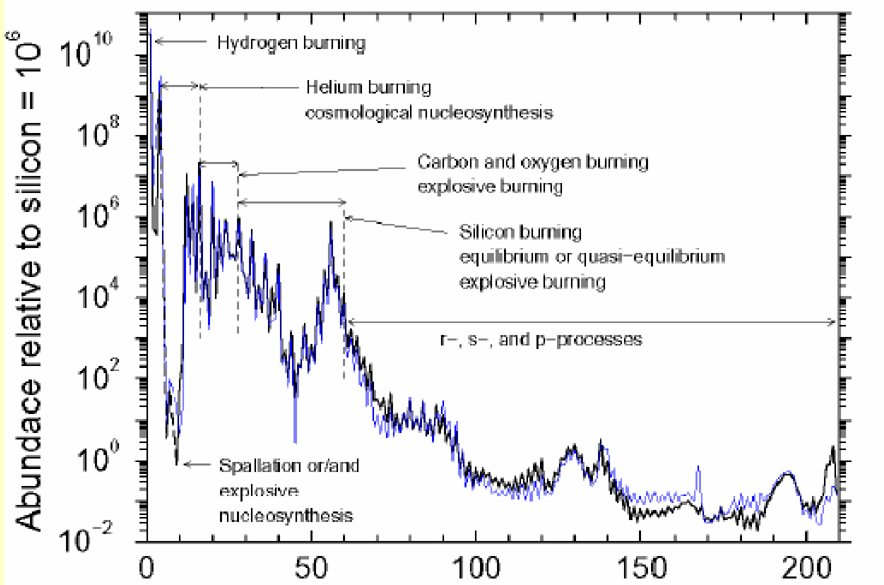
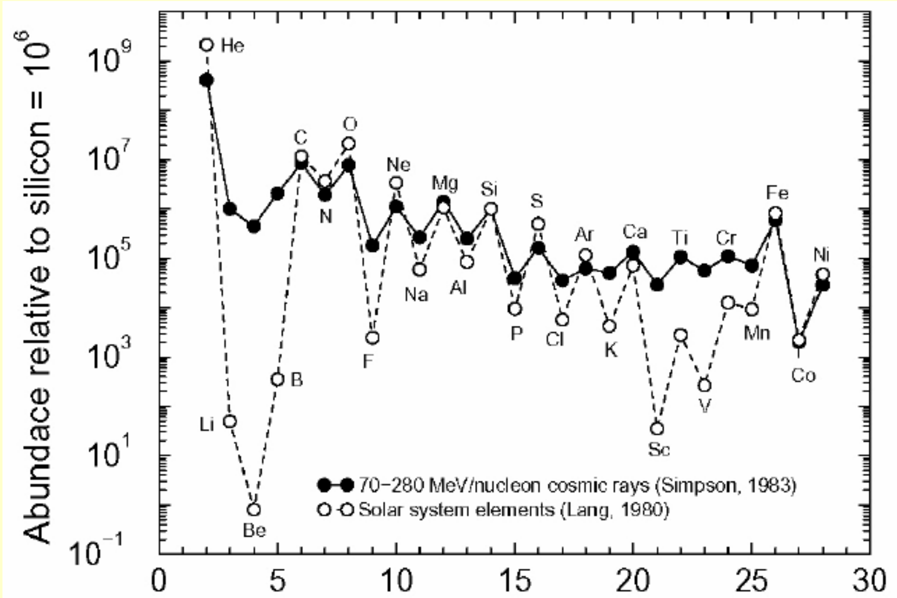


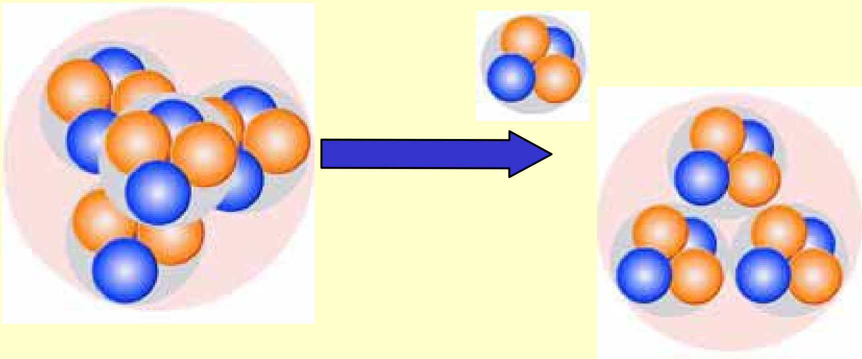
hydrogen (5x)
helium
C + O nuclei
iron
1
E-1
E-2
E-3
E-4
E-5
E-6
particles per m 2 s sr MeV/nucl
0.1
1
10
100
Energy (GeV/nucl)



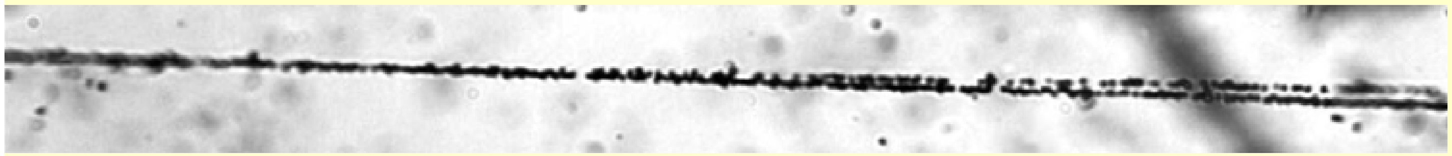
Hydrogen burning
Helium burning
cosmological nucleosynthesis
Carbon and oxygen burning
explosive burning
Silicon burning
equilibrium or quasi-equilibrium
explosive burning
r–, s–, and p–processes
Spallation or/and
explosive
nucleosynthesis
Abundace relative to silicon = 10^6
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
0
50
100
150
200

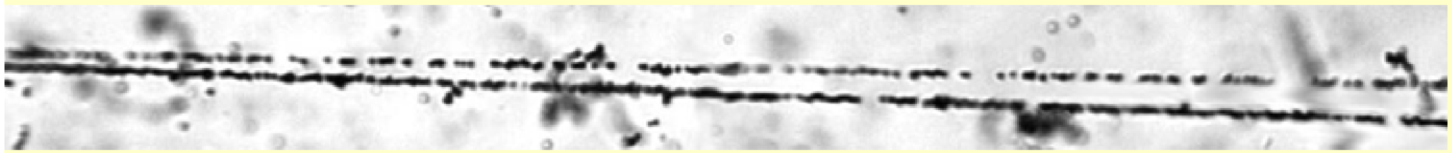


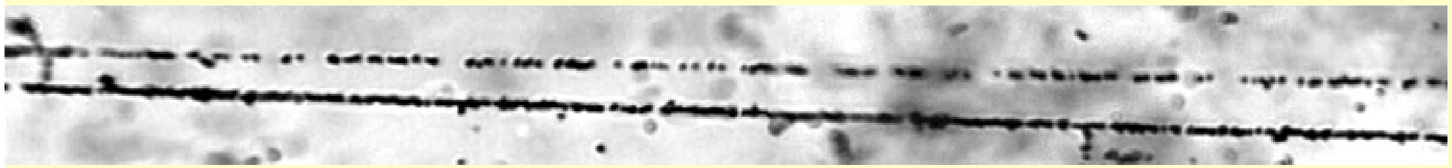
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
70–280 MeV/nucleon cosmic rays (Simpson, 1983)
Solar system elements (Lang, 1980)
Abundace relative to silicon = 10^6
10^9
10^7
10^5
10^3
10^1
10^-1
0
5
10
15
20
25
30

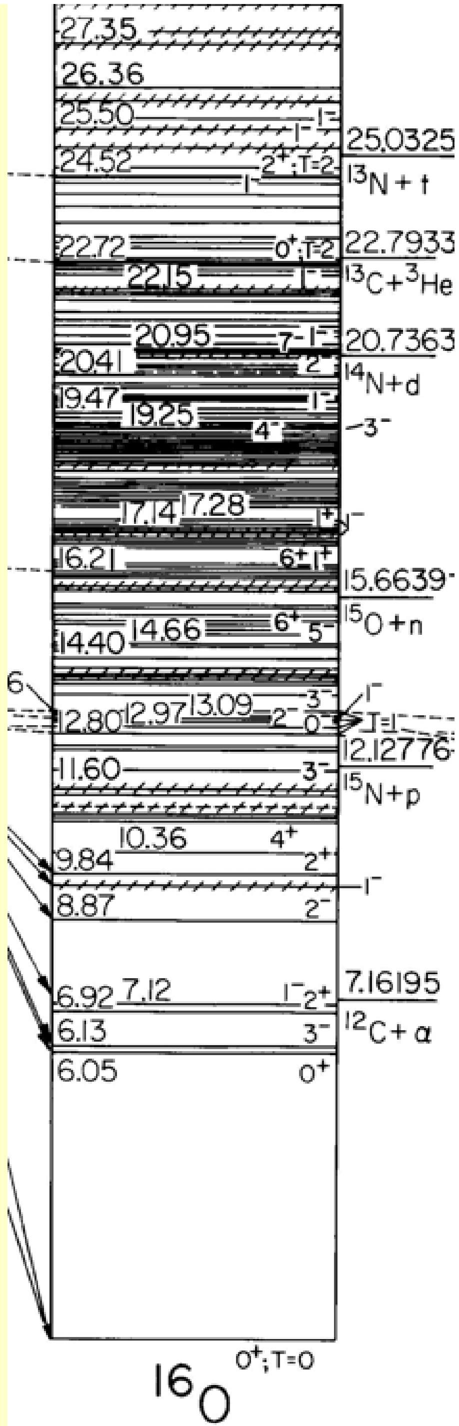


4.5 A GeV/c ^{16}O

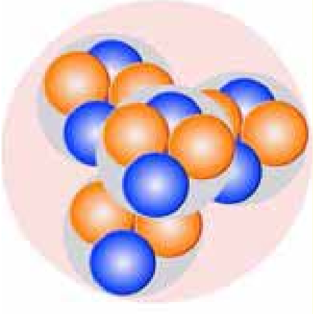


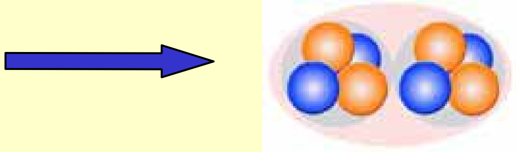




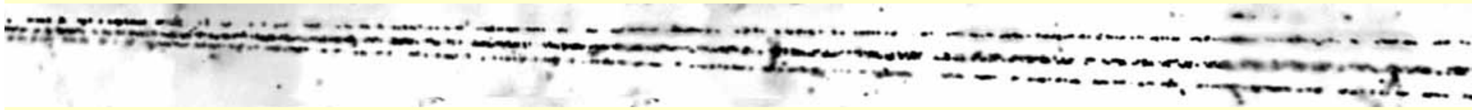


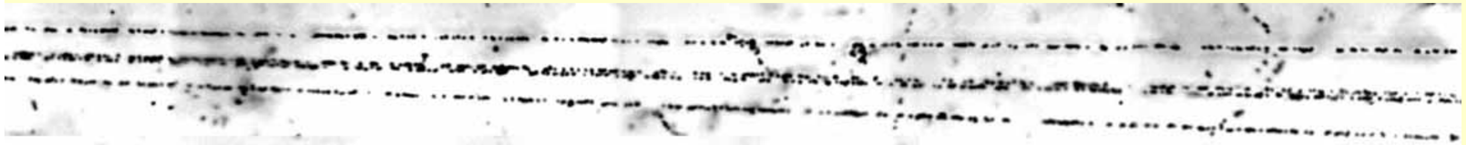
27.35
26.36
25.50
24.52
25.0325
$^{13}N + t$
22.72
22.15
22.7933
$^{13}C + ^3He$
20.95
20.41
20.7363
$^{14}N + d$
19.47
19.25
17.14
17.28
16.21
15.6639
$^{15}O + n$
14.40
14.66
12.80
12.97
13.09
12.12776
11.60
$^{15}N + p$
9.84
10.36
8.87
6.92
7.12
7.16195
6.13
$^{12}C + \alpha$
6.05
^{16}O
$0^+; T=0$

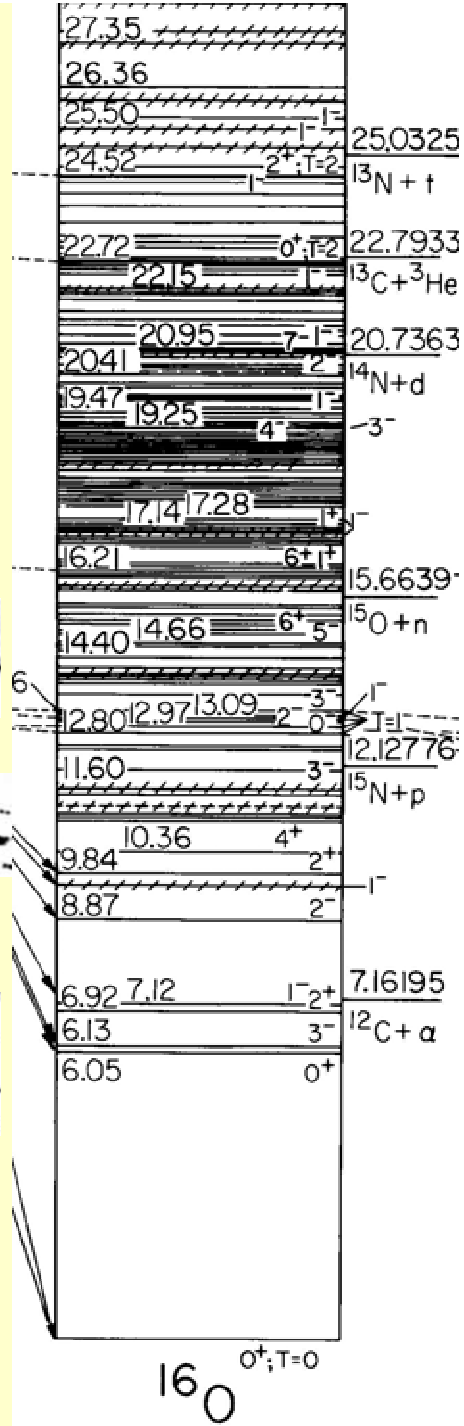


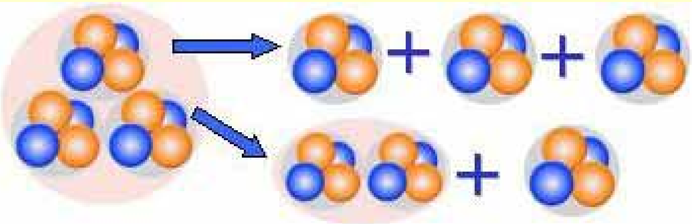


4.5A GeV/c ^{16}O

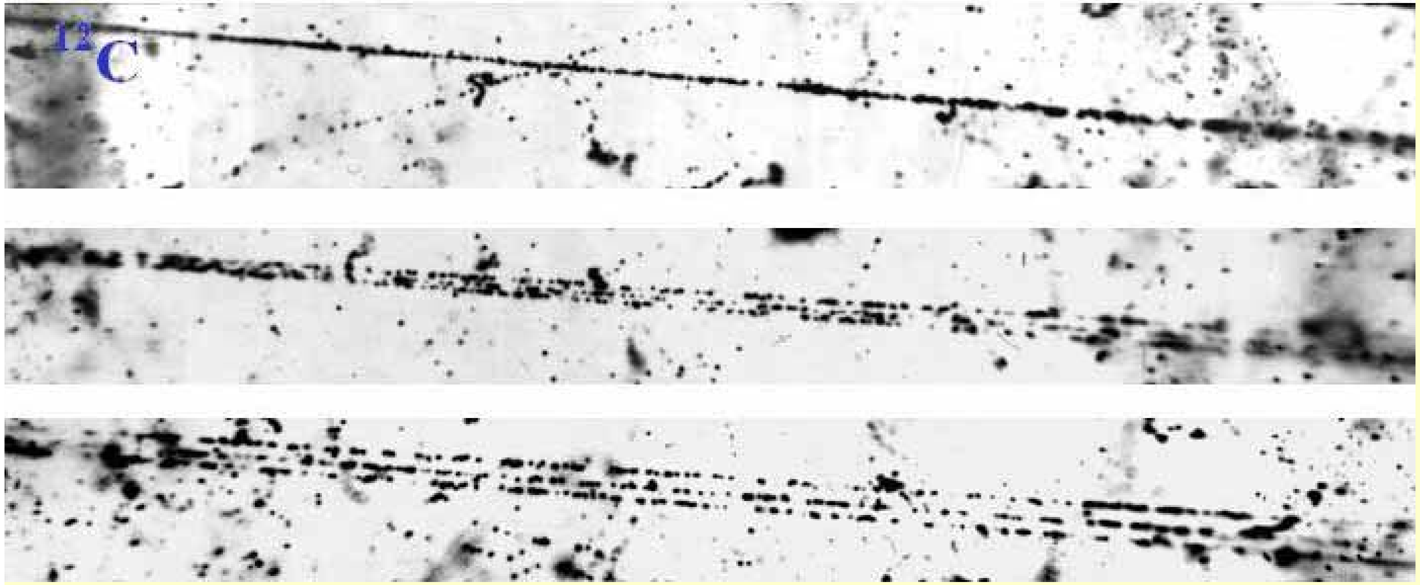


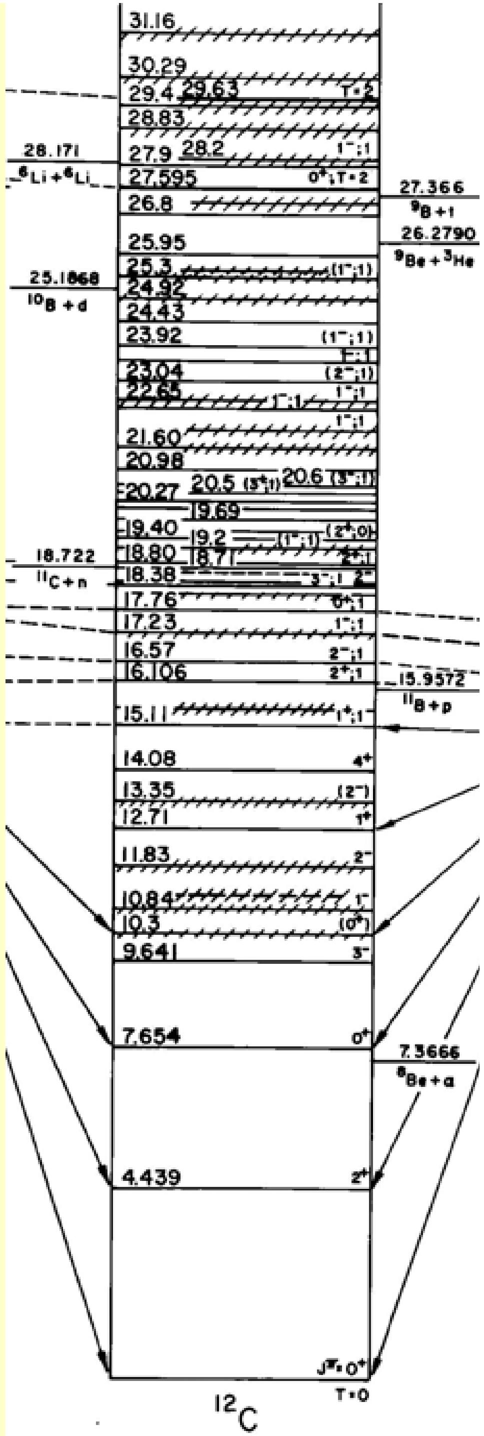


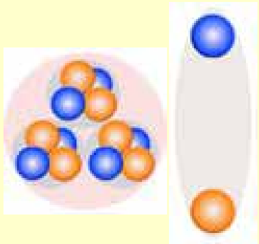

27.35
26.36
25.50
24.52
2+; T=2
25.0325
13N + t
22.72
0+; T=2
22.15
22.7933
13C+3He
20.95
20.41
20.7363
14N+d
19.47
19.25
4-
-3-
17.14
17.28
16.21
6+
15.6639
15O +n
14.40
14.66
6+
5-
12.80
12.97
13.09
T=1
12.12776
11.60
3-
15N+p
10.36
4+
9.84
2+
1-
8.87
2-
6.92
7.12
2+
7.16195
12C+ α
6.13
3-
6.05
0+
16O
0+; T=0



