Correlation between E_{CM}/u and unexplained experimental observables

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Normal nuclear reaction studies:

- Thin targets (µm to mm)
- Mono-energetic projectiles

yield differential data

e.g. Energy loss or cross-sections for

- Reaction mechanisms like: fusion, fusion-fission, deep inelastic, QET, fragmentation, …

- Reaction products, e.g. individual isotopes

- Production of secondary particles, e.g. $\pi^{+,-,0}$, n, p, d, α, ….

Some differential cross-sections are easily modelled:

e.g. total inelastic cross-section

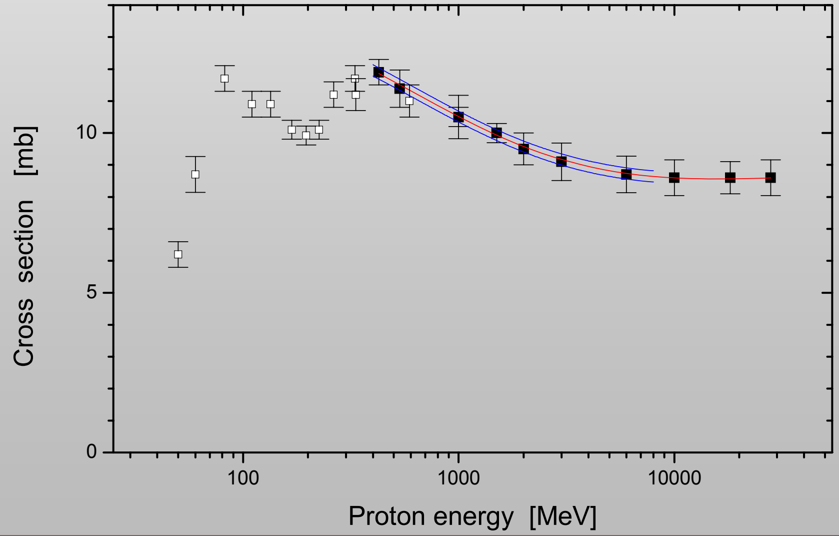
$$\sigma_i = \pi R^2 * (1 - B/\varepsilon)$$

e.g. quasielastic cross-section

$$\sigma_{QET} = \sigma_i - (10\pi (\hbar\, l(t_m))^2 / (2\mu\varepsilon)$$

Moreover, many excitation functions are well determined

Excitation function : ^{27}Al (p,3pn) ^{24}Na



A little more complicated:

Reaction in thick targets (>mm) where projectiles lose lots of energy, sometimes even down to the interaction barrier

$$\langle \sigma_i \rangle = 10\,\pi\,R^2 * (\varepsilon - B - B*\ln[\varepsilon/B]) / (\varepsilon - B)$$

Experiments that are normally avoided:

Extremely high projectile energies (GeV) on very thick targets

where secondary particles also interact

We will deal with exactly this:

Target thickness	several cm, up to 60 cm
Projectile energies	≥ 1 GeV/amu

Consequence:

- integral data (= sum of many differential data?)
- many reactions of secondaries

Modelling via Monte-Carlo

There are only few experimental results available

Experiment (Vassilko et al.): neutron production in 60 cm long Pb-target having 20 cm Ø

Ion	*Mass A*	*Number of neutrons n at 1 GeV per nucleon*	*Number of neutrons n at 3.7 GeV per nucleon*	$\frac{n \text{ at } (E_{Total}/A=3.7\text{ GeV})}{n \text{ at } (E_{Total}/A=1.0\text{ GeV})}$
H	1	21.3 ± 0.6	68.1 ± 2.5	**3.2 ± 0.2**
H	2	45.8 ± 1.2	157 ± 3	3.4 ± 0.2
α	4	71.2 ± 2.8	277 ± 9	3.9 ± 0.2
C	12	129 ± 5	641 ± 22	**5.0 ± 0.3**