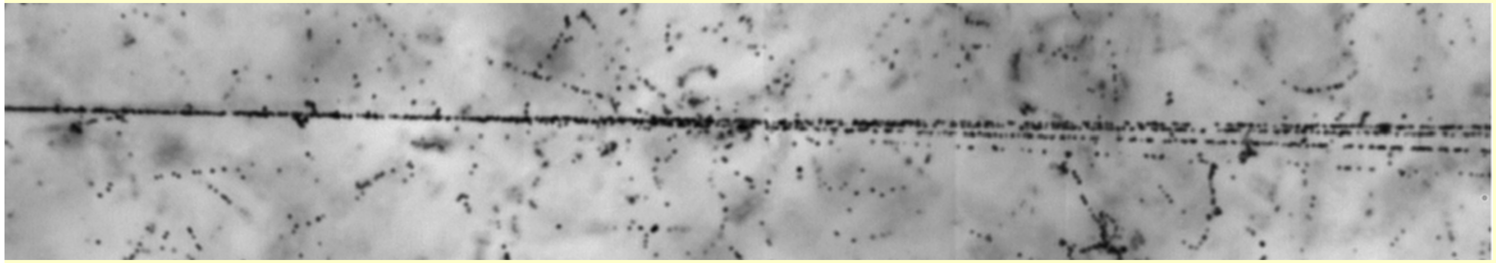
4.5A GeV/c ^{12}C Coherent Dissociation

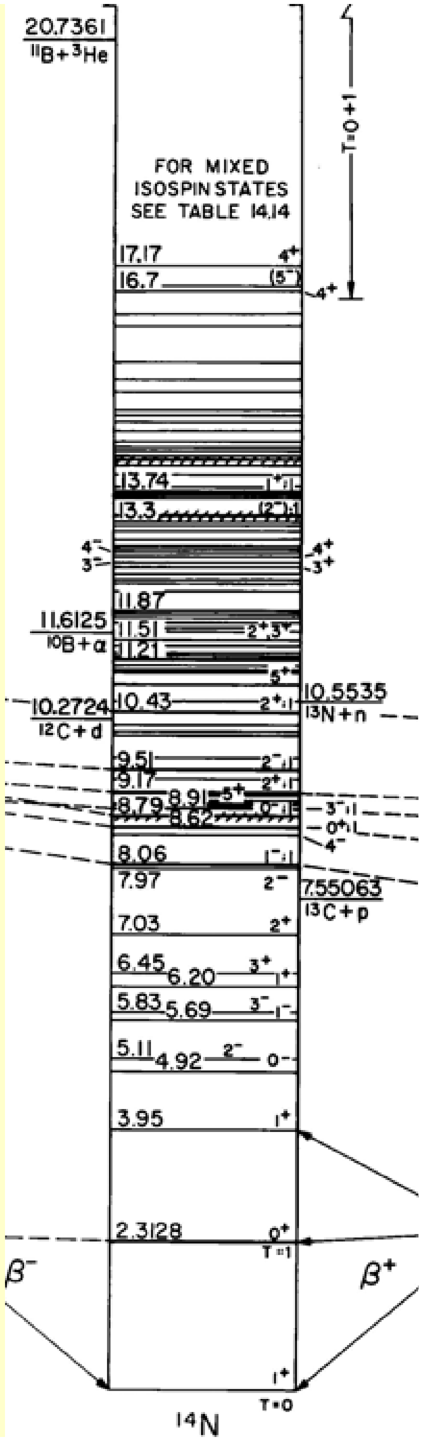






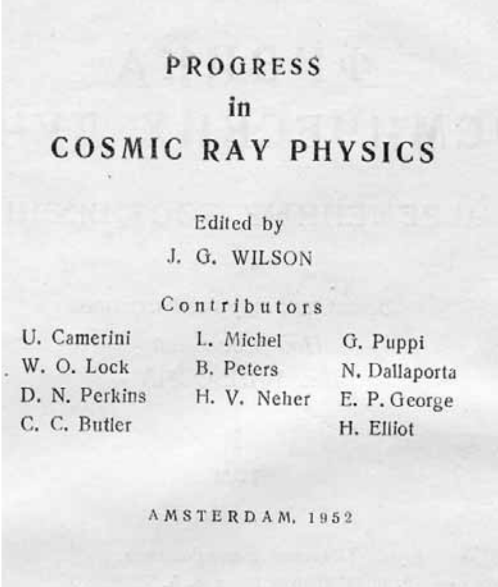
2.9A GeV/c ^{14}N





20.7361
11B+3He
FOR MIXED ISOSPIN STATES SEE TABLE 14.14
T=0+1
17.17
16.7
13.74
13.3
11.87
11.6125
10B+α
11.51
11.21
10.43
10.2724
12C+d
10.5535
13N+n
9.51
9.17
8.79
8.91
8.62
8.06
7.97
7.55063
13C+p
7.03
6.45
6.20
5.83
5.69
5.11
4.92
3.95
2.3128
T=1
β−
β+
T=0
14N

^{14}N Dissociation with ^{8}Be like fragmentation


PROGRESS
in
COSMIC RAY PHYSICS

Edited by
J. G. WILSON

Contributors

U. Camerini — L. Michel — G. Puppi
W. O. Lock — B. Peters — N. Dallaporta
D. N. Perkins — H. V. Neher — E. P. George
C. C. Butler — H. Elliot

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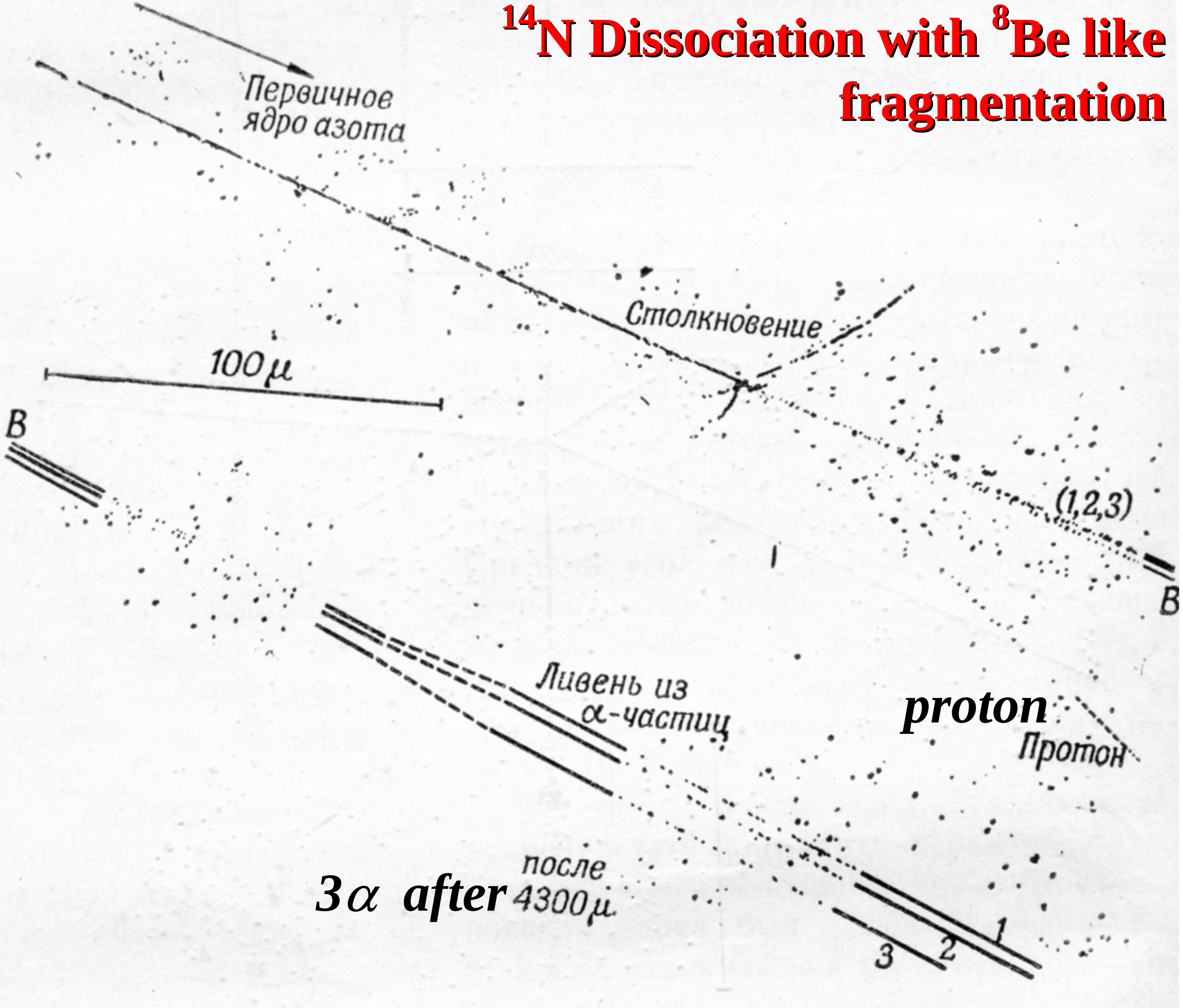
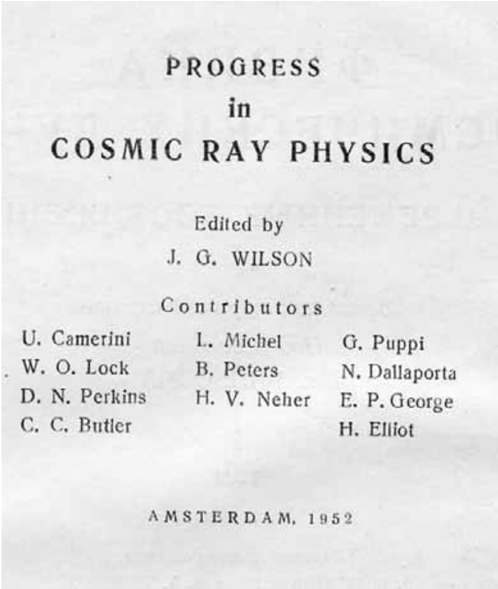


Фиг. 7. Ядро азота столкнулось с ядром эмульсии. Повидимому, произошло скользящее столкновение, при котором заряд первичного ядра уменьшается на единицу. Остаток, представляющий собой возбужденное ядро углерода, распадается затем на 3 α-частицы, которые в лабораторной системе испускаются в узком конусе в направлении движения первичной частицы

Mg-Si Dissociation into charge state 2+2+2+2+2+1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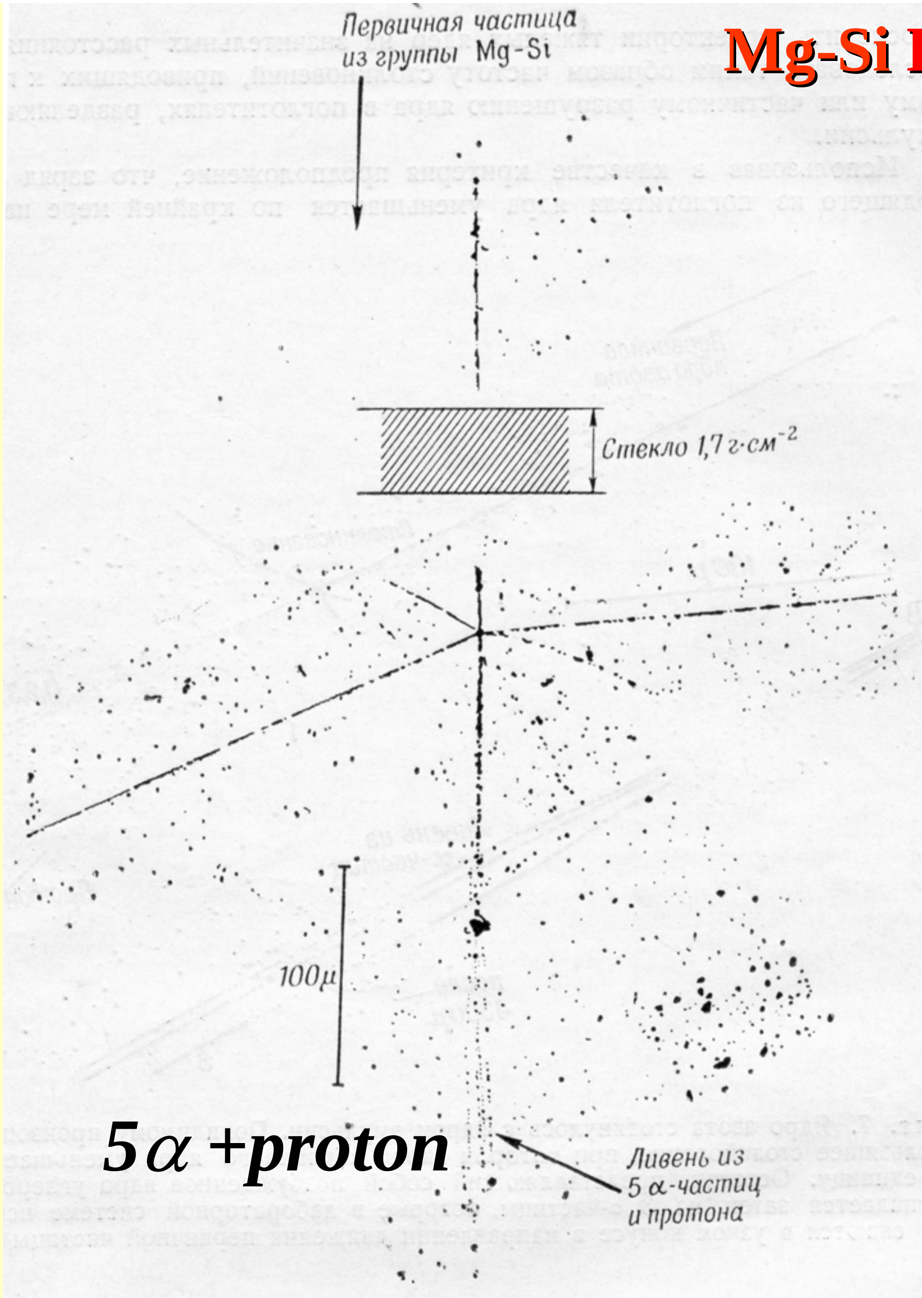
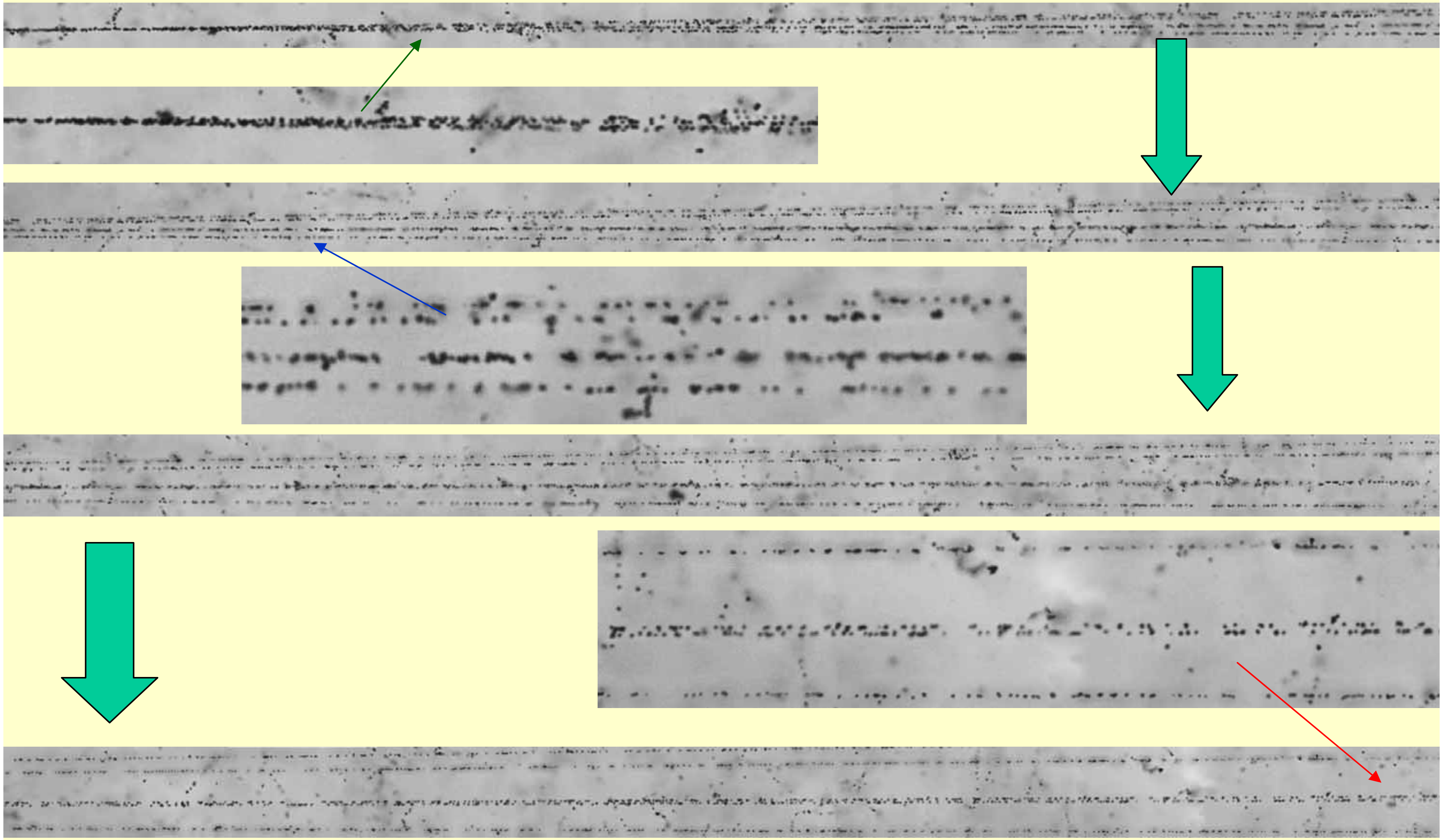
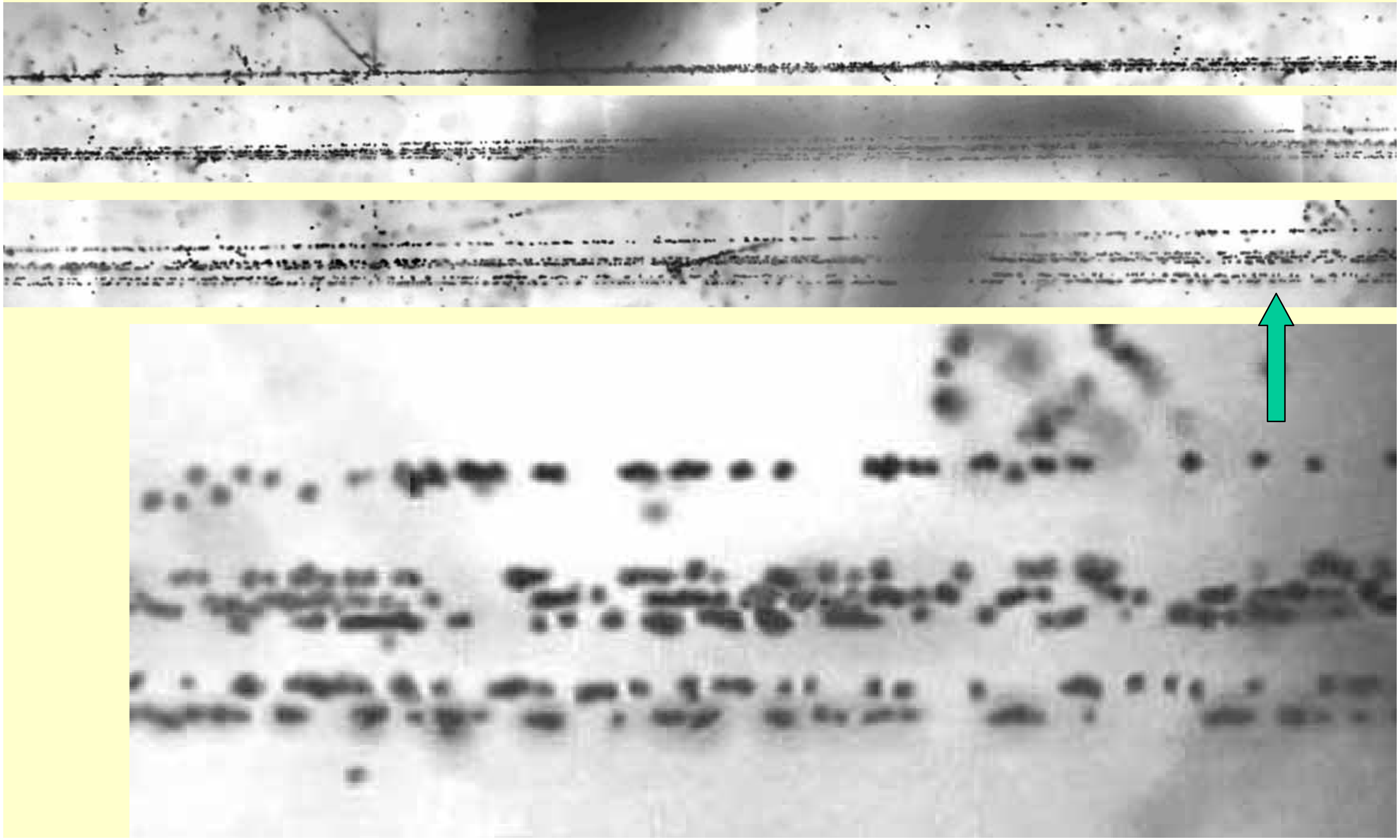


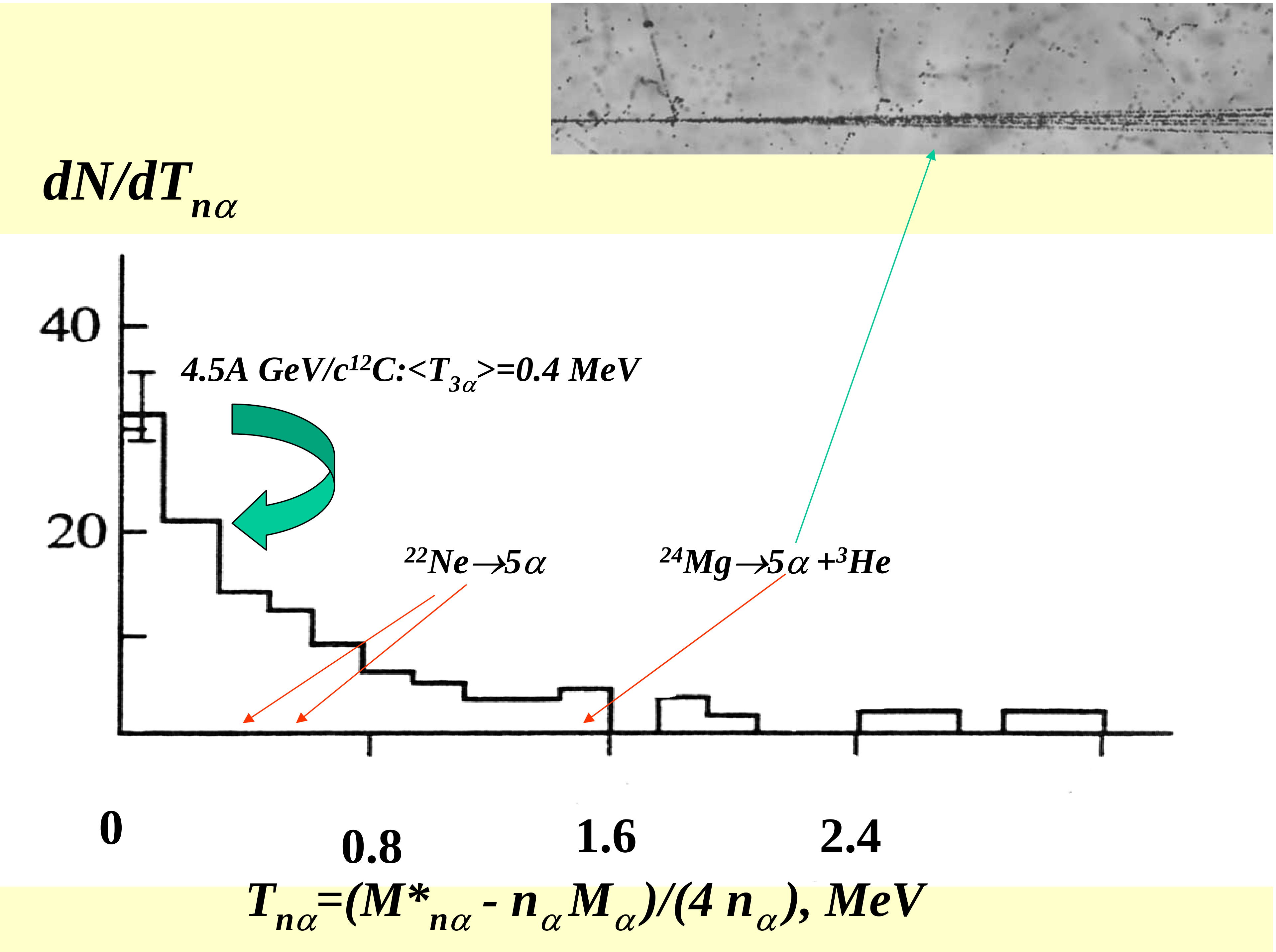
Фиг. 6. Ядро из группы Mg — Si столкнулось с ядром эмульсии. Предполагают, что узкий ливень, состоящий из протона и 5 α-частиц, возник в результате испарения первичного ядра, возбужденного столкновением. Остальные частицы, испущенные в звезде, являются, по-видимому, осколками ядра мишени.

4.5A GeV/c ^{20}Ne Peripheral Dissociation into charge state 2+2+2+2+2 with ^{8}Be like fragments



4.5A GeV/c ^{24}Mg Peripheral Dissociation into charge state 2+2+2+2+2+2 with ^{8}Be and ^{12}C* like fragments





dN/dT nα
40
20
4.5A GeV/c 12C:<T 3α>=0.4 MeV
22Ne→5α
24Mg→5α +3He
0
0.8
1.6
2.4
T nα=(M* nα - n α M α)/(4 n α), MeV

Boltzmann constant, k /approx 10^{-4} eV K^{-1}
Typical Temperature Range, Ŧ /approx $5 \cdot 10^{8-9}$ K per α

$p_\alpha = \sqrt{(2m_\alpha \cdot T_\alpha)}$ p_α /approx 20-120 MeV

Planck constant, ħ /approx 200 MeV fm

λ=ħ/p de Broglie wave lengths /approx 1-10 fm

$\lambda^{coh}{}_\alpha$ /approx R_α $\lambda^{coh}{}_{He}$ /approx R_{He}

$T_\alpha / T_{He} = Ŧ_\alpha / Ŧ_{He} = (R_{He}/R_\alpha)^2$ /approx 10^{10}

Macroscopic quantum coherence phenomena in atomic physics /approx 1 K

Macroscopic quantum coherence phenomena in atomic physics /approx 10^{10} K

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Topology of "White Stars" in the Relativistic Fragmentation of Light Nuclei

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The BECQUEREL Collaboration

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Abstract—Experimental observations of the multifragmentation of relativistic light nuclei by means of emulsions are surveyed. Events that belong to the type of "white stars" and in which the dissociation of relativistic nuclei is not accompanied by the production of mesons and target-nucleus fragments are considered. An almost complete suppression of the binary splitting of nuclei to fragments of charge in excess of two, $Z > 2$, is a feature peculiar to charge topology in the dissociation of Ne, Mg, Si, and S nuclei. An increase in the degree of nuclear fragmentation manifests itself in the growth of the multiplicity of singly and doubly charged fragments ($Z = 1, 2$) as the charge of the unexcited fragmenting-nucleus part (which is the main part) decreases. Features of the production of systems formed by extremely light nuclei α, d, and t are studied in the dissociation of the stable isotopes of Li, Be, B, C, N, and O to charged fragments. Manifestations of ^{3}He clustering can be observed in "white stars" in the dissociation of neutron-deficient isotopes of Be, B, C, and N. © *2005 Pleiades Publishing, Inc.*

Table 1. Charge-topology distribution of white stars in the dissociation of ^{24}Mg nuclei with an energy of 3.65 GeV per nucleon

Z_f	11	10	10	9	9	8	8	8	7	7	6	5	5	5	4	4	3	–	–	–
$N_{Z=1}$	1	2	–	3	1	4	2	–	3	1	2	5	3	1	6	4	5	6	4	2
$N_{Z=2}$	–	–	1	–	1	–	1	2	1	2	2	1	2	3	1	2	2	3	4	5
N_{ev}	10	14	8	5	9	1	7	4	4	2	4	2	1	1	2	1	3	1	2	2

Table 2. Charge-topology distribution of white stars in the dissociation of ^{22}Ne nuclei with an energy of 3.3 GeV per nucleon

Z_f	9	8	8	7	6	6	5	5	5 + 3	4	4 + 3	–	–
$N_{Z=1}$	1	–	2	1	–	2	1	3	–	–	3	2	–
$N_{Z=2}$	–	1	–	1	2	1	2	1	1	3	–	4	5
N_{ev}	22	51	6	7	5	2	1	1	1	2	1	1	3

Table 3. Charge-topology distribution of white stars in the dissociation of ^{28}Si nuclei with an energy of 3.65 GeV per nucleon

Z_f	13	12	12	11	11	10	10	10	9	9	9	8	8	8	7	7	7	6	6	6	6	5	5	4	–	–	–
$N_{Z=1}$	1	–	2	1	3	–	2	4	1	3	5	6	2	4	3	5	7	2	4	6	8	3	5	2	2	8	10
$N_{Z=2}$	–	1	–	1	–	2	1	–	2	1	–	–	2	1	2	1	–	3	2	1	–	3	2	4	6	3	2
N_{ev}	9	3	15	11	6	2	7	2	2	8	3	2	5	6	1	3	3	3	5	8	1	1	3	1	1	2	3

Table 4. Charge-topology distribution of white stars in the dissociation of ^{32}S nuclei with an energy of 200 GeV per nucleon

Z_f	15	14	14	13	13	12	12	11	11	10	10	10	9	8	8	7 + 3	7	5 + 3
$N_{Z=1}$	1	–	2	1	3	2	4	3	5	2	4	6	3	–	6	4	3	4
$N_{Z=2}$	–	1	–	1	–	1	–	1	–	2	1	–	2	4	1	1	3	2
N_{ev}	99	11	48	7	6	3	4	4	1	1	2	1	1	1	1	1	1	1

Table 5. Charge-topology distribution of white stars in the dissociation of ^{16}O nuclei with an energy of 3.65 GeV per nucleon

Z_f	7	6	6	5	5	4	4	–	–
$N_{Z=1}$	1	2	–	3	1	–	2	–	2
$N_{Z=2}$	–	–	1	–	1	2	1	4	3
N_{ev}	18	7	21	2	10	1	1	9	3

Table 6. Charge-topology distribution of white stars in the dissociation of ^{16}O nuclei with an energy of 200 GeV per nucleon

Z_f	7	6	6	5	5	4	3	3	–	–	–
$N_{Z=1}$	1	–	2	1	3	2	1	3	–	2	4
$N_{Z=2}$	–	1	–	1	–	1	2	1	4	3	2
N_{ev}	49	6	10	5	1	3	2	2	2	4	2

Table 7. Charge-topology distribution of white stars in the dissociation of ^{10}B nuclei with an energy of 1 GeV per nucleon

Z_f	4	3	–	–
$N_{Z=1}$	1	–	3	1
$N_{Z=2}$	–	1	1	2
N_{ev}	1	5	5	30

Table 8. Charge-topology distribution of white stars in the dissociation of ^{14}N nuclei with an energy of 2.1 GeV per nucleon

Z_f	6	5	5	4	3	3	–	–
$N_{Z=1}$	1	–	2	1	4	2	3	1
$N_{Z=2}$	–	1	–	1	–	1	2	3
N_{ev}	6	3	2	1	1	1	1	10

Table 9. Charge-topology distribution of white stars in the dissociation of ^7Be nuclei of energy 1.23 GeV per nucleon

Z_f	3	–	–	–
$N_{Z=1}$	1	4	2	–
$N_{Z=2}$	–	–	1	2
N_{ev}	7	2	38	28

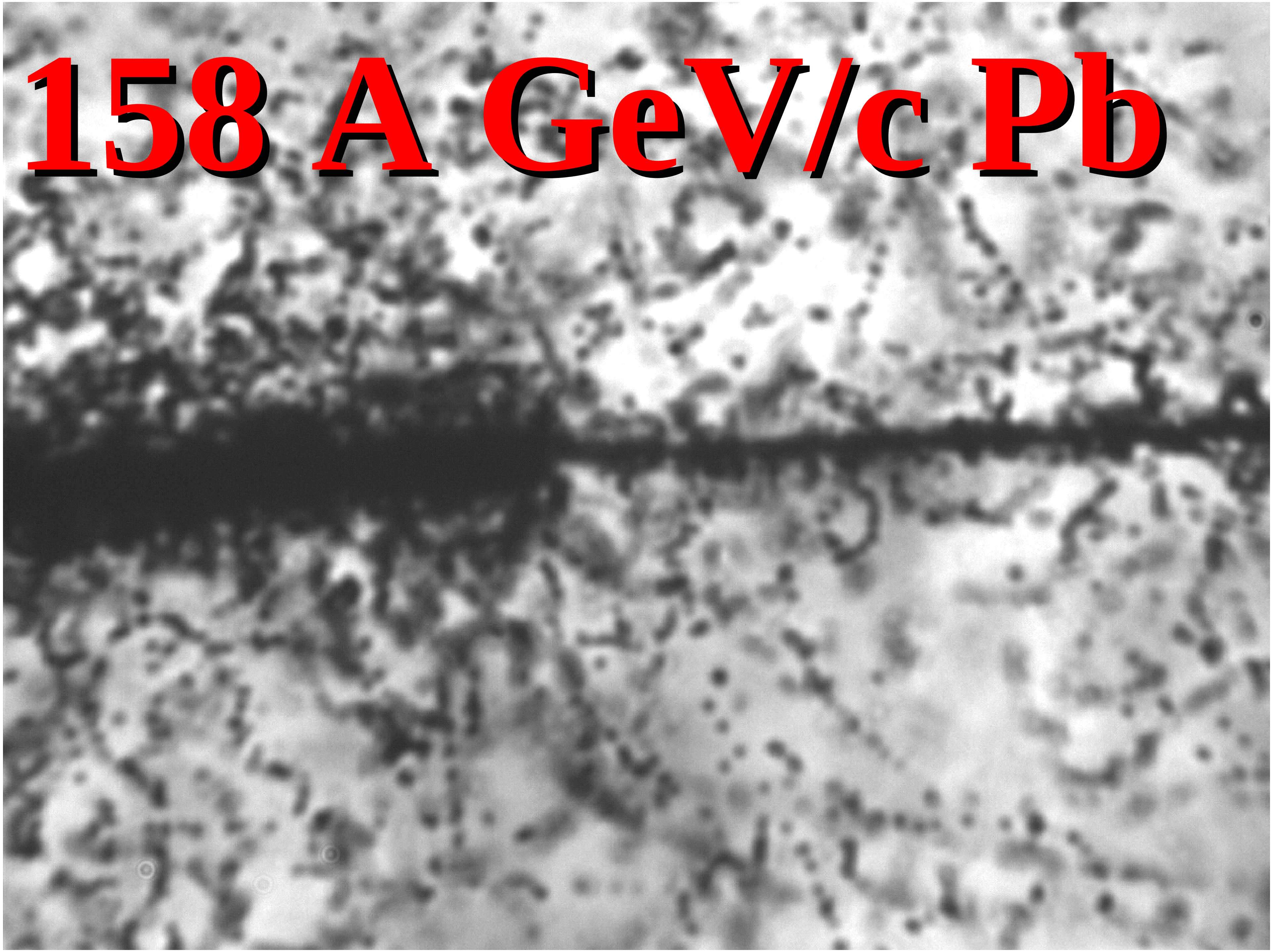
Number of events of ^6Li coherent dissociation

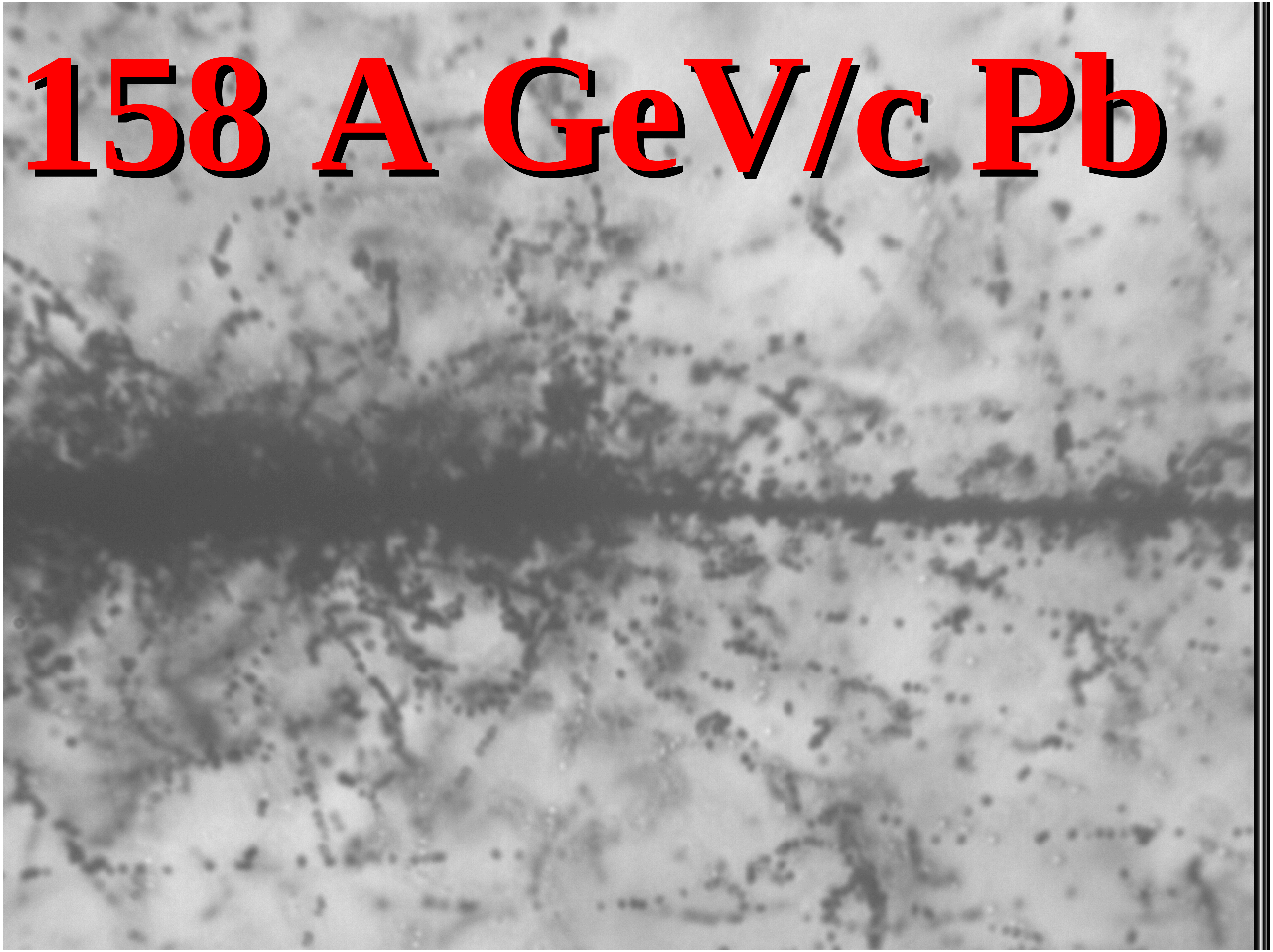
Dissociation channel	Number of events	
	without the excitation of the target nucleus ($N_h = 0$)	with the excitation of the target nucleus ($N_h \neq 0$)
$^4He + d$	23	24
$^3He + t$	4	1
$t + d + p$	4	3
$d + d + d$	0	2

The common topological feature for fragmentation of the Ne, Mg, and Si nuclei consists in a suppression of binary splitting to fragments with charges larger than 2.

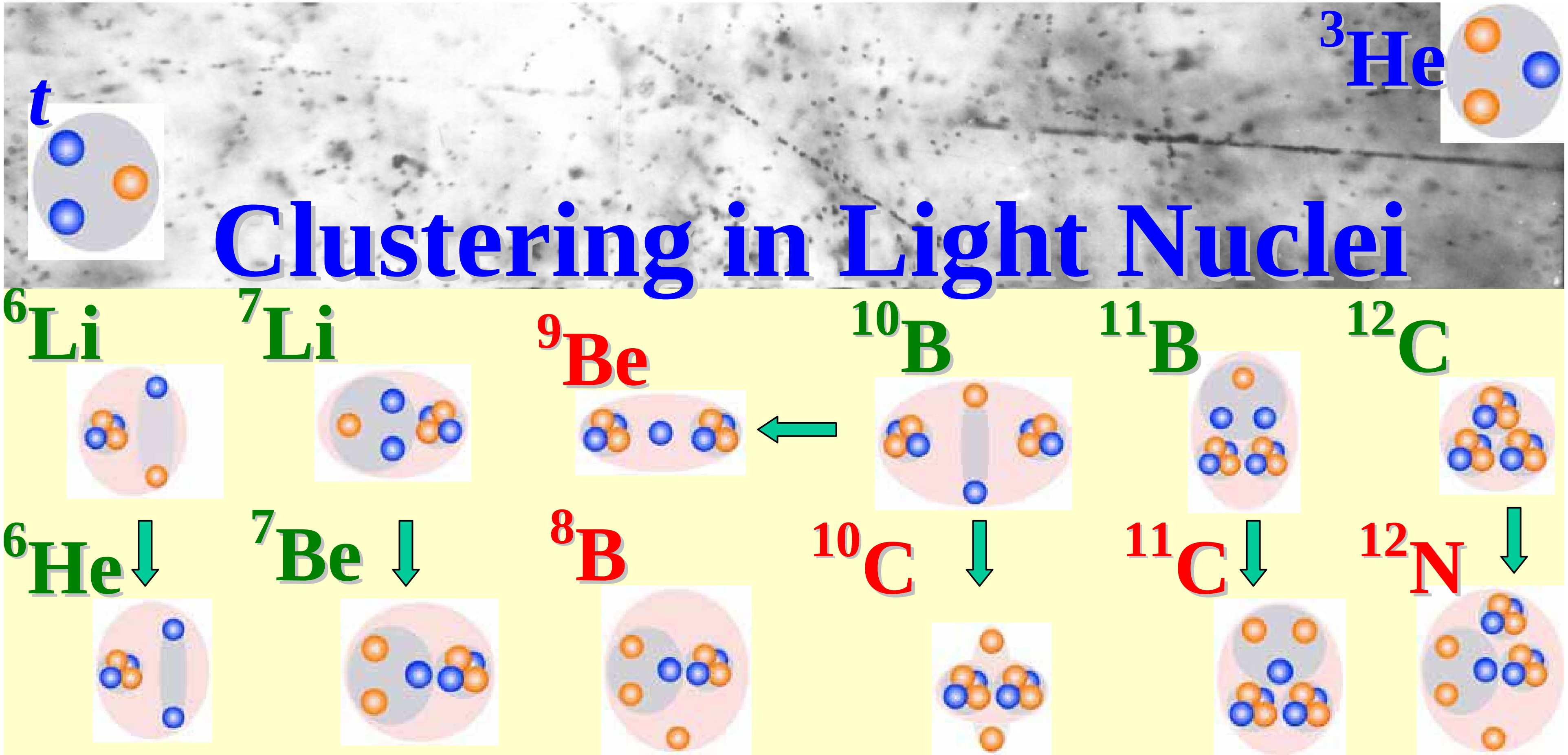
The growth of the fragmentation degree is revealed in an increase of the multiplicity of singly and doubly charged fragments up to complete dissociation with increasing of excitation.

This circumstance shows in an obvious way on a domination of the multiple cluster states having high density over the binary states having lower energy thresholds.