Theory: Calculations with MCNPX 2.7a

Ion	*Mass A*	*Number of neutrons n at 1 GeV per nucleon*	*Number of neutrons n at 3.7 GeV per nucleon*	$\frac{n \text{ at } (E_{Total}/A=3.7\text{ GeV})}{n \text{ at } (E_{Total}/A=1.0\text{ GeV})}$
H	1	23.5	73.4	**3.1**
H	2	48.0	118.9	2.5
α	4	77.5	201.6	2.6
C	12	**134.8**	**494.3**	**3.7**

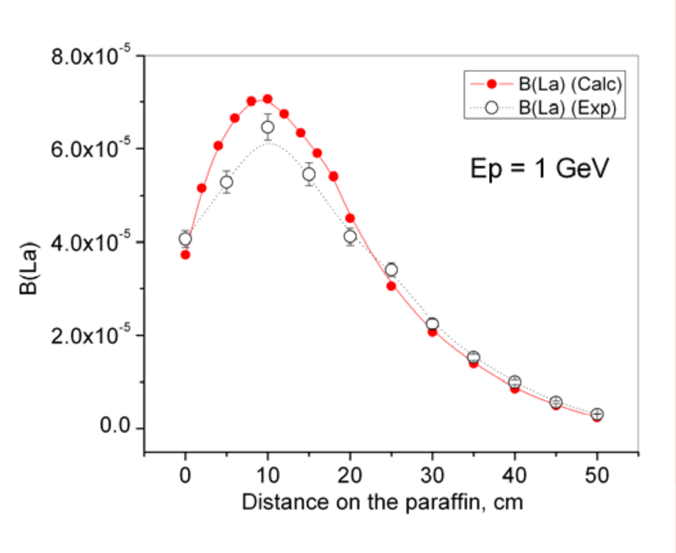
Measurement of neutron density on GAMMA-2

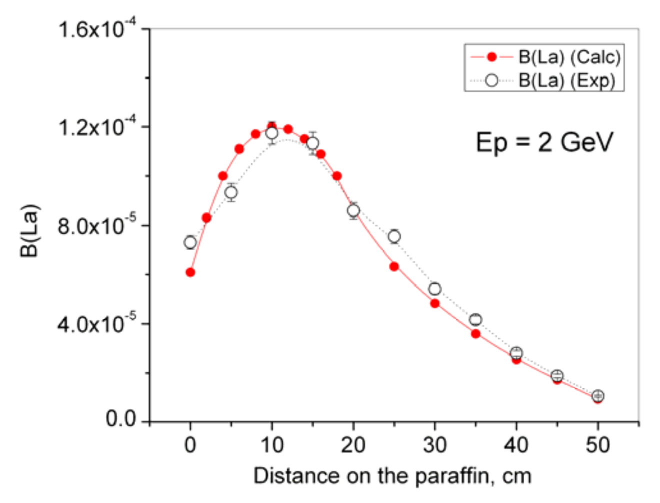
Spallation core :
8 cm diameter,
20 cm or 50 cm long
Lead or Copper

Moderator:
6 cm thick paraffin

The B-value for production of ^{140}La is measured on top of the moderator → neutron density

Experiment: Protons on 50 cm Pb-target, (n,γ)-reactions on top of 6 cm thick paraffin moderator