158 A GeV/c Pb


158 A GeV/c Pb

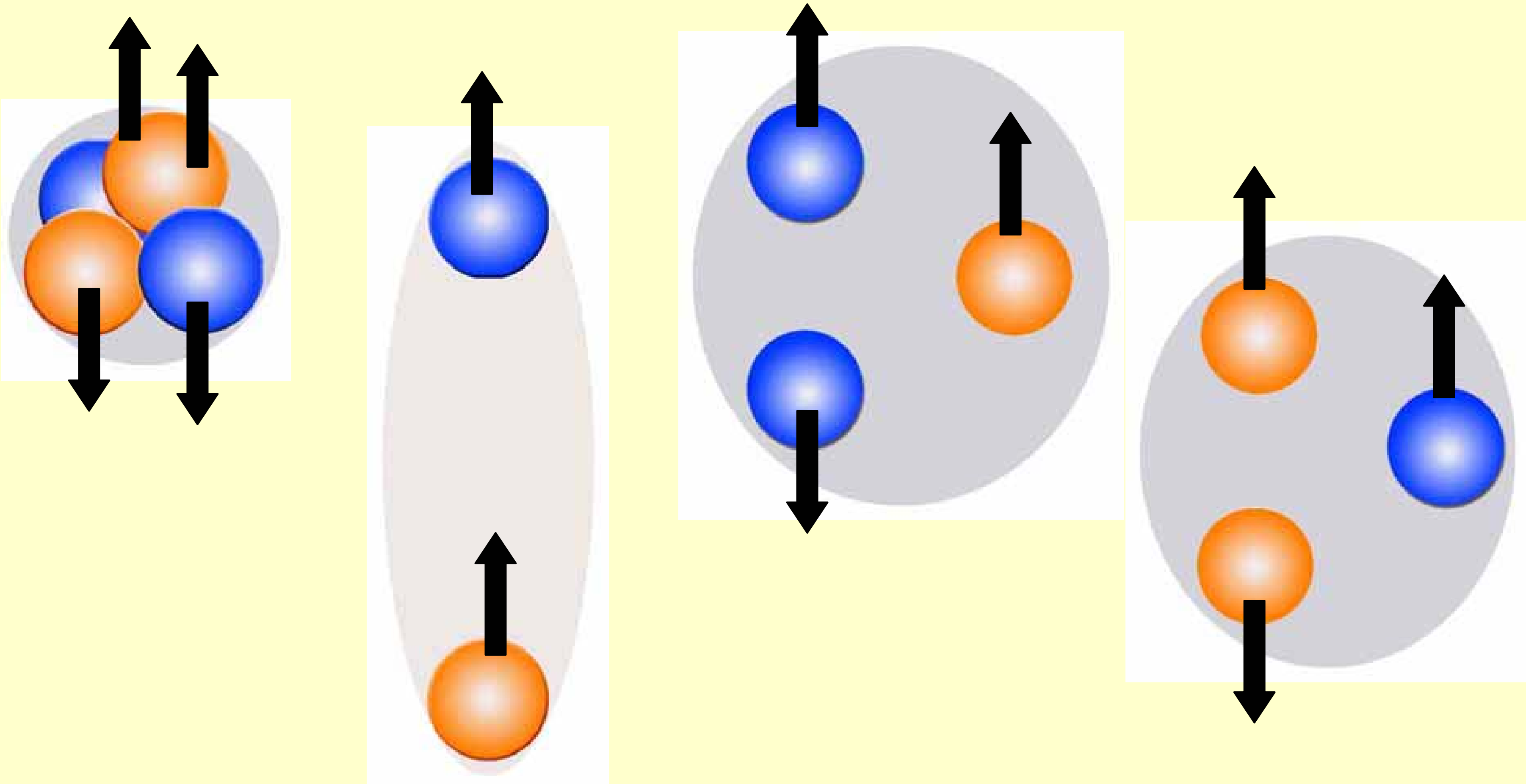
Clustering in Light Nuclei



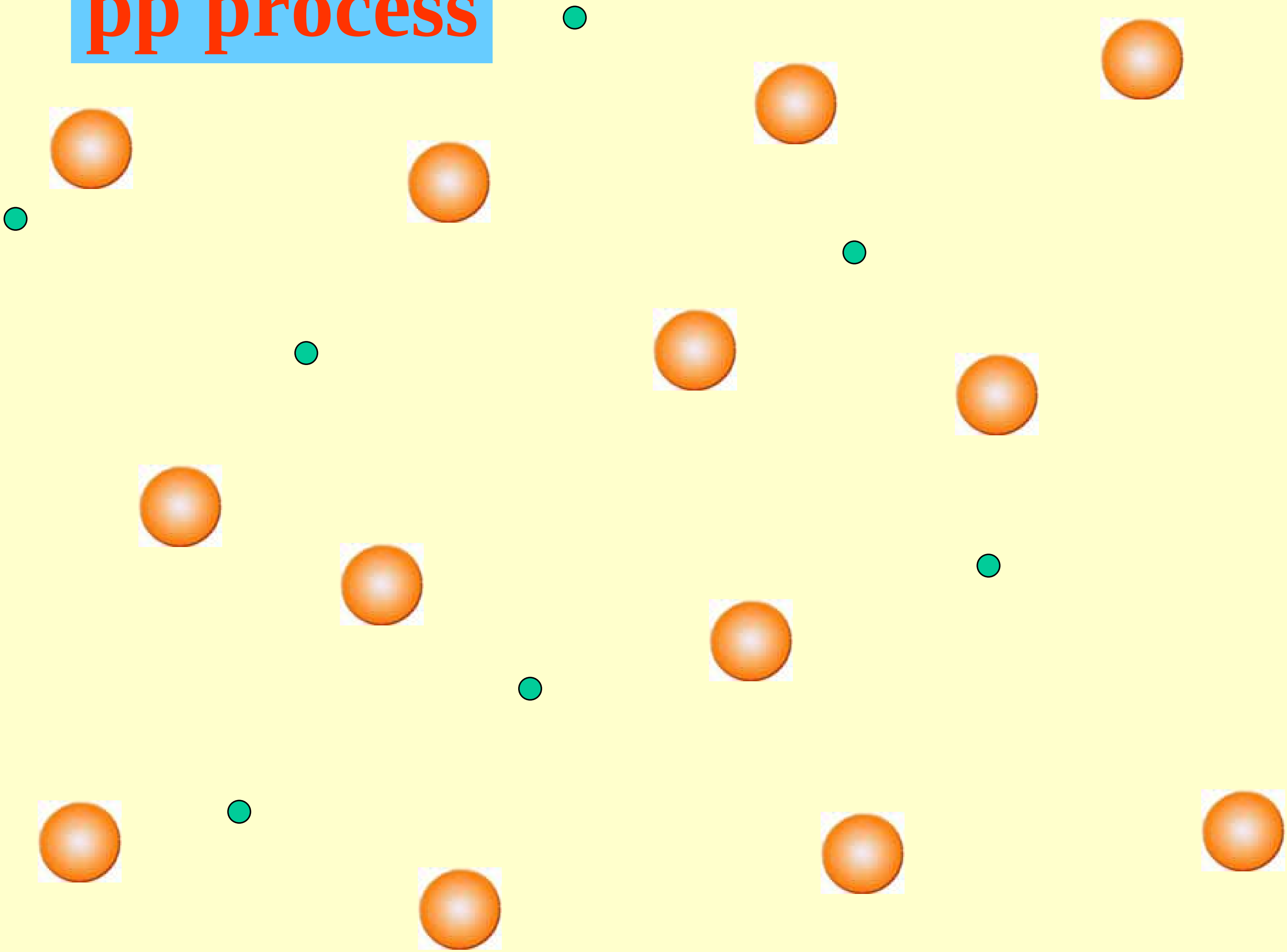
Secondary beams of light radioactive nuclei will be produced mostly via charge exchange reactions. ^{8}B and ^{9}Be beams has been formed via fragmentation of ^{10}B.

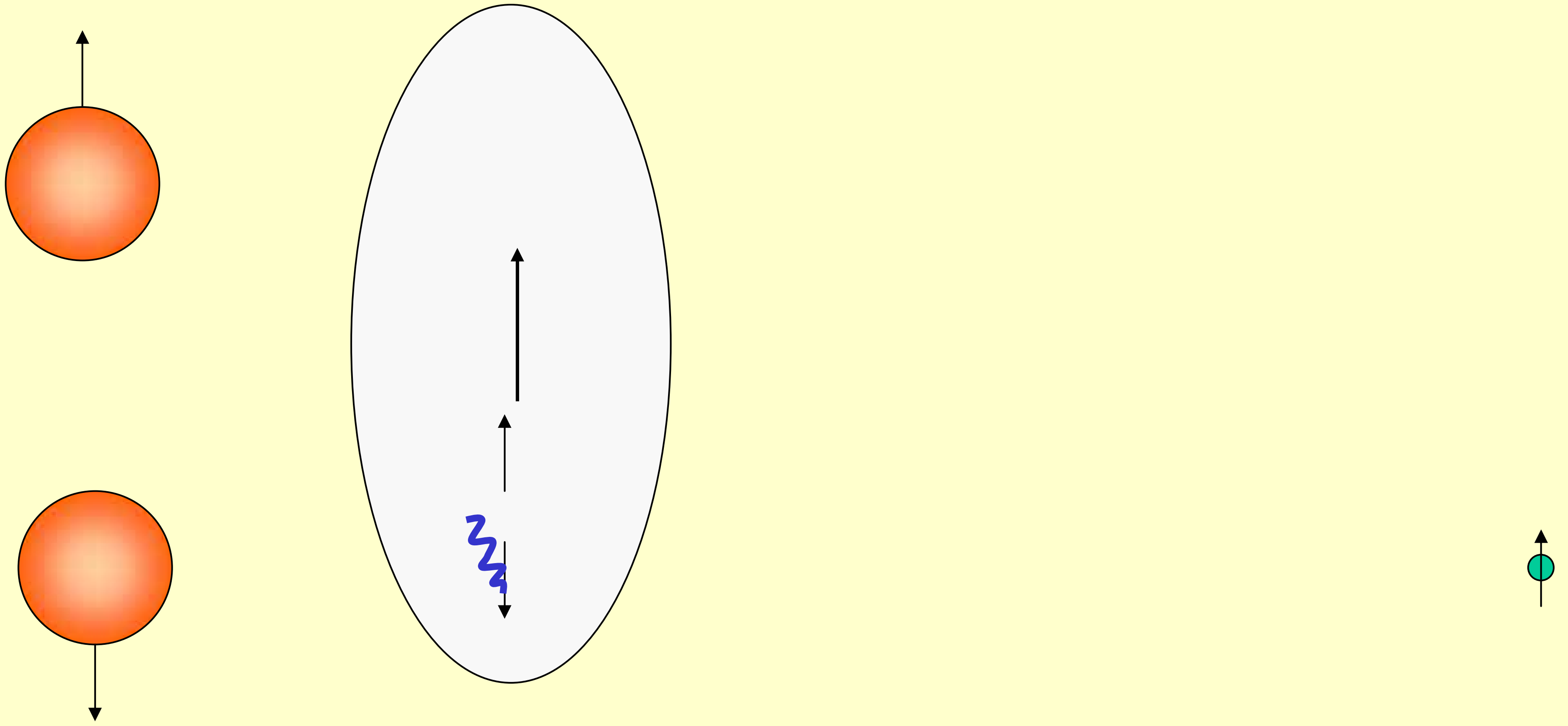
Clustering building blocks:

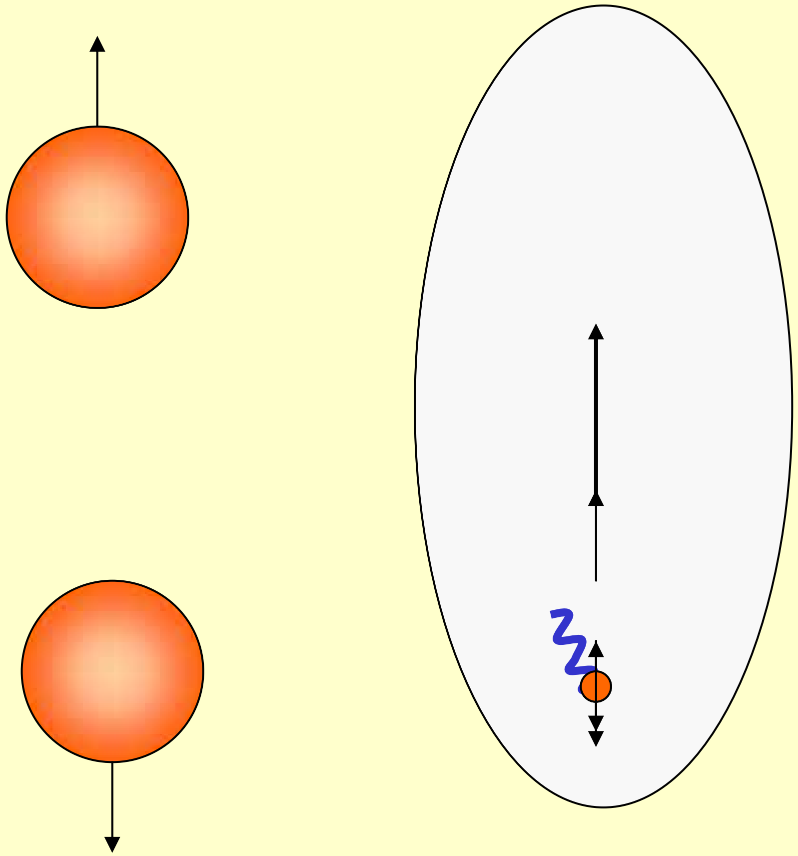
more than one nucleon bound, stable & no exited states below particle decay thresholds – deuteron, triton, ^{4}He, and ^{3}He nuclei

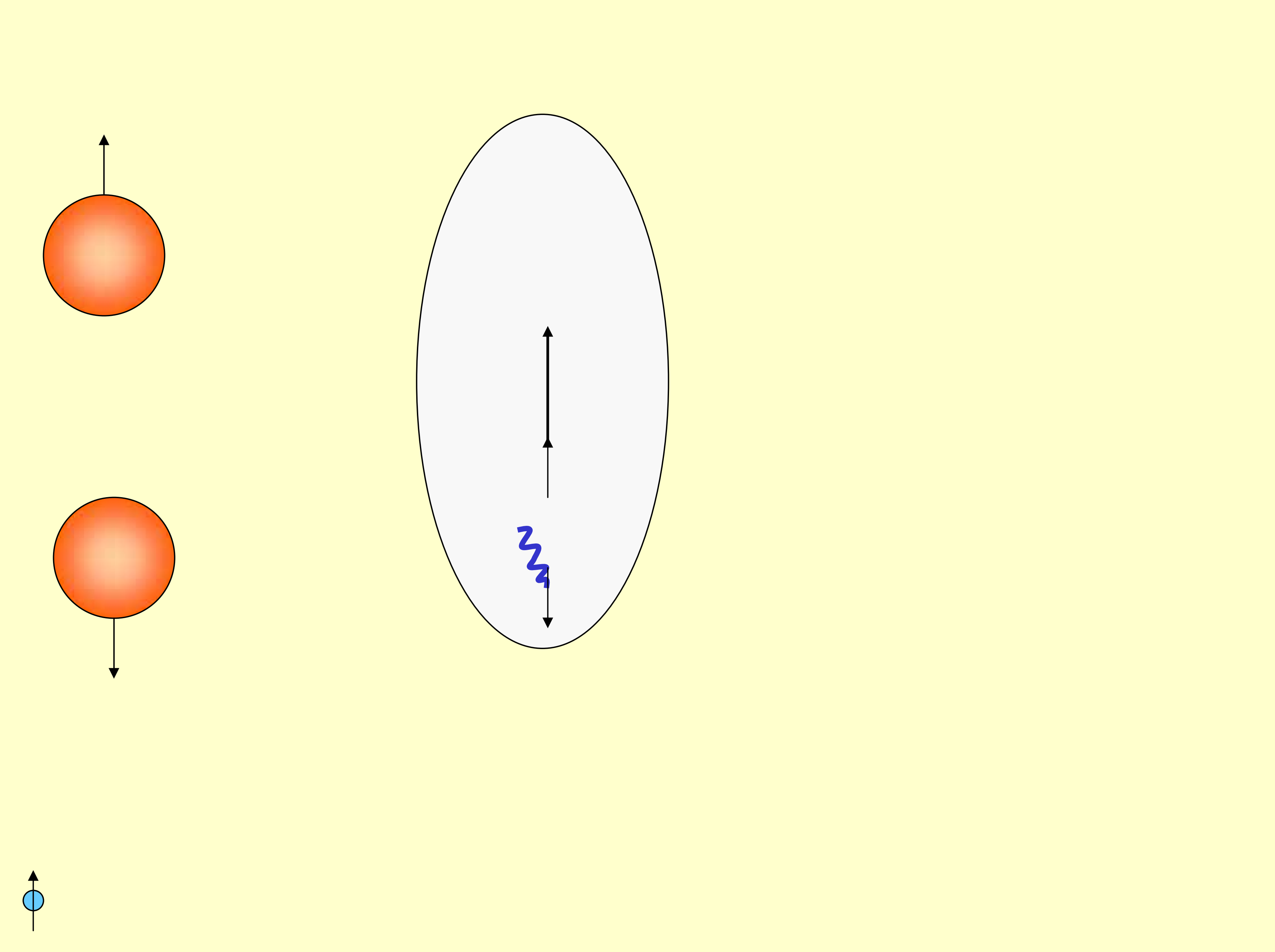


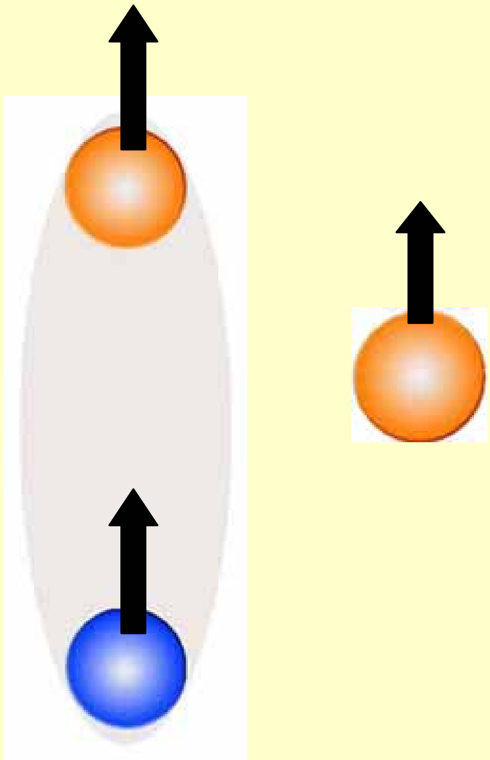
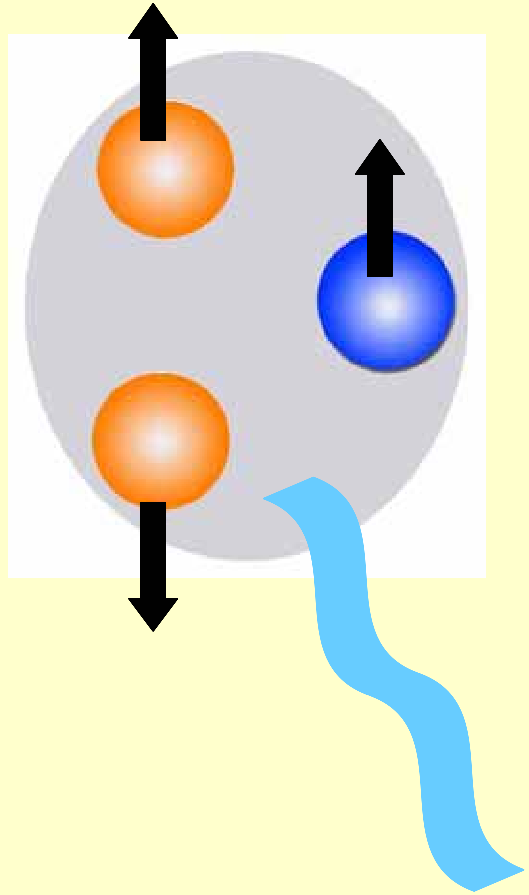
pp process