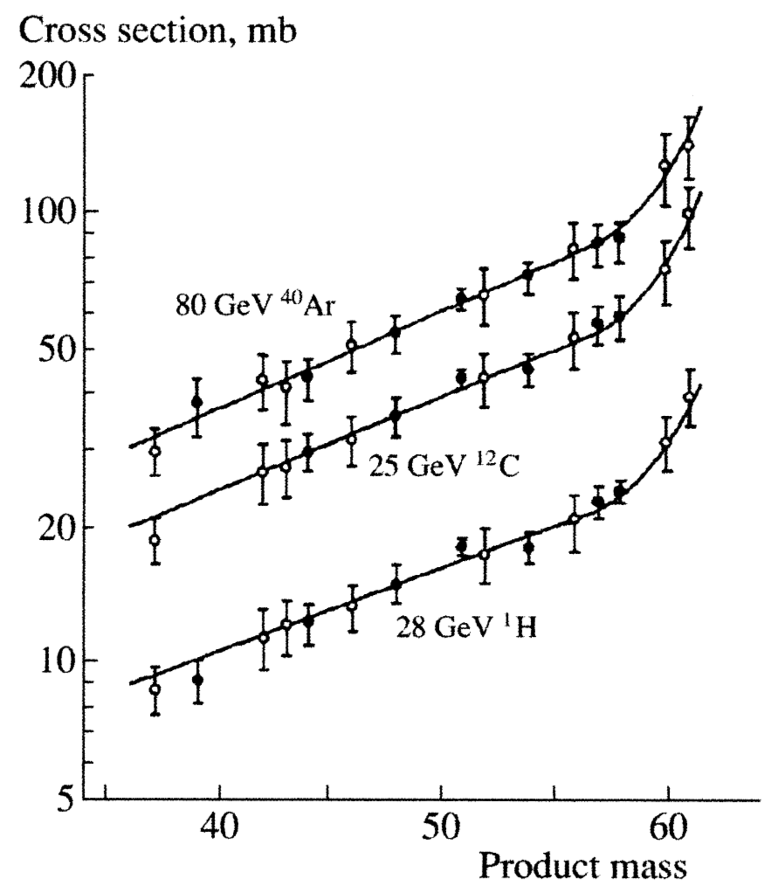




Calculation with MCNPX: Beam scattering – fast cascade – evaporation - neutron transport – n-secondary reactions – (n,γ)-reaction with a neutron spectrum

<Agreement>: @ 1 GeV ± 7%, @ 2 GeV ± 2%

Example: High energy projectiles on a thin Cu-target

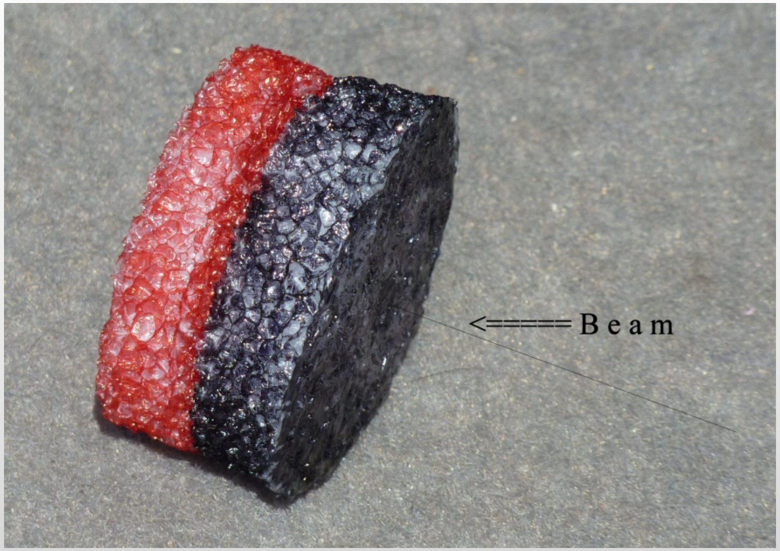


„Limited Fragmentation“ means:
highest cross-section near target mass,
the distribution falls with rising ΔA.

„Factorisation“ means:
product distributions in the same target are similar, just scaling in cross-section with projectile mass and energy.

Limited Fragmentation and Factorisation are always valid in thin targets.

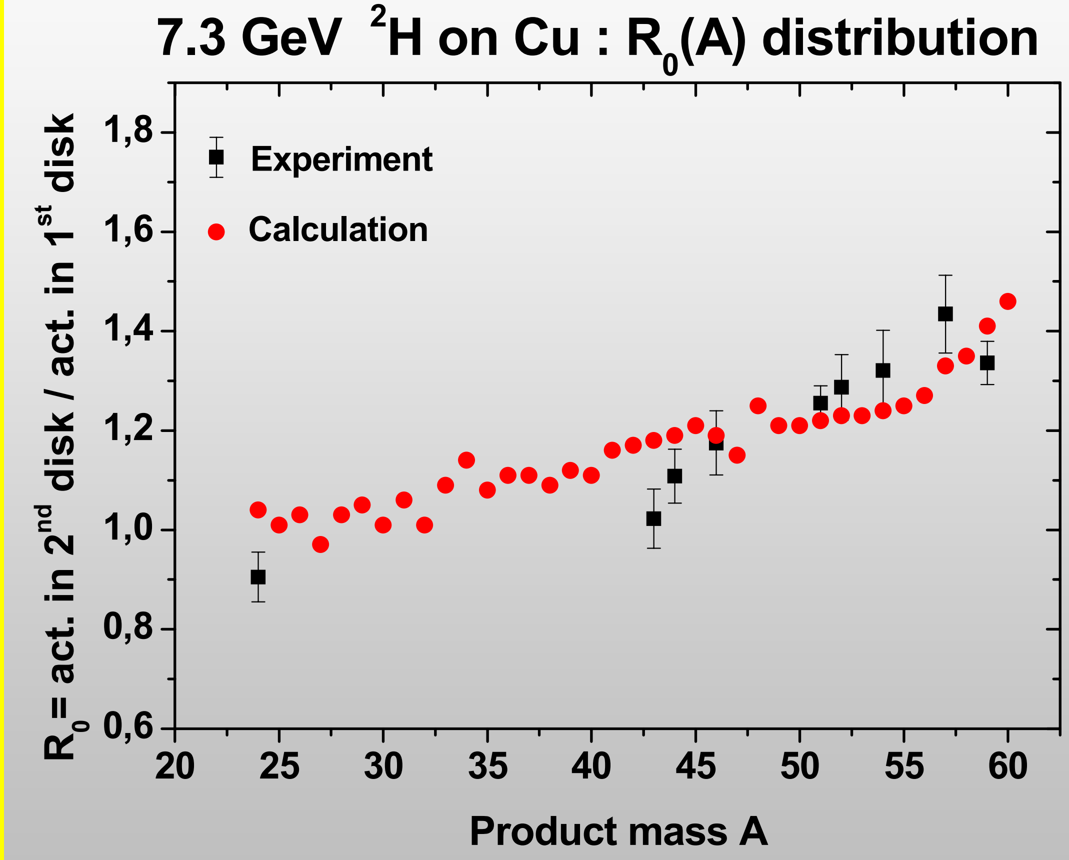
What happens in thick targets (theory)?



- Second target is exposed to less full-energy beam = less products
- Additional secondaries with lower energy hit second target = more products just below the target mass

- **R_0=N(2)/N(1) is ≤1 far away from the target mass**
  is ≥1 near to the target mass
- **As most secondaries have low energies the maximum of R_0 is just below target mass**

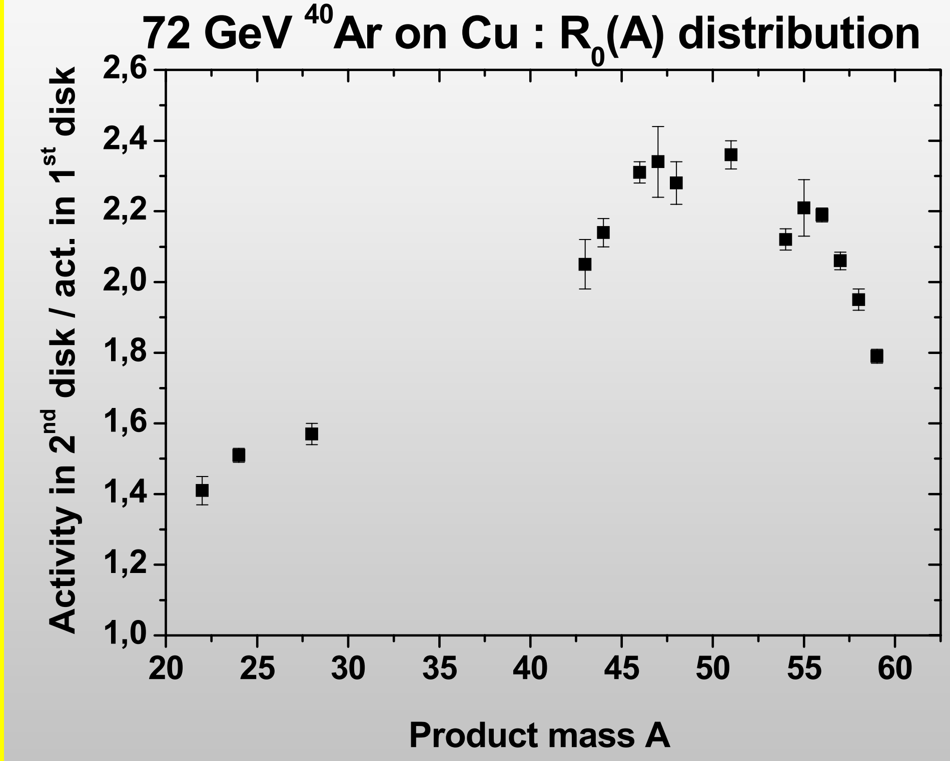
What happens in thick target (experiment)?