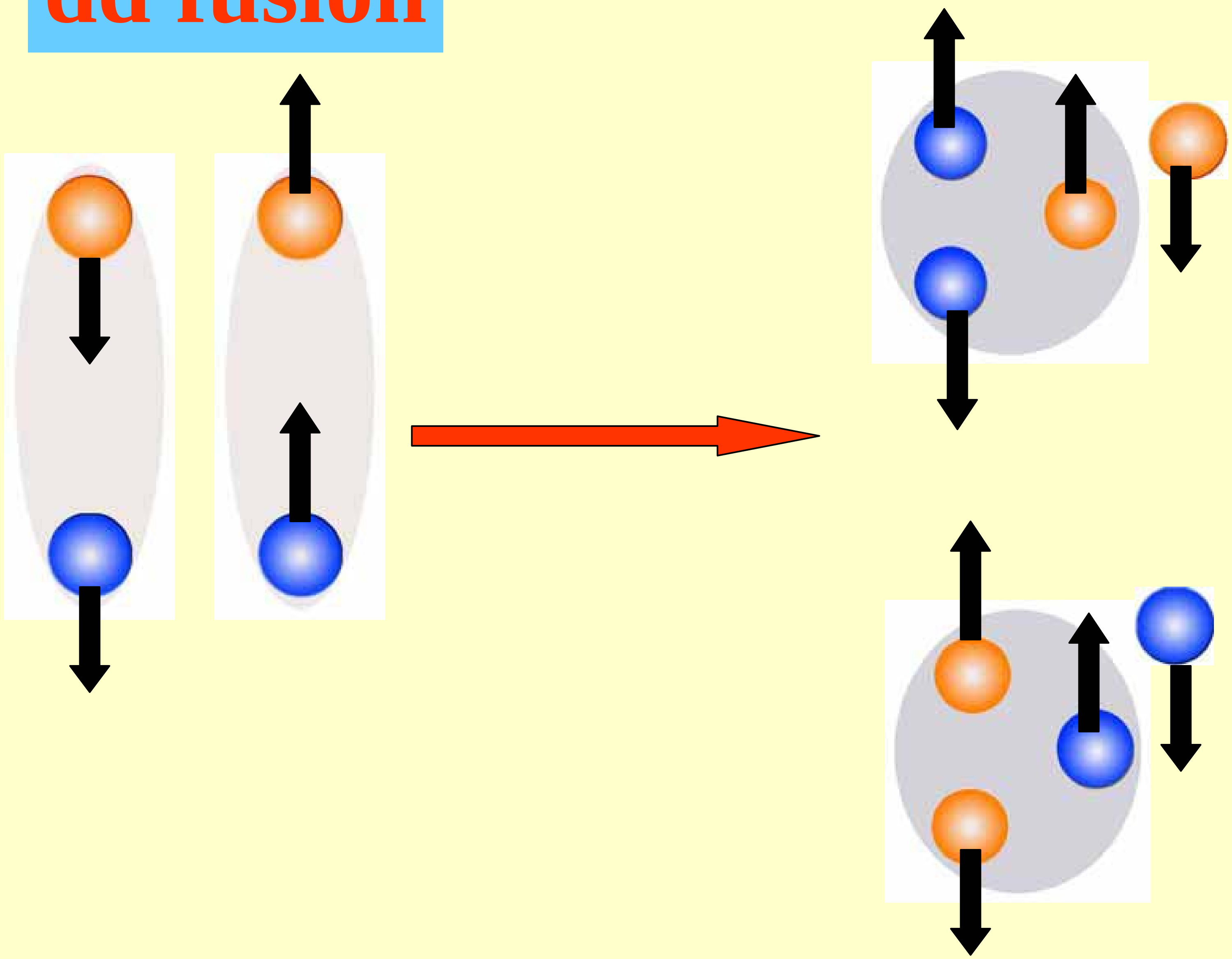




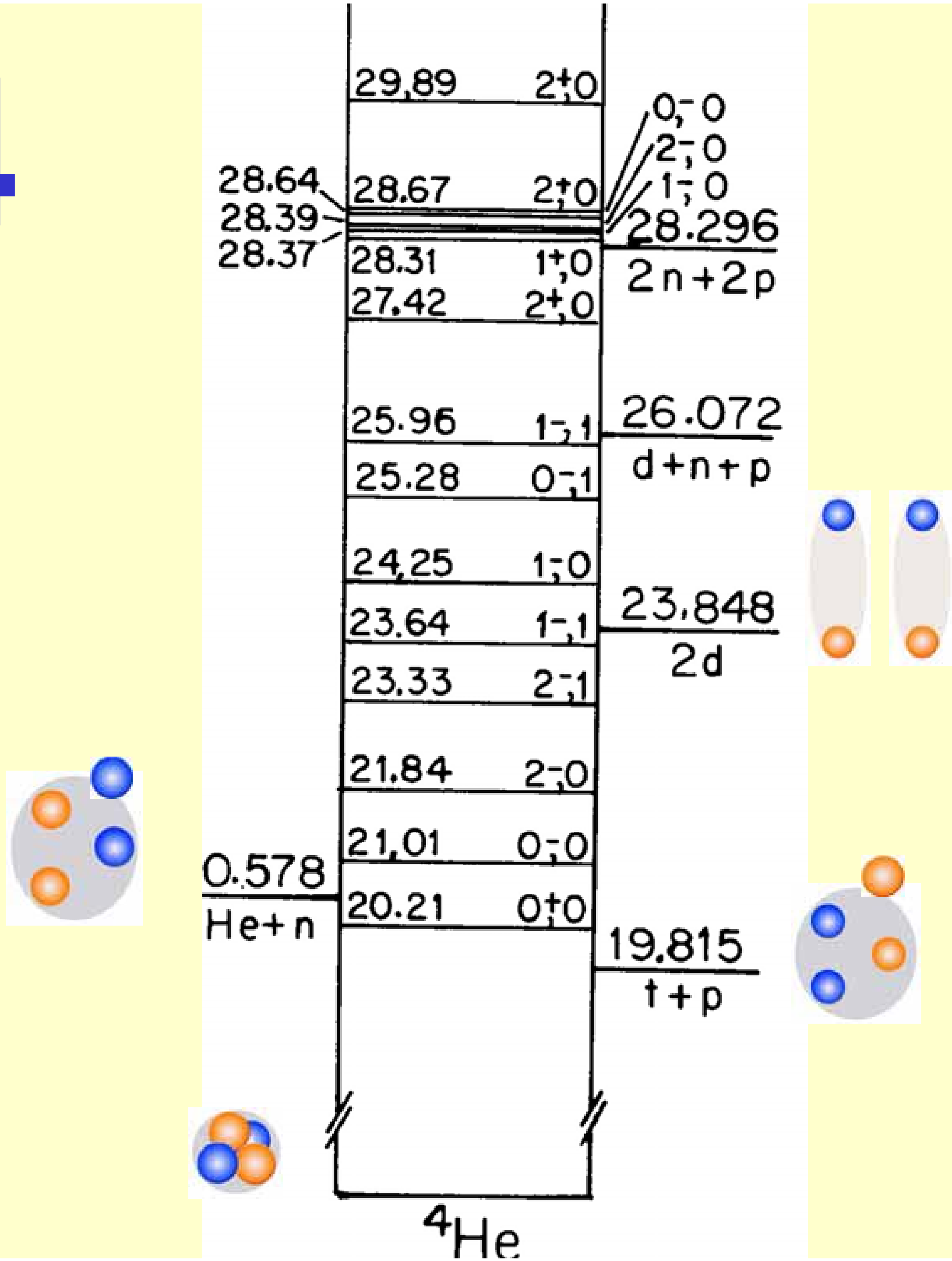


dd fusion

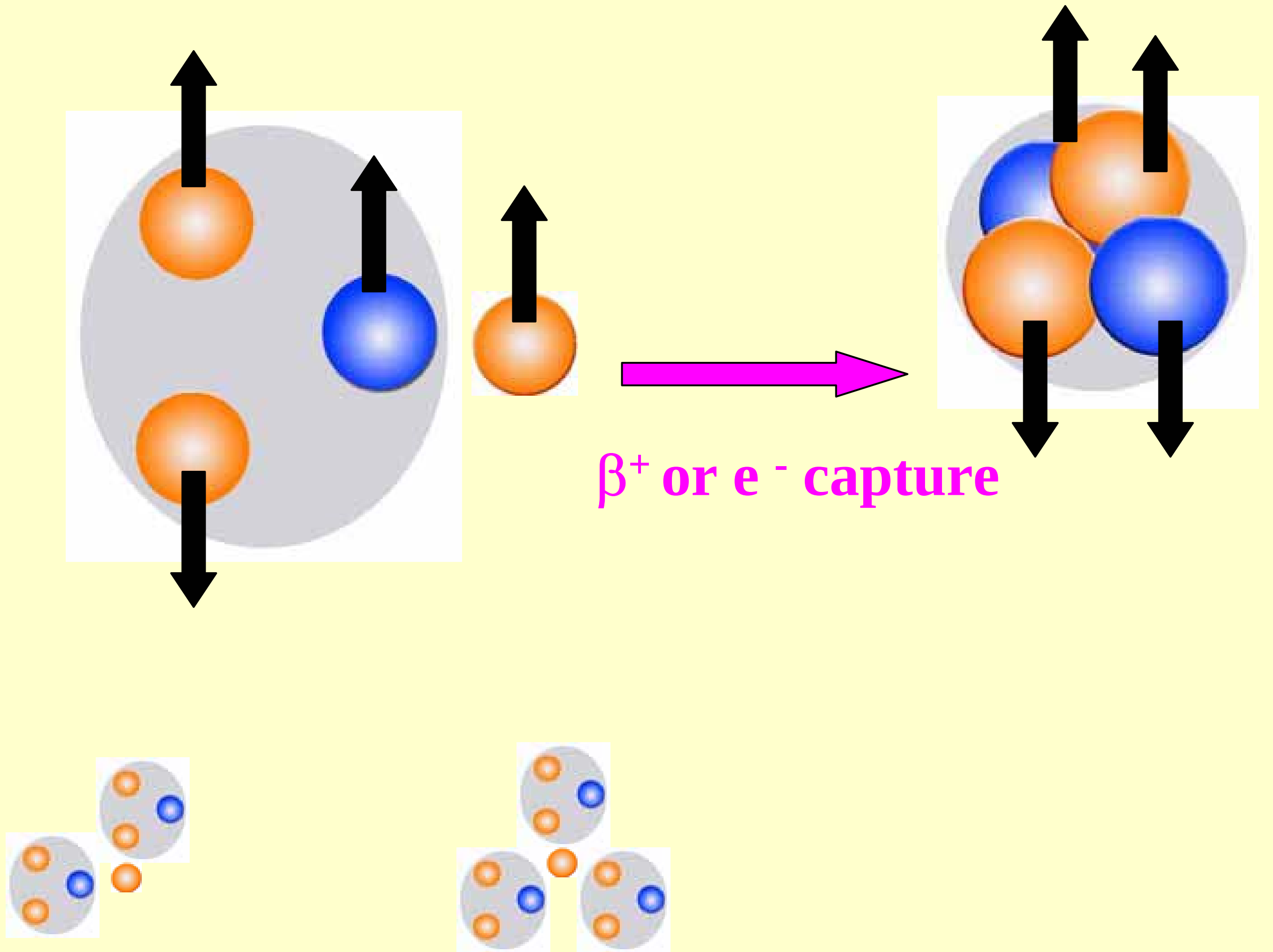


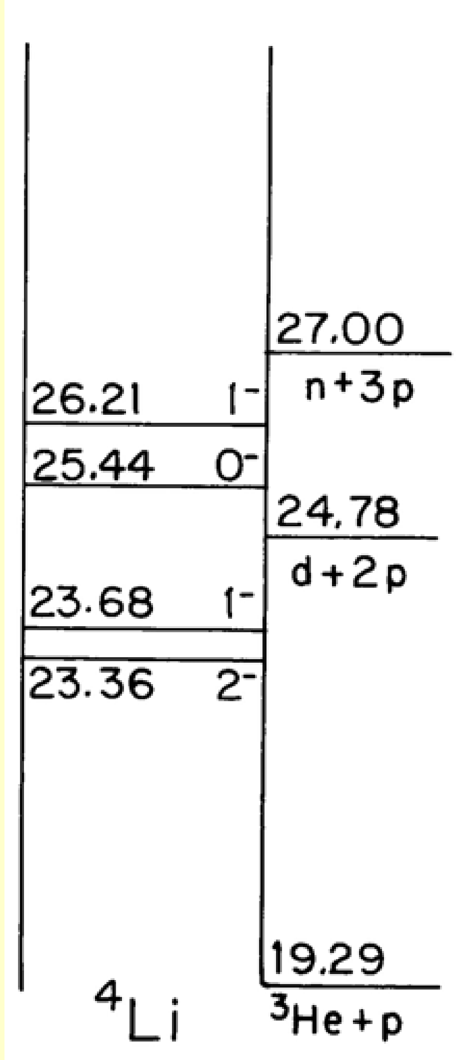
A=4

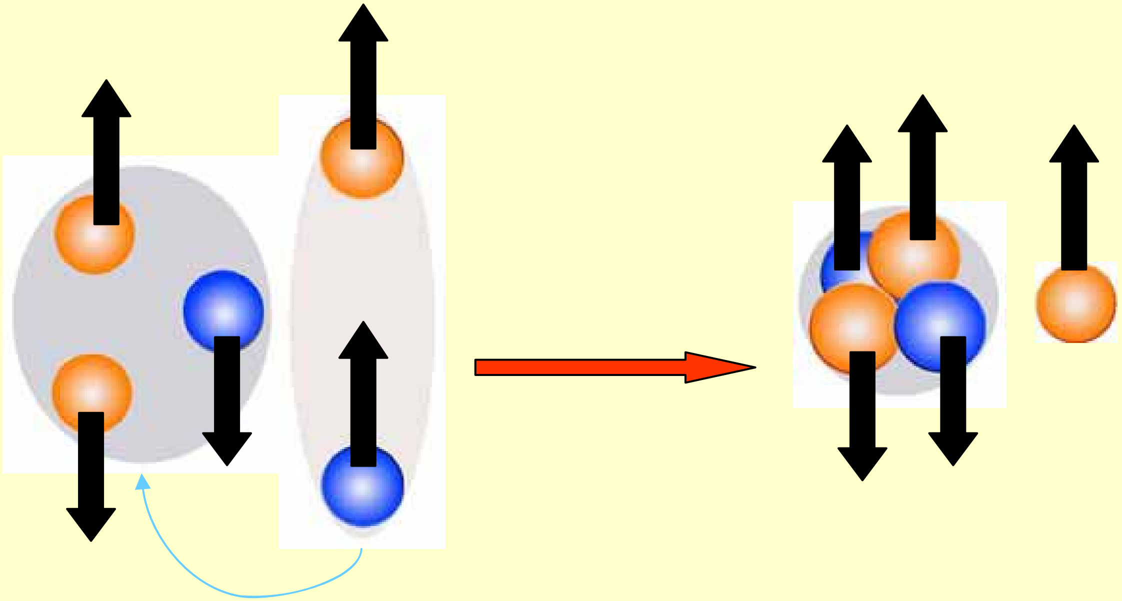


29.89 2+;0
28.64
28.39
28.37
28.67 2+;0
0-;0
2-;0
1-;0
28.296
2n+2p
28.31 1+;0
27.42 2+;0
25.96 1-;1
26.072
d+n+p
25.28 0-;1
24.25 1-;0
23.64 1-;1
23.848
2d
23.33 2-;1
21.84 2-;0
21.01 0-;0
0.578
He+n
20.21 0+;0
19.815
t+p
^{4}He

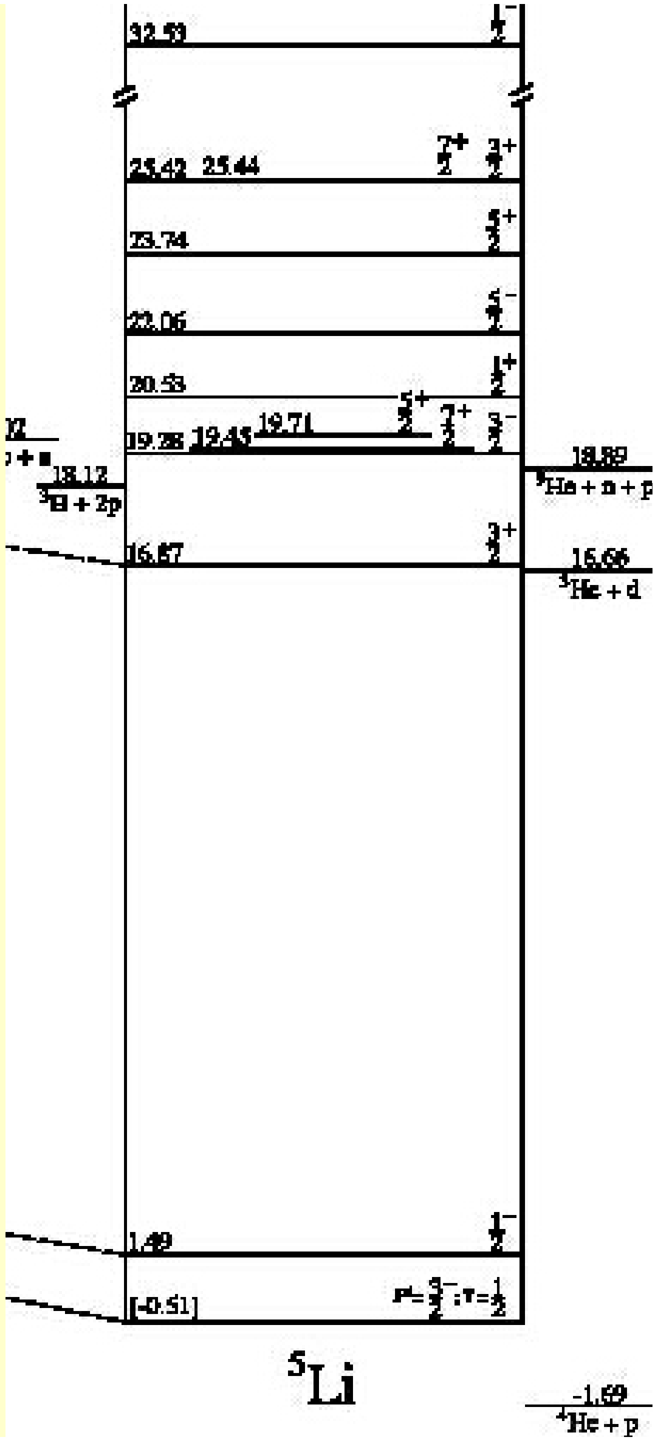
Hep Process


β+ or e - capture

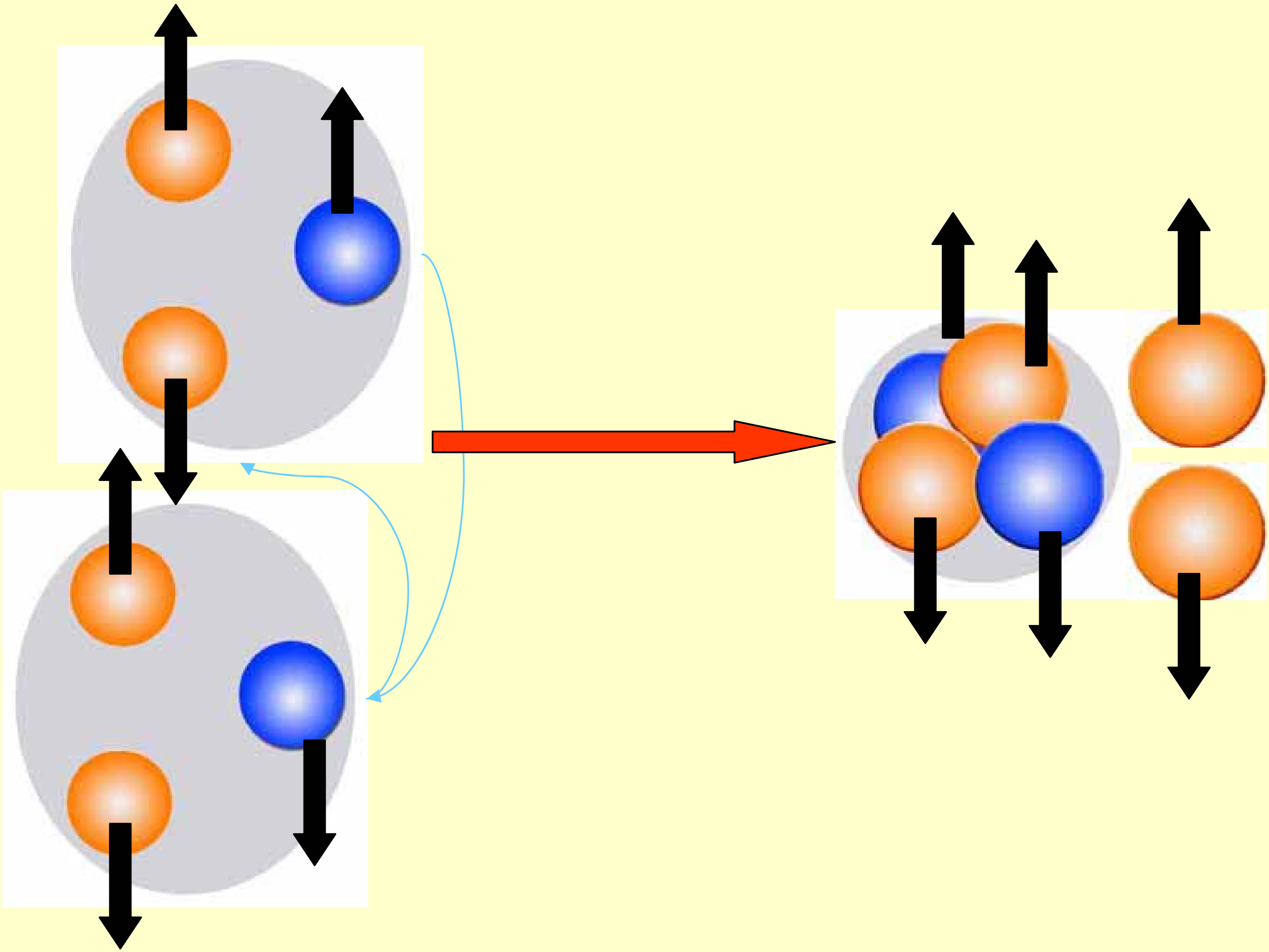

27.00
n+3p
26.21 1-
25.44 0-
24.78
d+2p
23.68 1-
23.36 2-
19.29
4Li
3He+p



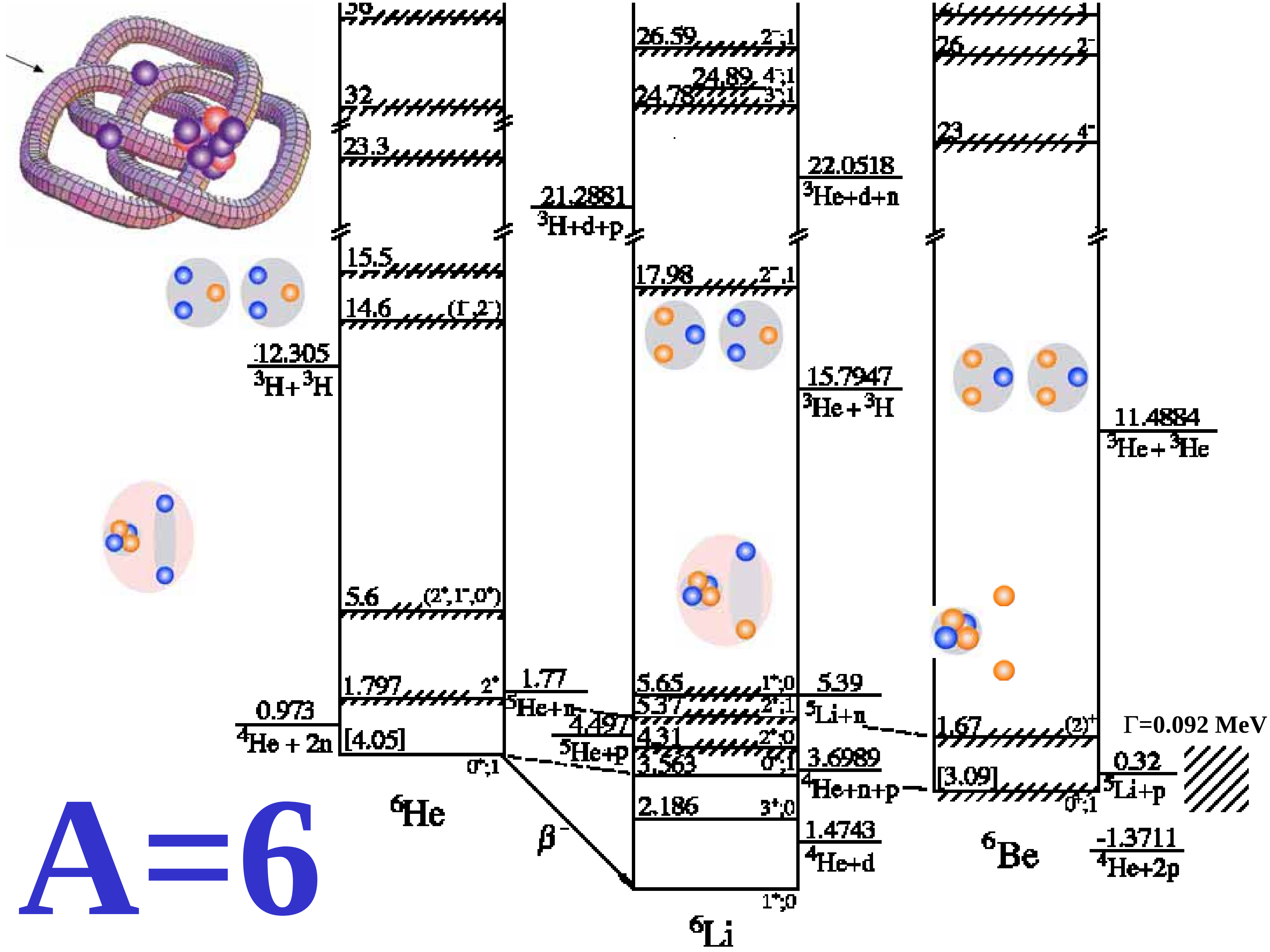
A=5



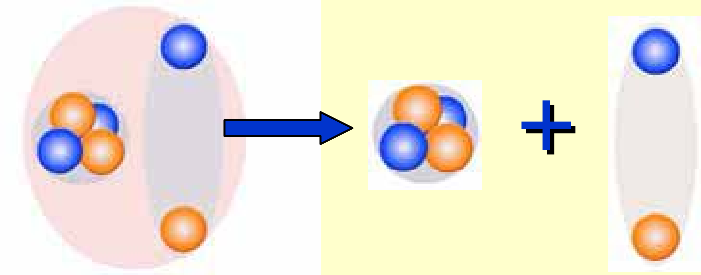
32.53
25.42
25.44
23.74
22.06
20.53
19.28
19.43
19.71
18.12
16.87
18.59
16.66
1.49
[-0.51]
5Li
-1.69