It fits !

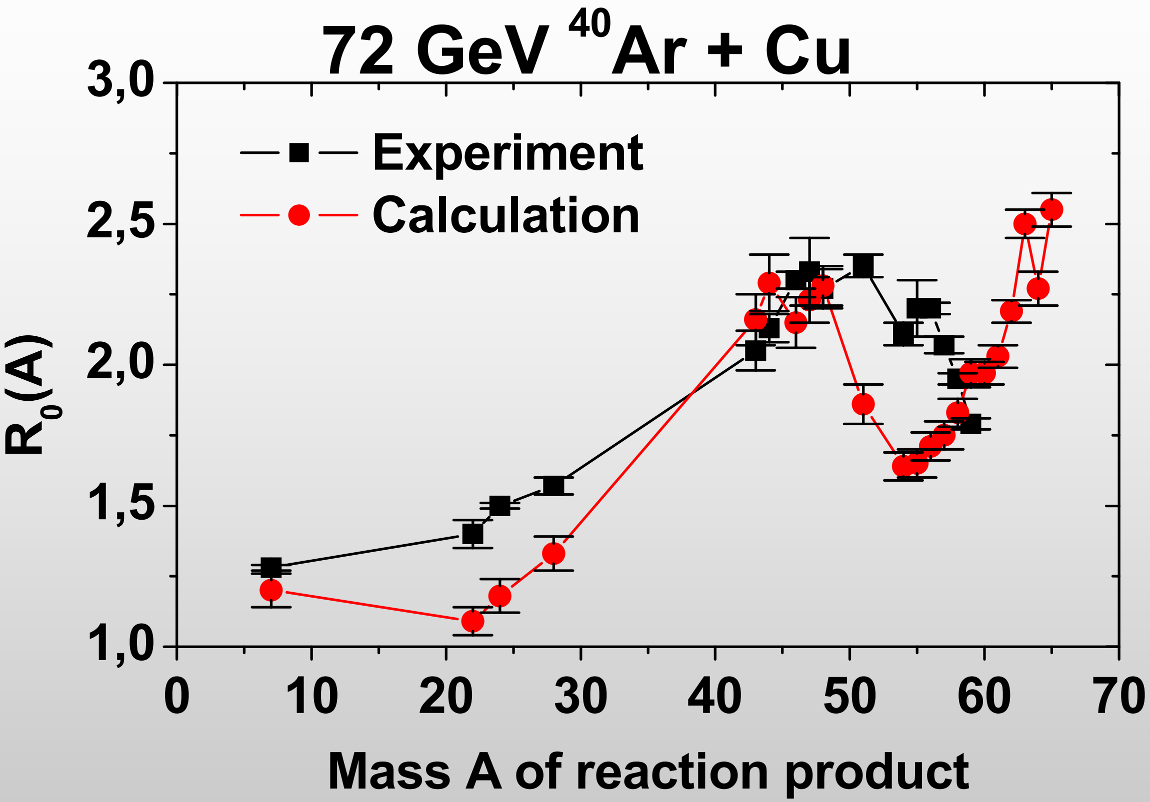
R_0 of very distant fragmentation product ^{24}Na is expected to be always unity or less

But : not at higher energy !