A=6

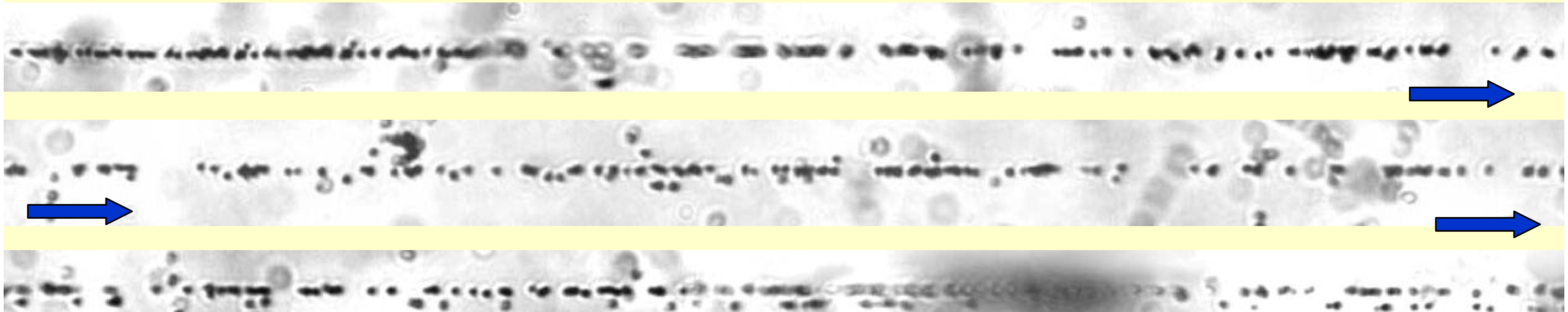
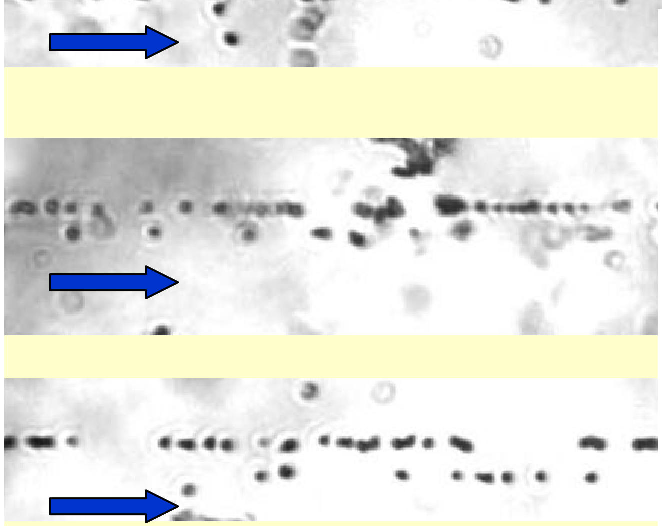
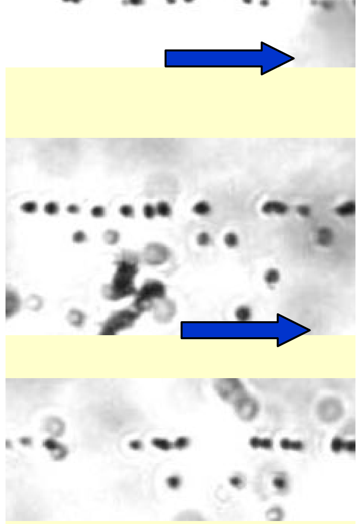


36
32
23.3
15.5
14.6 (1⁻,2⁻)
12.305
³H+³H
5.6 (2⁺,1⁻,0⁺)
1.797 2⁺
0.973
⁴He + 2n
[4.05]
0⁺;1
⁶He
21.2881
³H+d+p
1.77
⁵He+n
4.497
⁵He+p
β⁻
26.59 2⁻;1
24.89 4⁻;1
24.78 3⁻;1
17.98 2⁻;1
5.65 1⁺;0
5.37 2⁺;1
4.31 2⁺;0
3.563 0⁺;1
2.186 3⁺;0
1⁺;0
⁶Li
22.0518
³He+d+n
15.7947
³He+³H
5.39
⁵Li+n
3.6989
⁴He+n+p
1.4743
⁴He+d
26 2⁻
23 4⁻
1.67 (2)⁺
[3.09]
0⁺;1
⁶Be
11.4884
³He+³He
Γ=0.092 MeV
0.32
⁵Li+p
-1.3711
⁴He+2p



4.5A GeV/c ^{6}Li Coherent Dissociation (PAVICOM image)

^{6}Li

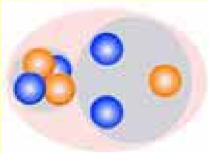




Number of events of ^{6}Li coherent dissociation

Dissociation channel	Number of events: without the excitation of the target nucleus ($N_h = 0$)	Number of events: with the excitation of the target nucleus ($N_h \neq 0$)
$^{4}He + d$	23	24
$^{3}He + t$	4	1
$t + d + p$	4	3
$d + d + d$	0	2

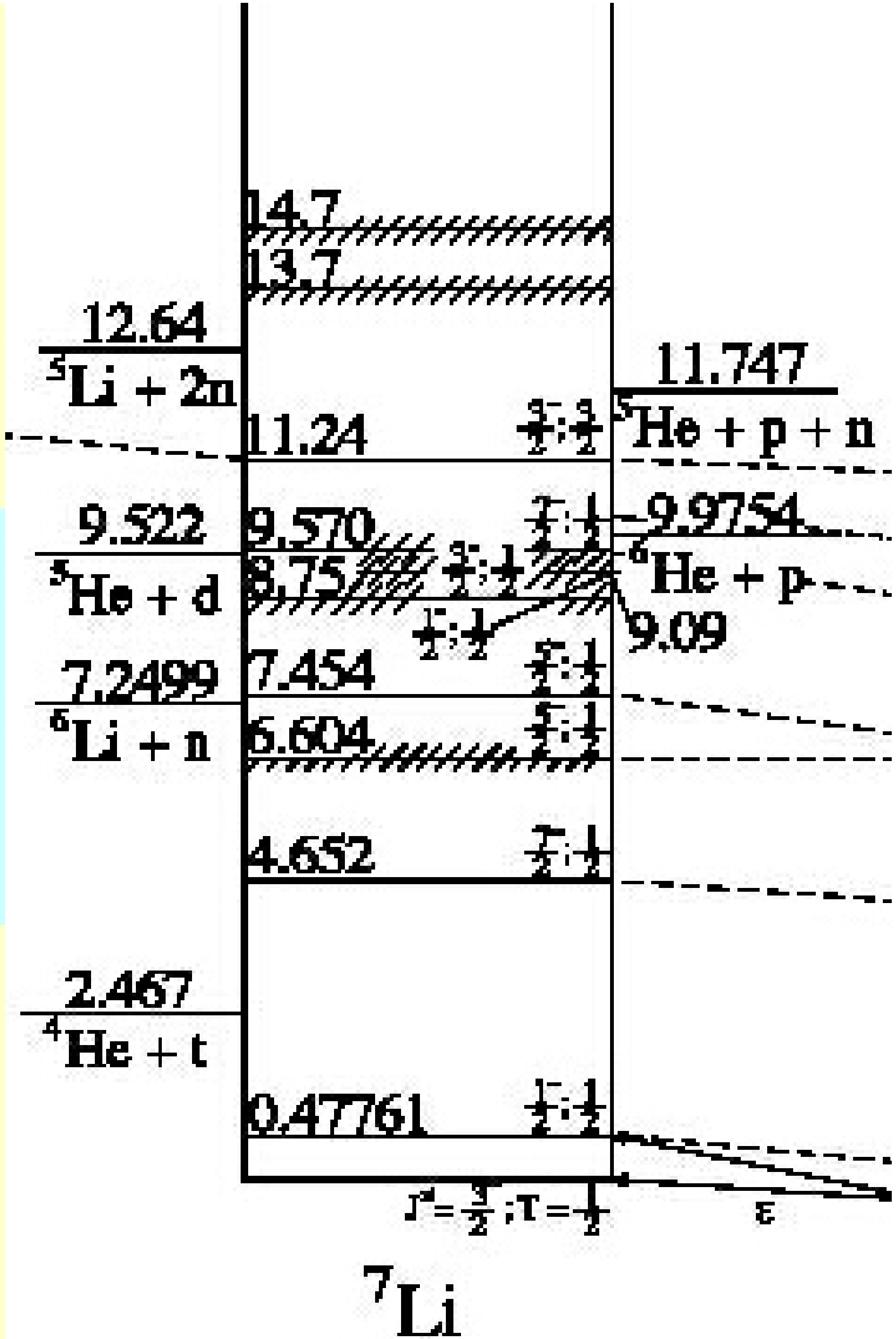
Triton Clustering

^{7}Li

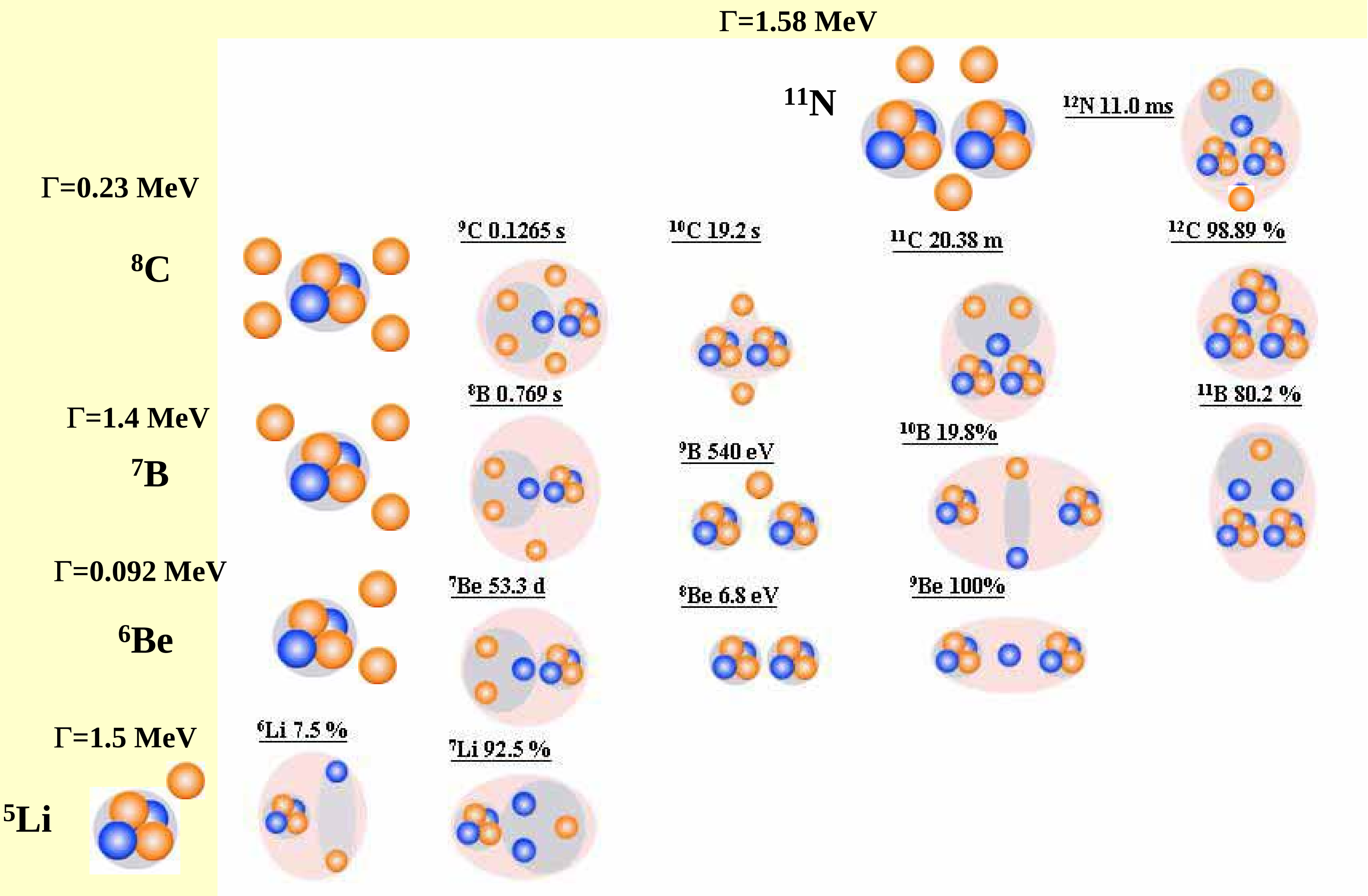


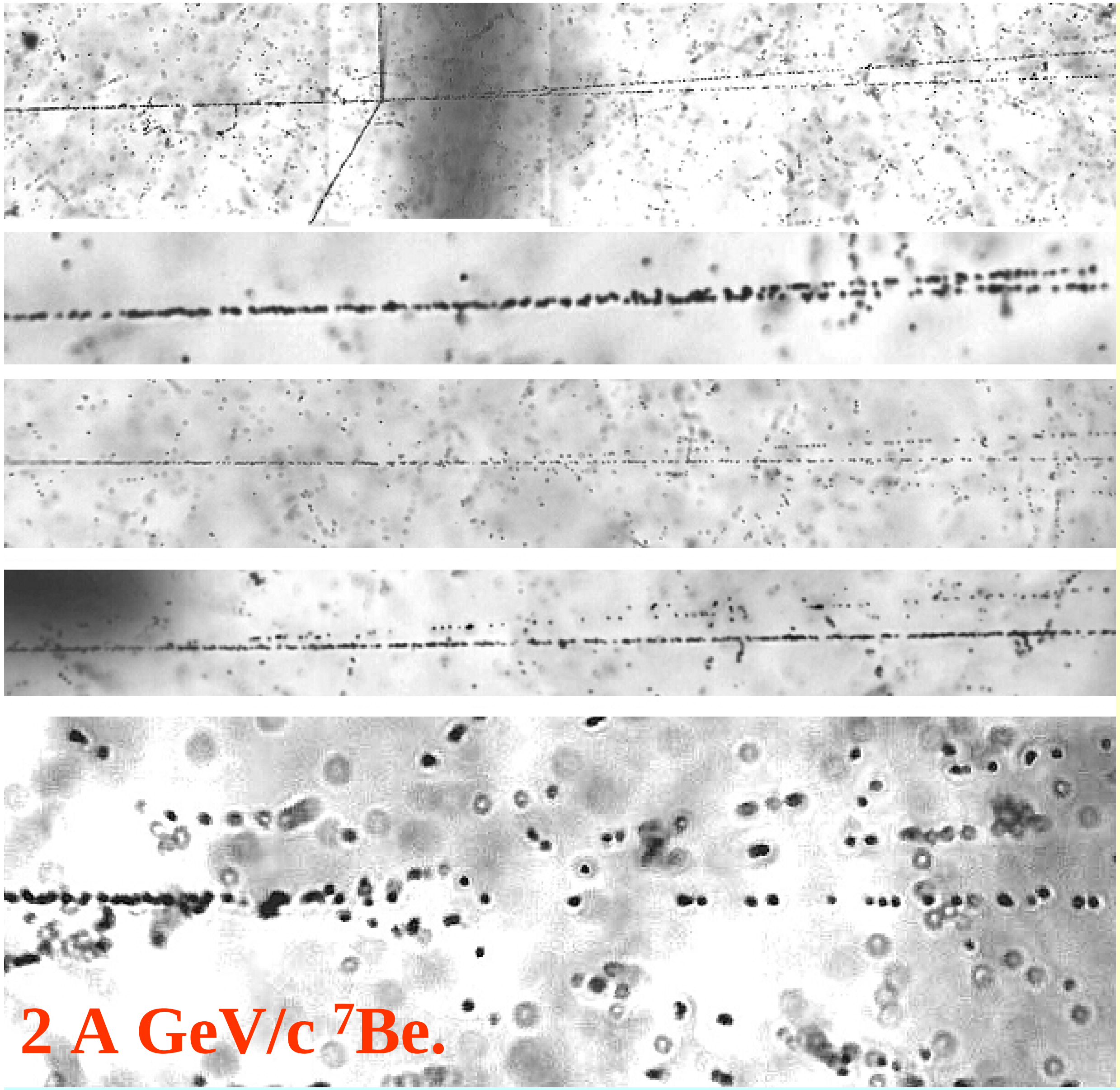
^{7}Li. About 7% of all inelastic interactions of ^{7}Li nuclei are "white" stars (80 events).

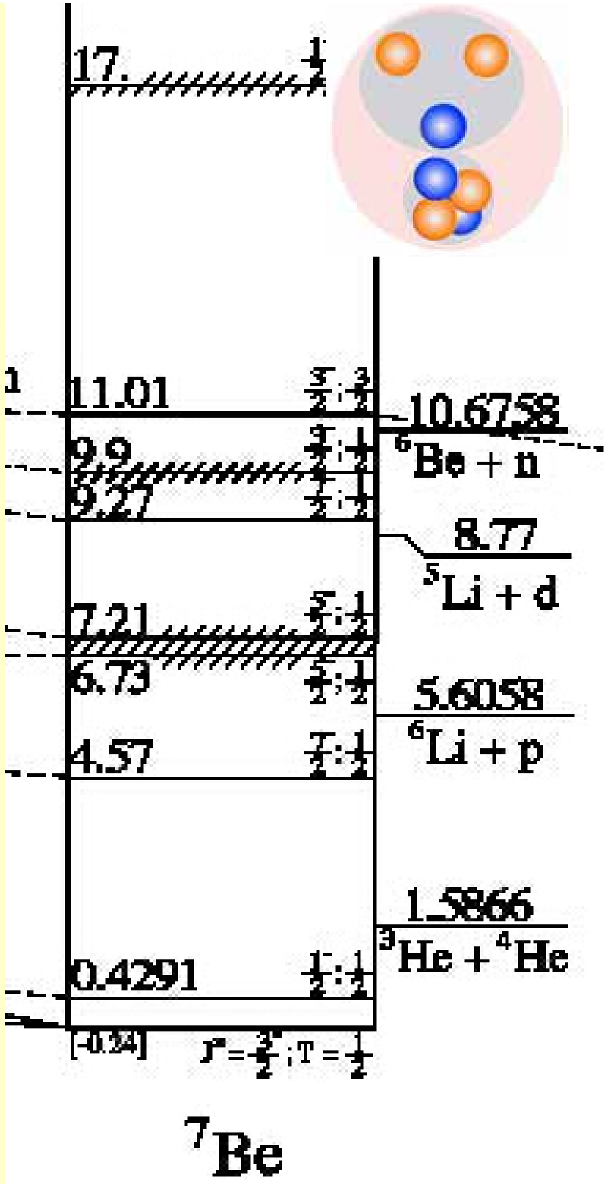
Decay of ^{7}Li nucleus to α-particle and triton - 40 events.



Toward stability frontier

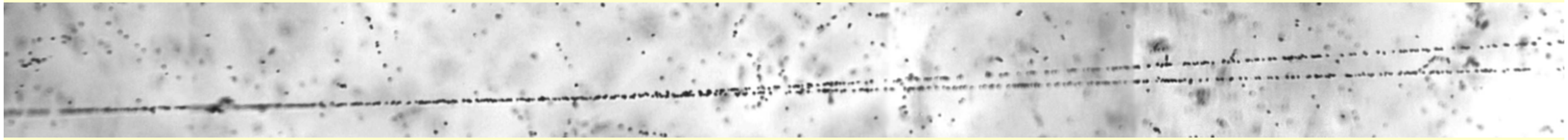


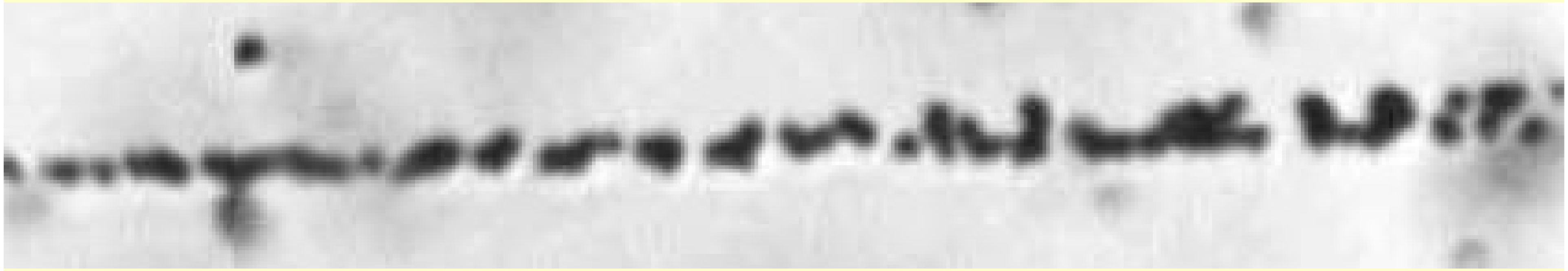




Splitting to HeHe with two target fragments, HeHe, HeHH, ^{6}Lip, and 4H.

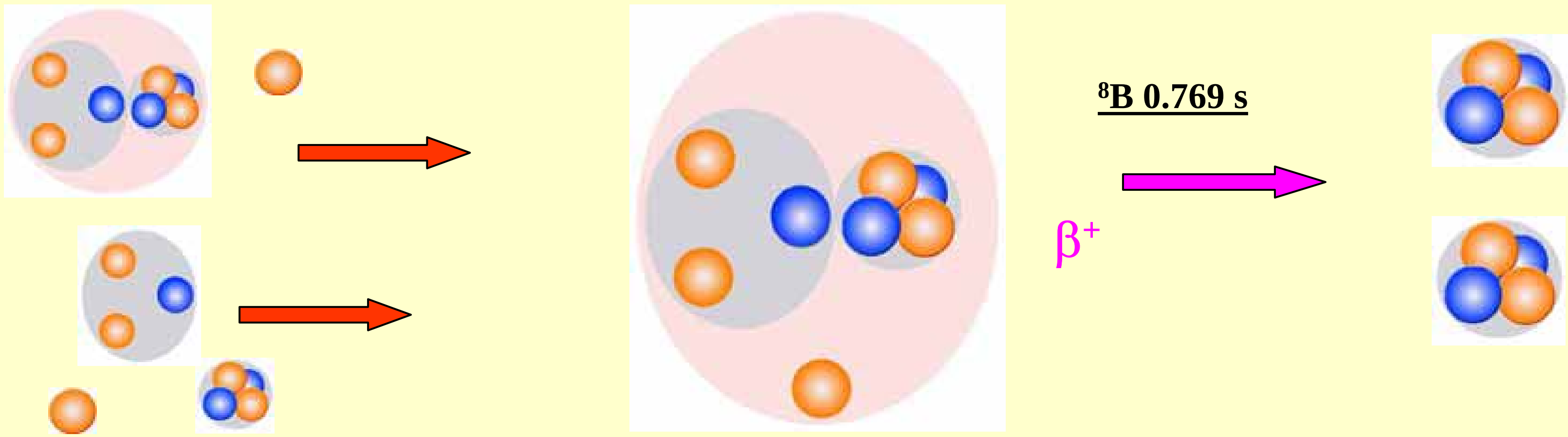
Relativistic ^{7}Be fragmentation: 2+2





The $^{7}Be^{*} \rightarrow \alpha\, ^{3}He$ decay is occured in 22 "white stars" with 2+2 topology. In the latter, 5 "white" stars are identified as the $^{7}Be^{*} \rightarrow (n)\, ^{3}He\, ^{3}He$ decay. Thus, a ^{3}He clustering is clearly demonstrated in dissociation of the ^{7}Be nucleus.