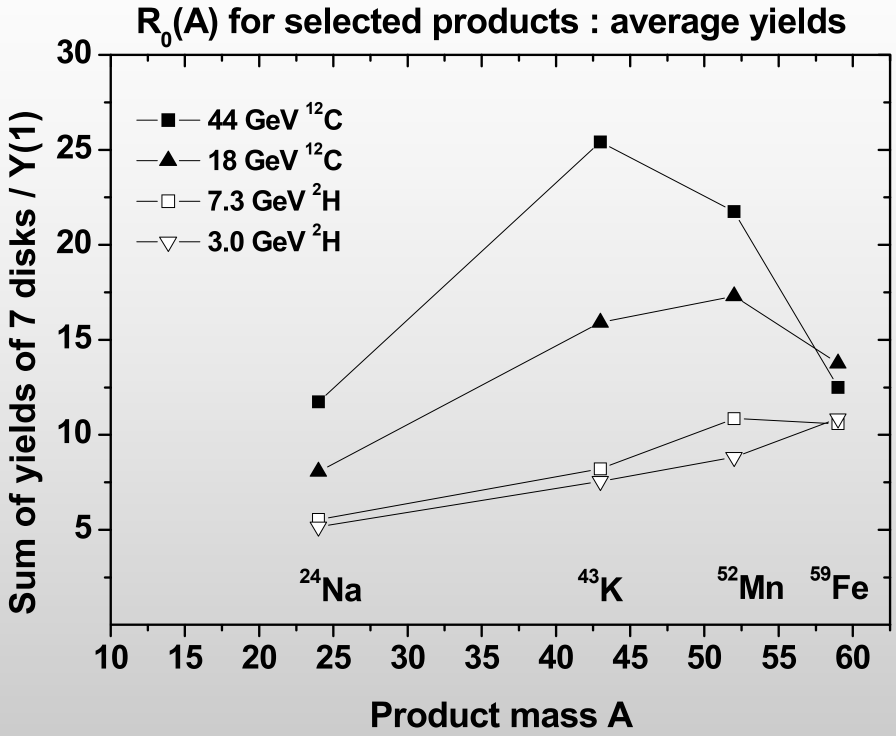
R_0 of ^{24}Na is >> 1

The maximum is far away from the target mass



Calculation with MCNPX cannot fit the experiment

Cross-sections are „pushed“ to smaller masses and forward into the second target!



Identical results in a stack of 20 targets of 1-cm thickness

At higher beam energy cross sections are pushed to smaller mass (bigger ΔA) and into forward targets!

It looks as if secondaries would transfer more energy than expected

R of ^{24}Na was determined in many experiments

48 GeV	^{4}He+Cu	1.21±0.02
44 GeV	^{12}C+Cu	1.24±0.02
72 GeV	^{40}Ar+Cu	1.50±0.02
24 GeV	^{1}H+Cu	1.10±0.02
25 GeV	^{12}C+Cu	1.13±0.03
36 GeV	^{40}Ar+Cu	1.17±0.02
18 GeV	^{12}C+Cu	1.08±0.10
22 GeV	^{22}Ne+Cu	1.08±0.02

At high beam energy (unexpected) > 1

Maxima in R(A) are far away from target mass

7.3 GeV	^{2}H+Cu	0.90±0.05
4.5 GeV	^{1}H+Cu	0.98±0.05
4 GeV	^{4}He+Cu	0.92±0.01
3 GeV	^{4}He+Cu	0.90±0.05
2.6 GeV	^{1}H+Cu	0.96±0.02
1.3 GeV	^{1}H+Cu	0.99±0.03

At low beam energy (as expected) < 1

Maxima in R(A) are close to target mass

Neutrons: Comparison with MCNPX calculation

72 GeV	^{40}Ar+Cu	Discrepancy
44 GeV	^{12}C+Cu	Discrepancy
44 GeV	^{12}C+Pb	Discrepancy
44 GeV	^{12}C+U	Discrepancy
7.4 GeV	^{2}H+Cu	ok
14.7GeV	^{4}He+Pb	ok
3 GeV	^{2}H+Cu	ok
7.4 GeV	^{2}H+Pb	ok
6 GeV	^{4}He+Pb	ok
3 GeV	^{4}H+Pb	ok
2 GeV	^{2}H+Pb	ok
1 GeV	^{2}H+Pb	ok

At low energies : Experiment = Calculation
At high energies : Experiment >> Calculation