“Ternary H&He Process”

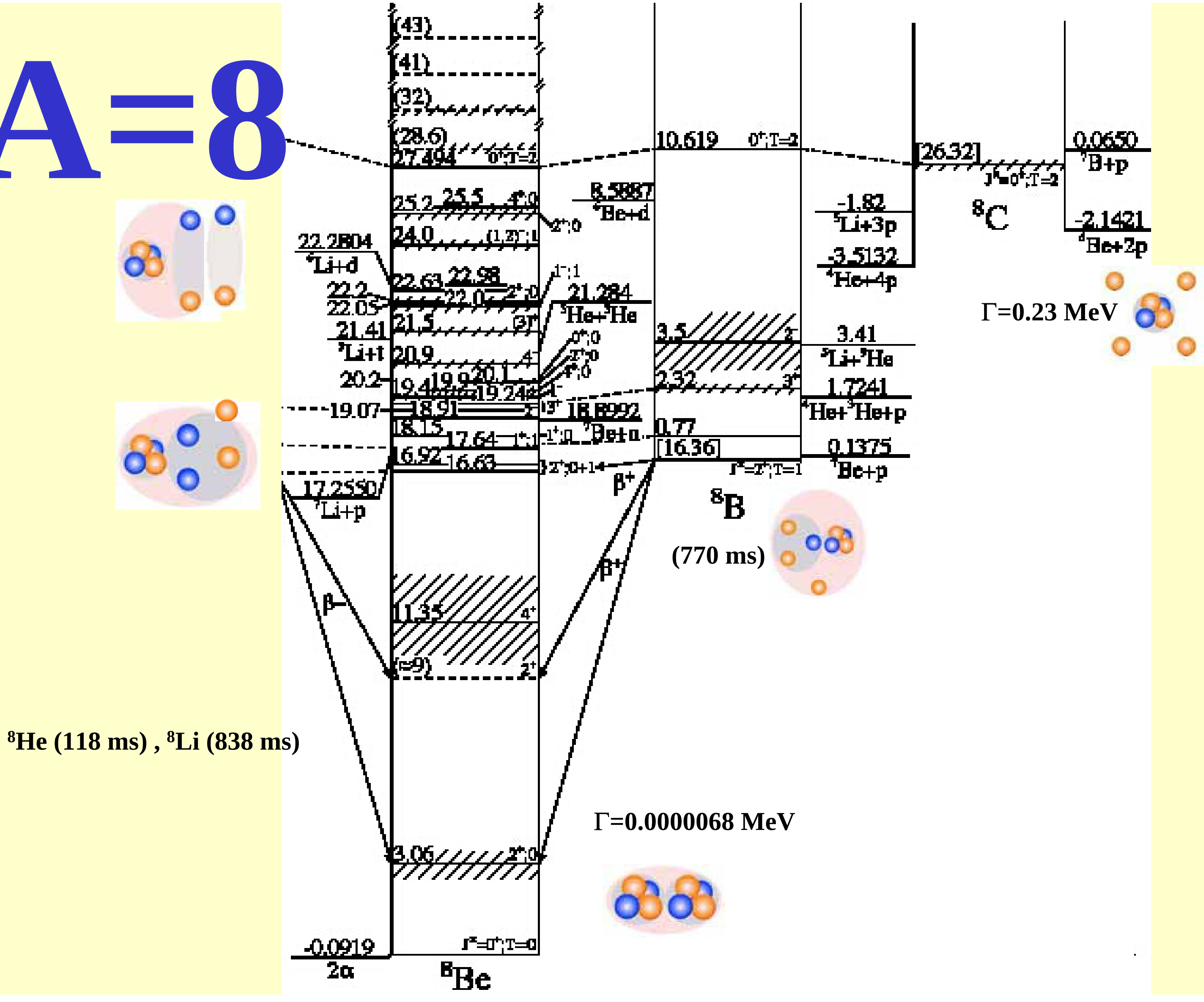


The ^{10}B nuclei with a momentum of 2A GeV/c and an intensity of about 10^8 nuclei per cycle were accelerated at the JINR nuclotron. A beam of secondary nuclei of a magnetic rigidity corresponding to Z/A = 5/8 ($^{10}B \rightarrow {}^{8}B$ fragmentation) was provided for emulsions.

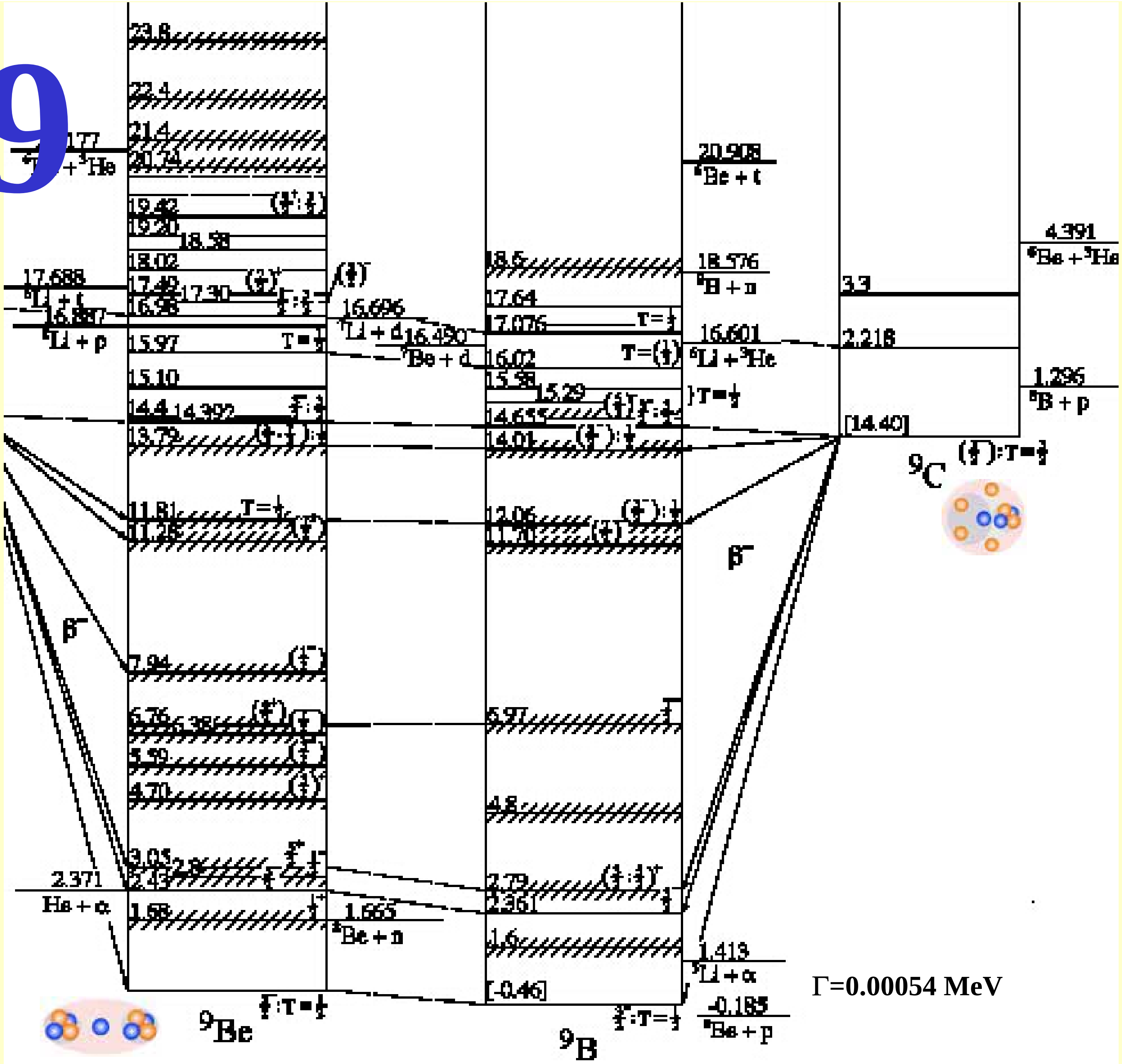
We plan to determine the probabilities

$^{8}B \rightarrow {}^{7}Bep$ (9), $^{3,4}He^{3}Hep$ (8), $^{6}Lipp$ (1), HeHHp (7) , and HHHpp (1).

A=8


Γ=0.23 MeV
(770 ms)
Γ=0.0000068 MeV
^{8}He (118 ms) , ^{8}Li (838 ms)
^{8}Be
^{8}B
^{8}C
2α
-0.0919
17.2550
^{7}Li+p
22.2804
^{6}Li+d
21.41
^{5}Li+t
19.07
20.2
22.2
22.05
3.06
11.35
16.92
16.63
17.64
18.15
18.91
27.494
(28.6)
(32)
(41)
(43)
25.2
25.5
24.0
22.63
22.98
22.0
21.5
20.9
19.4
19.9
20.1
19.24
8.5887
^{6}Be+d
21.284
^{3}He+^{5}He
18.8992
^{7}Be+n
β$^+$
β$^-$
10.619
3.5
2.32
0.77
[16.36]
3.41
1.7241
0.1375
^{7}Be+p
-1.82
-3.5132
[26.32]
0.0650
^{7}B+p
-2.1421
^{6}Be+2p

A=9

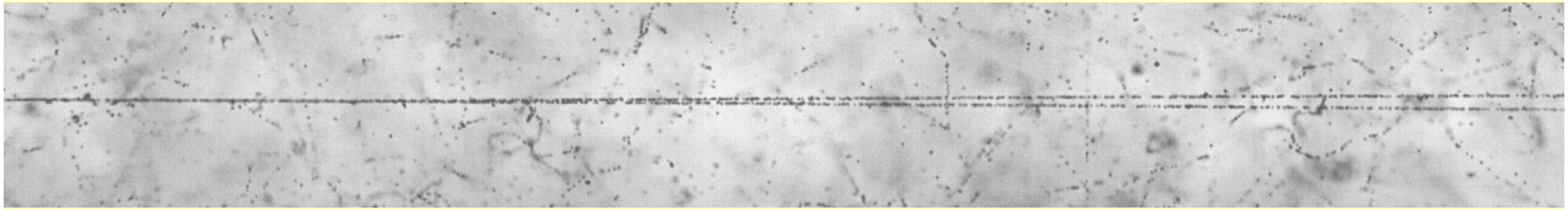


^{9}Be
^{9}B
^{9}C
β⁻
Γ=0.00054 MeV
2.371
He + α
1.665
^{8}Be + n
16.696
^{7}Li + d
16.490
^{7}Be + d
17.688
15.97
1.413
-0.185
^{8}Be + p
20.908
18.576
16.601
4.391
1.296
[14.40]
[-0.46]
3.3
2.218

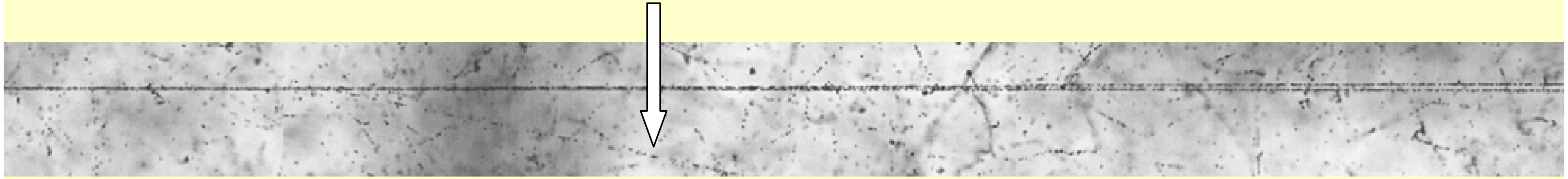
1.3A GeV ^{9}Be dissociation in 2+2.

$^{10}B \to {}^{9}Be$, Nuclotron, 2004.

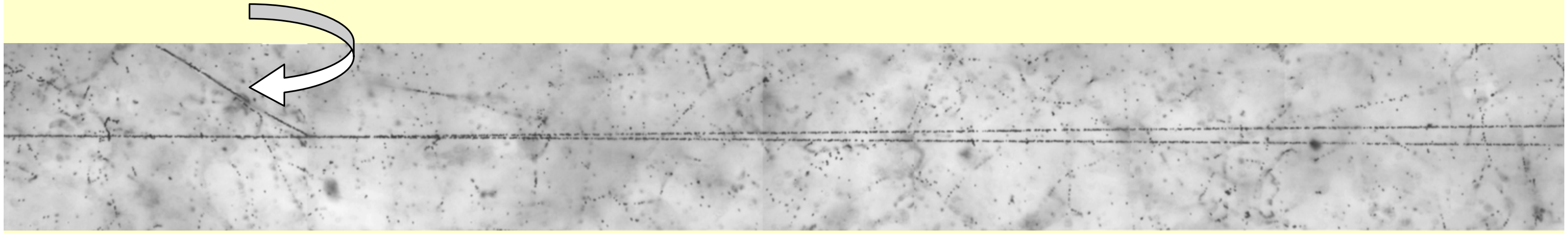
“white” star



with recoil proton



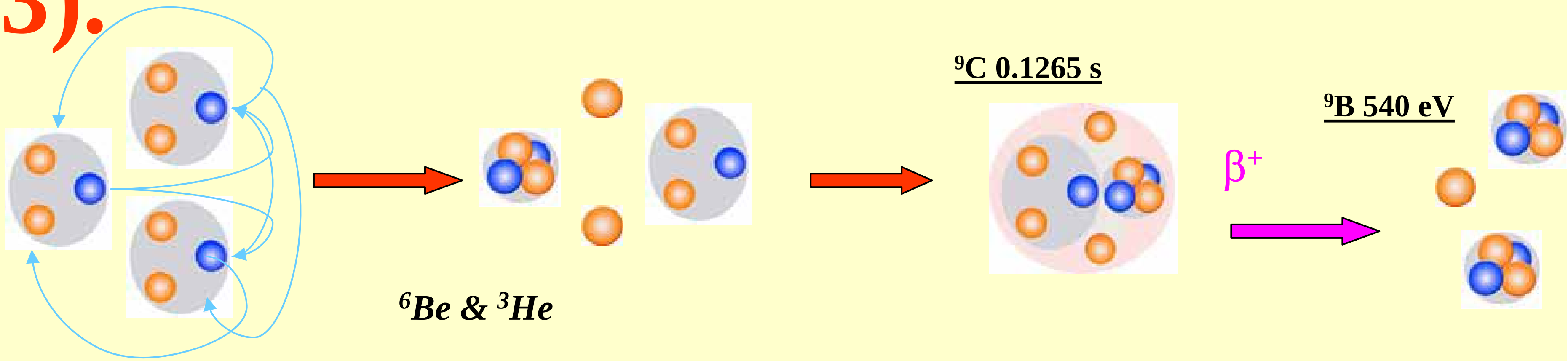
with heavy fragment of target nucleus

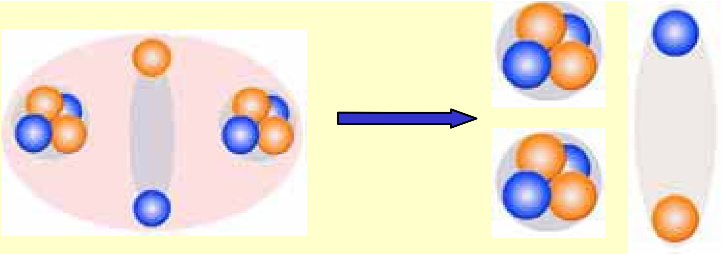


“Ternary ^{3}He Process”

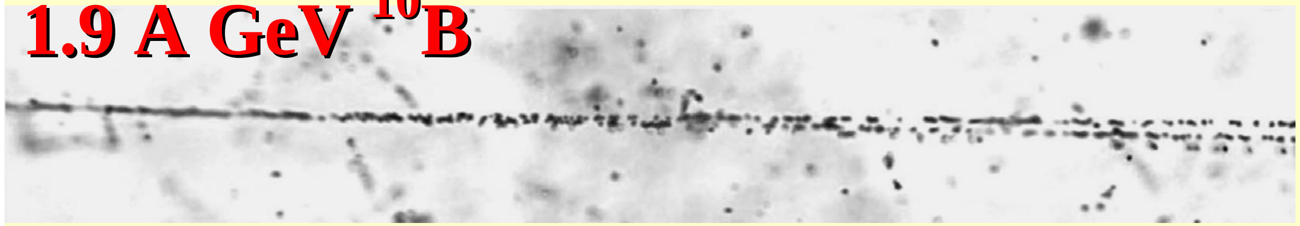
2 A GeV/c carbon beam of a magnetic rigidity Z/A = 6/9 ($^{12}C \rightarrow {}^{9}C$) was provided for emulsions to determine the probabilities

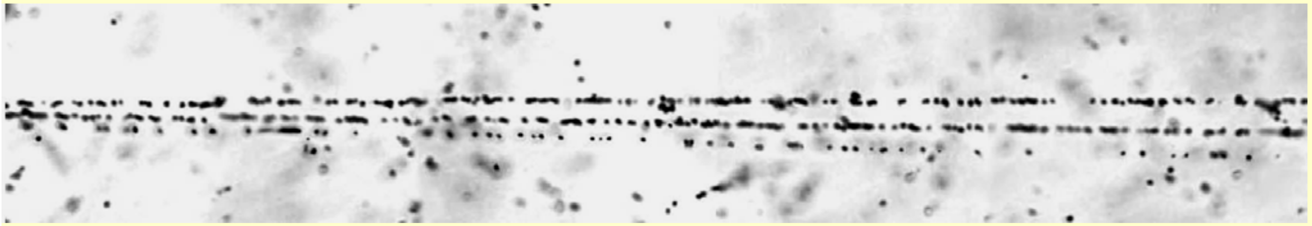
$^9C \rightarrow {}^8Bp$ (1) , ^7Bepp (2) , HeHepp (7), ^6Lipp (0) , HeHHpp (5) , HeHeHe (3).





1.9 A GeV ^{10}B





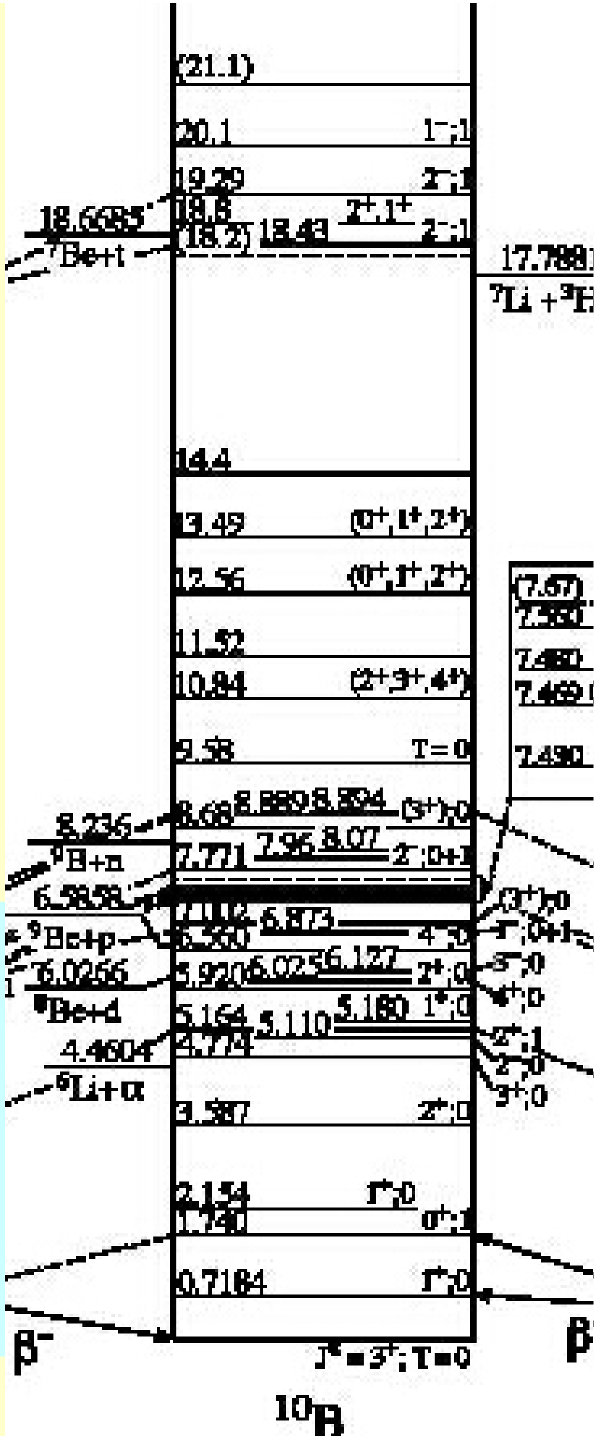
^{10}B is disintegrated to 2 doubly charged and 1singly

charged particles in 70% of “white” stars.

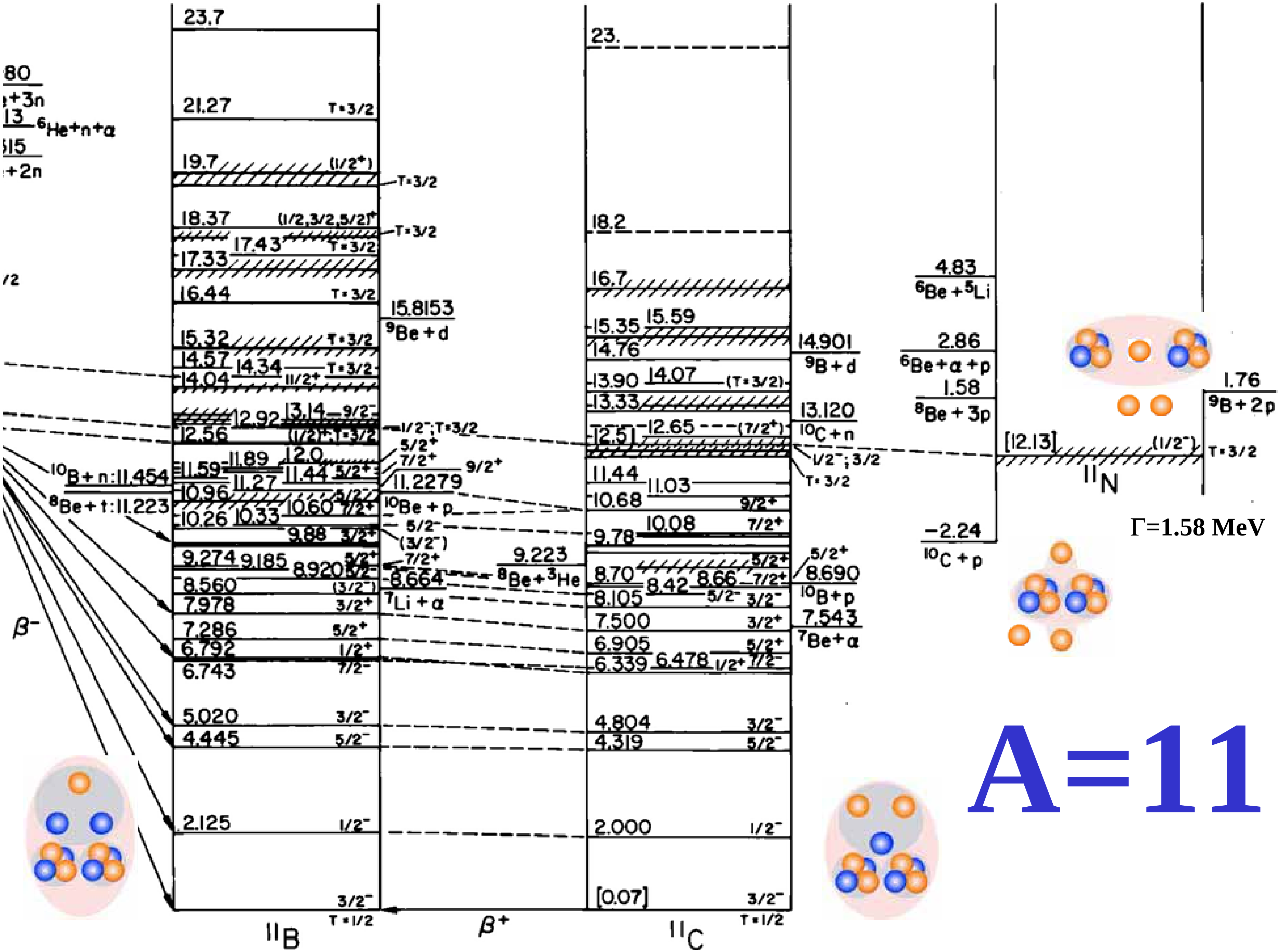
A singly charged particle is the deuteron in 40% like in case of ^{6}Li.

^{8}Be contribution is 20%.

$^{10}B \rightarrow {}^{9}Bep$ – 3%

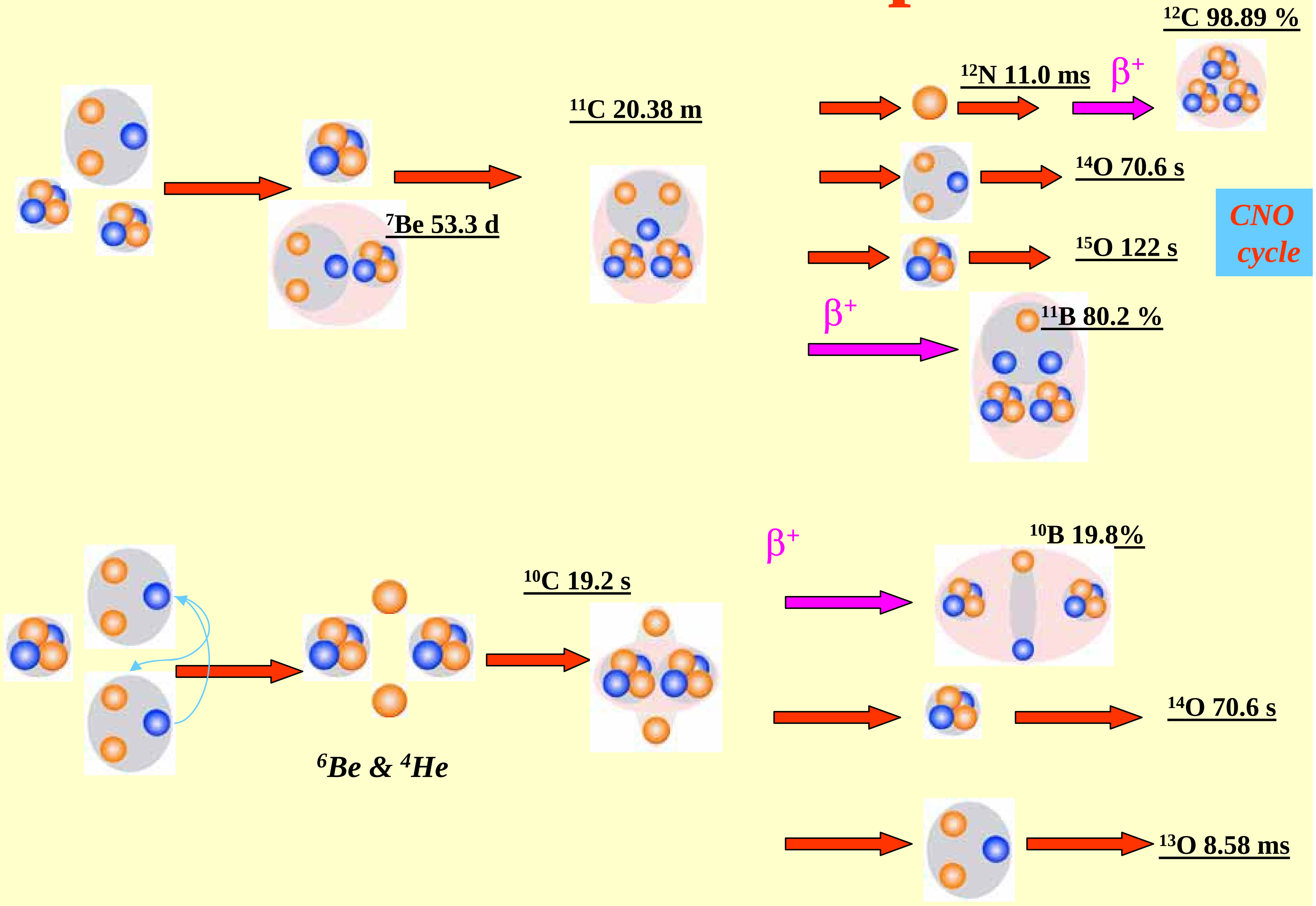


A=11

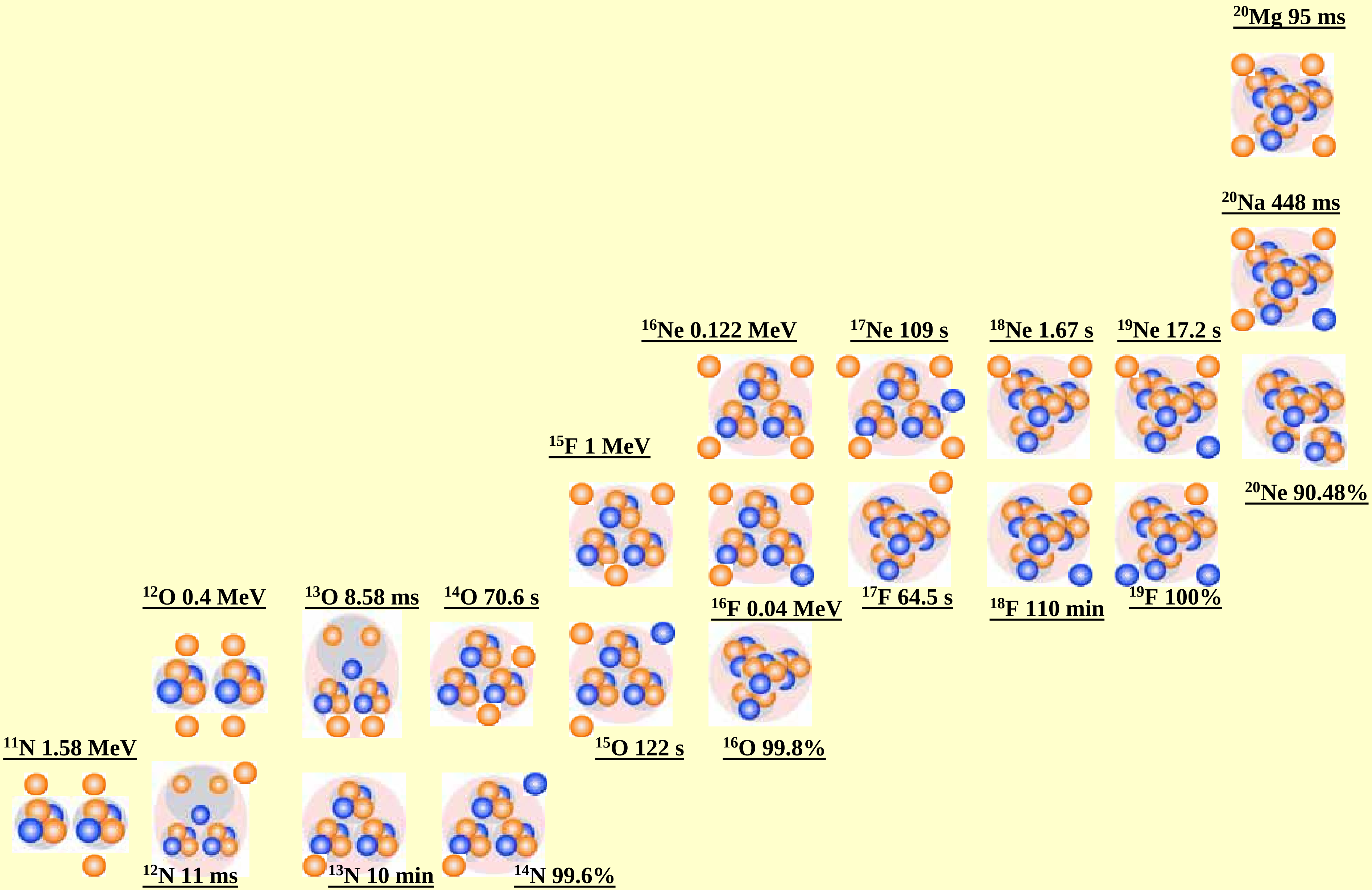


23.7
21.27
19.7
18.37
17.43
17.33
16.44
15.32
14.57
14.34
14.04
12.92
13.14
12.56
11.59
11.89
12.0
11.27
11.44
10.96
10.26
10.33
10.60
9.88
9.274
9.185
8.920
8.560
7.978
7.286
6.792
6.743
5.020
4.445
2.125
15.8153
9Be+d
11.2279
10Be+p
8.664
7Li+α
9.223
8Be+3He
10B+n:11.454
8Be+t:11.223
β−
β+
11B
T=1/2
23.
18.2
16.7
15.35
15.59
14.76
13.90
14.07
13.33
12.65
12.51
11.44
11.03
10.68
9.78
10.08
8.70
8.42
8.66
8.105
7.500
6.905
6.339
6.478
4.804
4.319
2.000
[0.07]
11C
14.901
9B+d
13.120
10C+n
8.690
10B+p
7.543
7Be+α
4.83
6Be+5Li
2.86
6Be+α+p
1.58
8Be+3p
−2.24
10C+p
[12.13]
11N
1.76
9B+2p
T=3/2
Γ=1.58 MeV

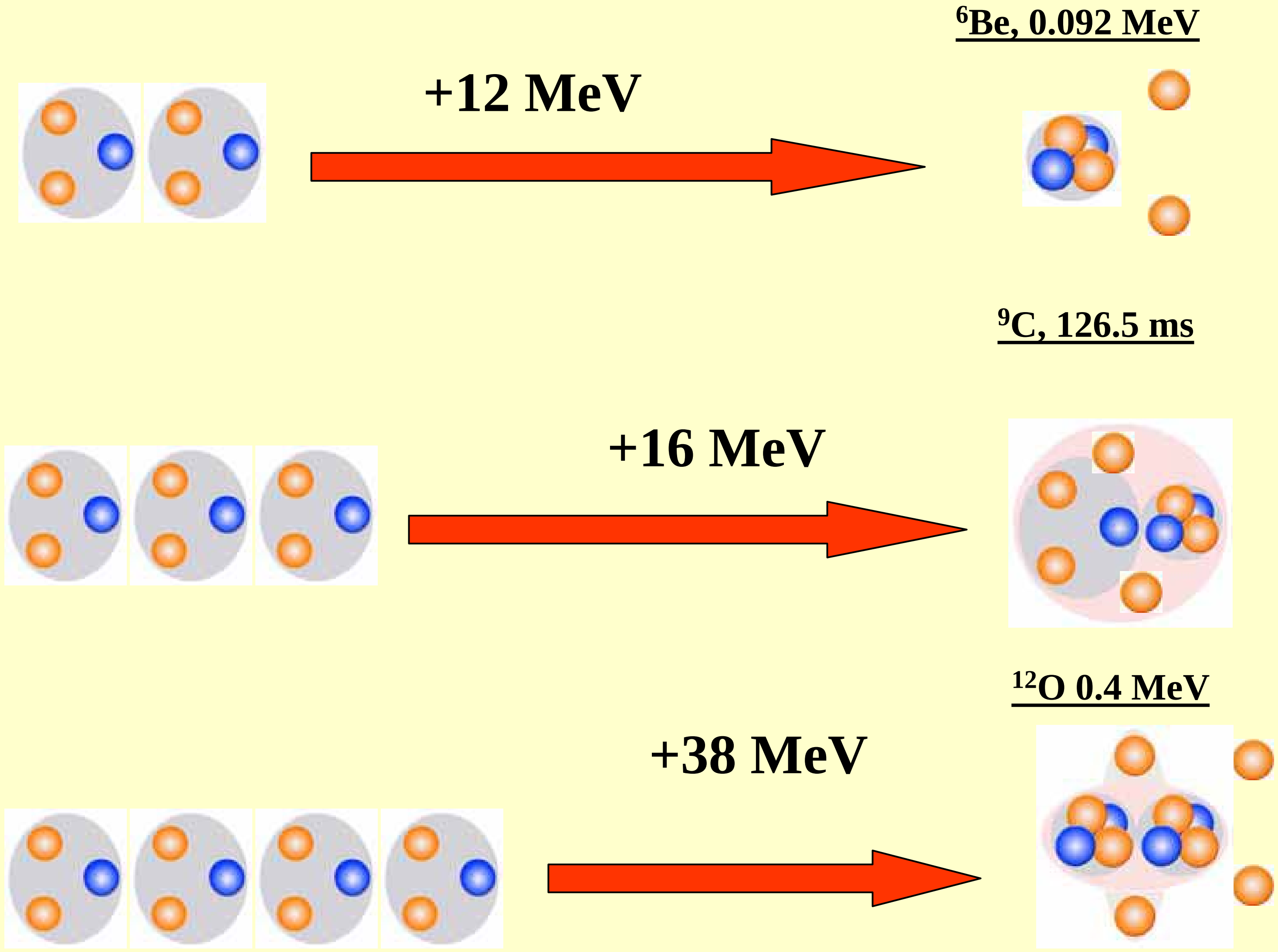
“3He Process: mixed isotope fusion”



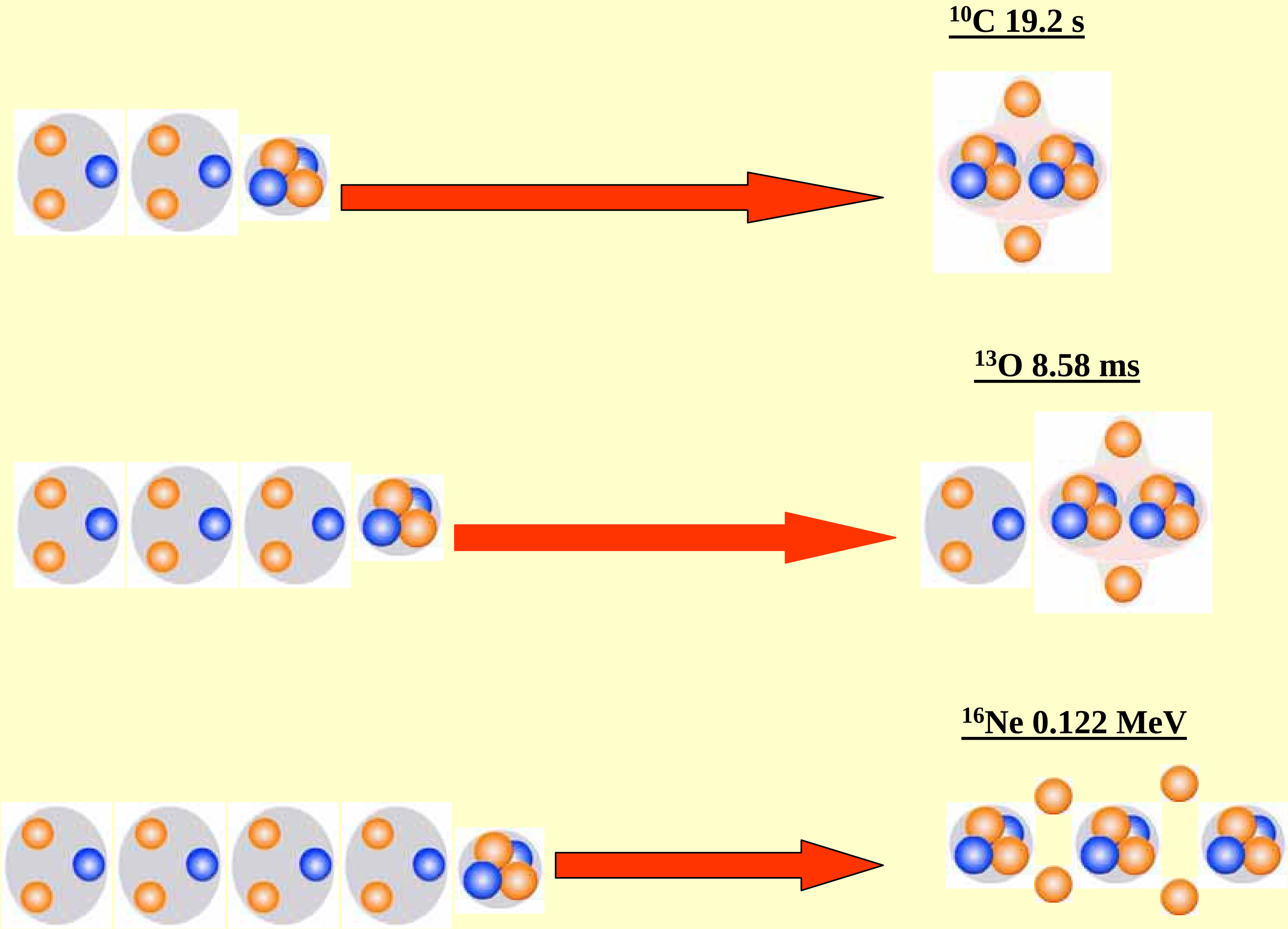
Walking along proton stability line



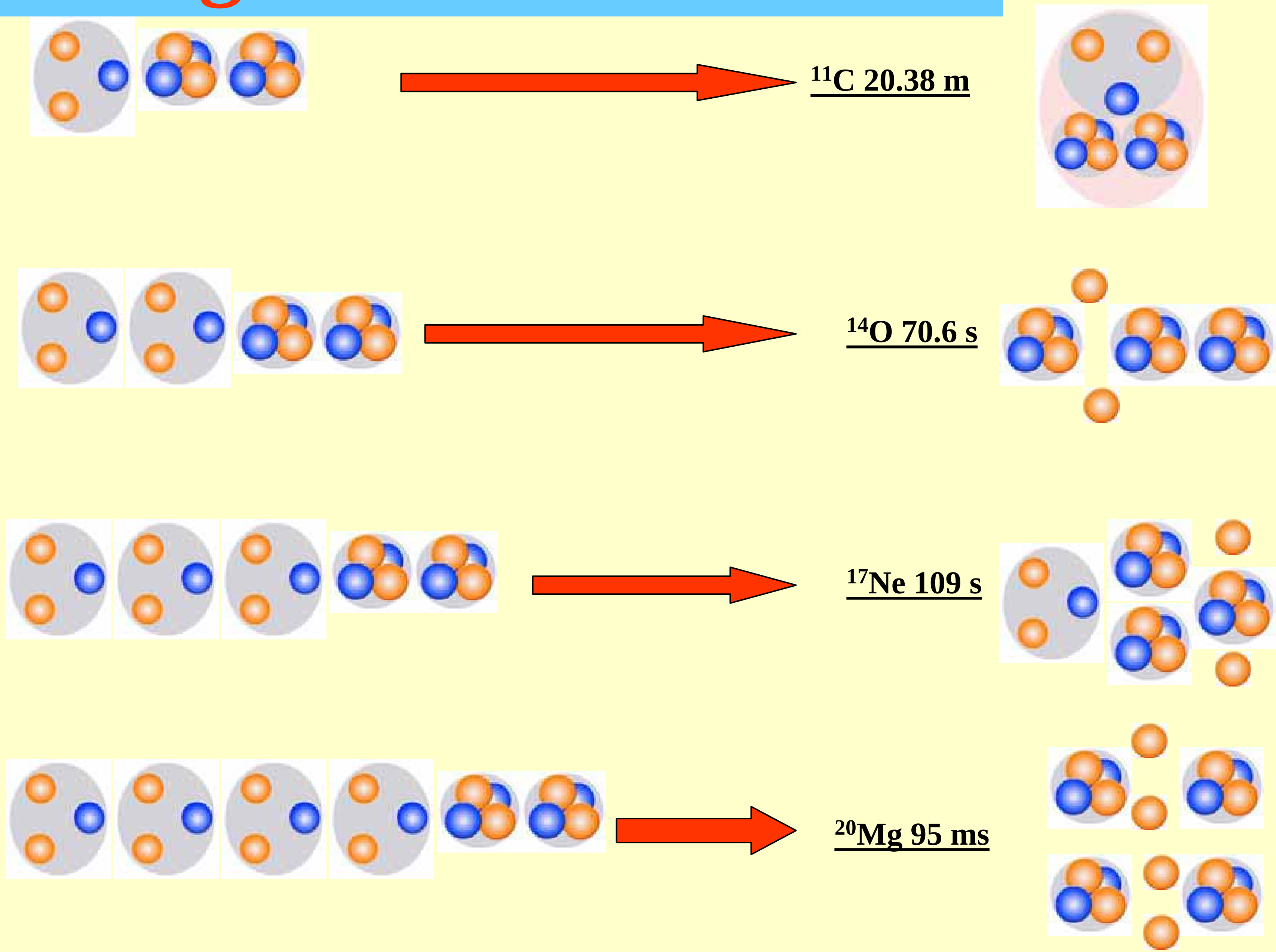
Multifragmentation in H&He



Multifragmentation in H&He



Multifragmentation in H&He

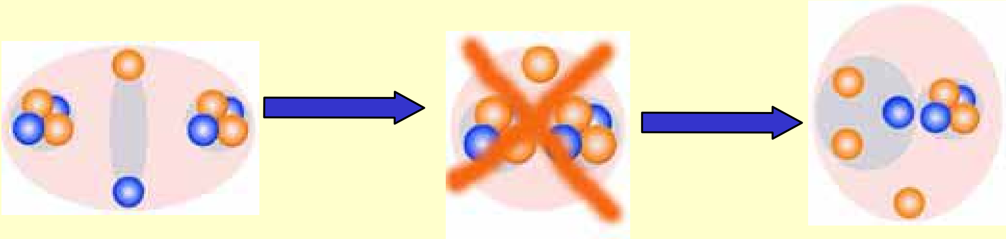


Fragmentation of relativistic nuclei provides an excellent quantum "laboratory" to explore the transition of nuclei from the ground state to a gas-like phase composed of nucleons and few-nucleon clusters having no excited states, i. e. d, t, ^{3}He, and α.

The research challenge is to find indications for the formation of quasi-stable systems significantly exceeding the sizes of the fragments.

Search for such states is of interest since they can play a role of intermediate states for a stellar nuclear fusion due to dramatically reduced Coulomb repulsion.

The fragmentation features might assist one to disclose the scenarios of few-body fusions as processes inverse to fragmentation.



2 A GeV/c $^{10}B \rightarrow {}^{8}B$