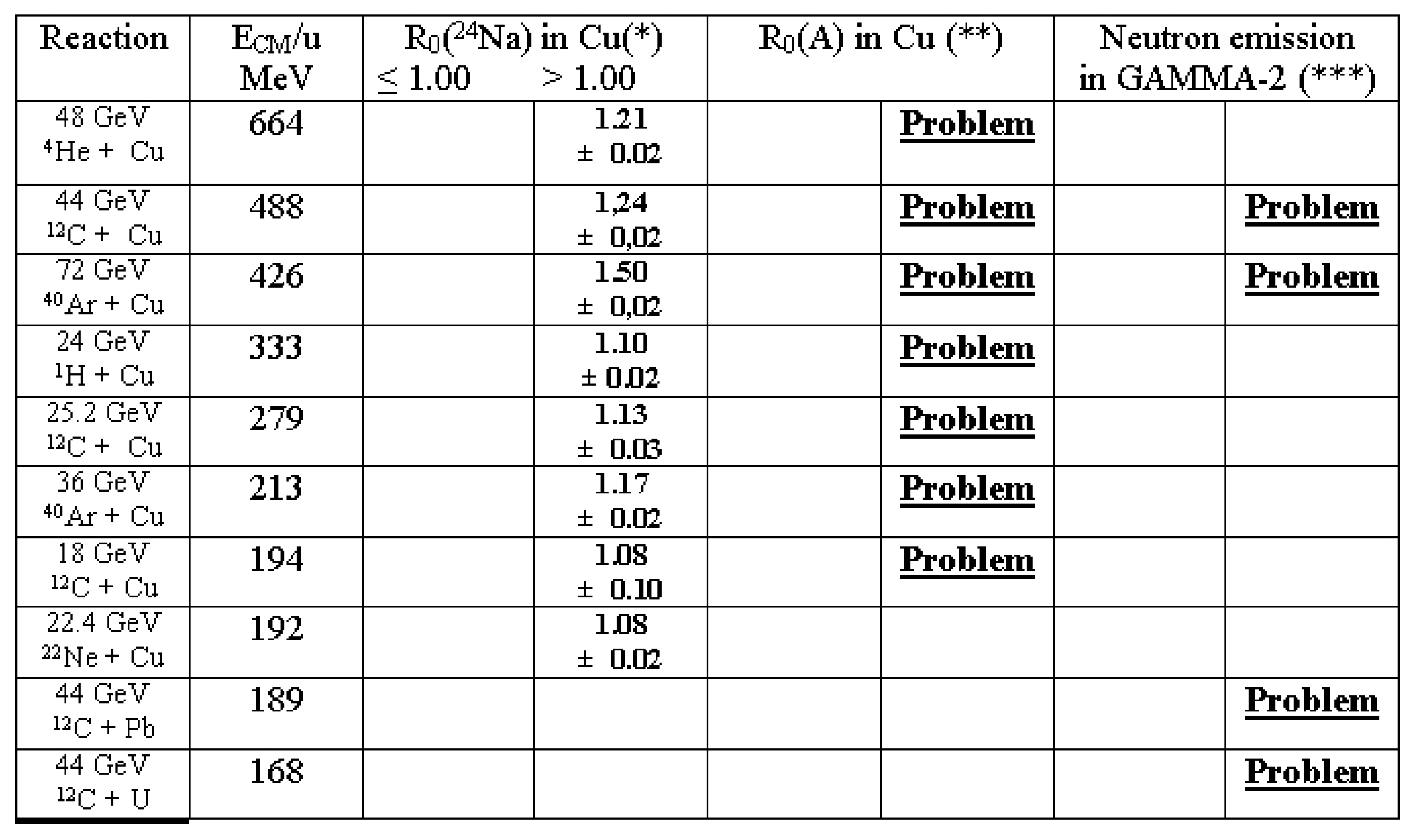
What is the transition energy?

Energy in system is $E_{CM} = E_{lab} * A_T / (A_P+A_T)$

Assumption:
It looks as if more energy were transferred (by secondaries?) than expected.

Thus, data are scaled in units of CM energy per nucleon E_{CM}/u

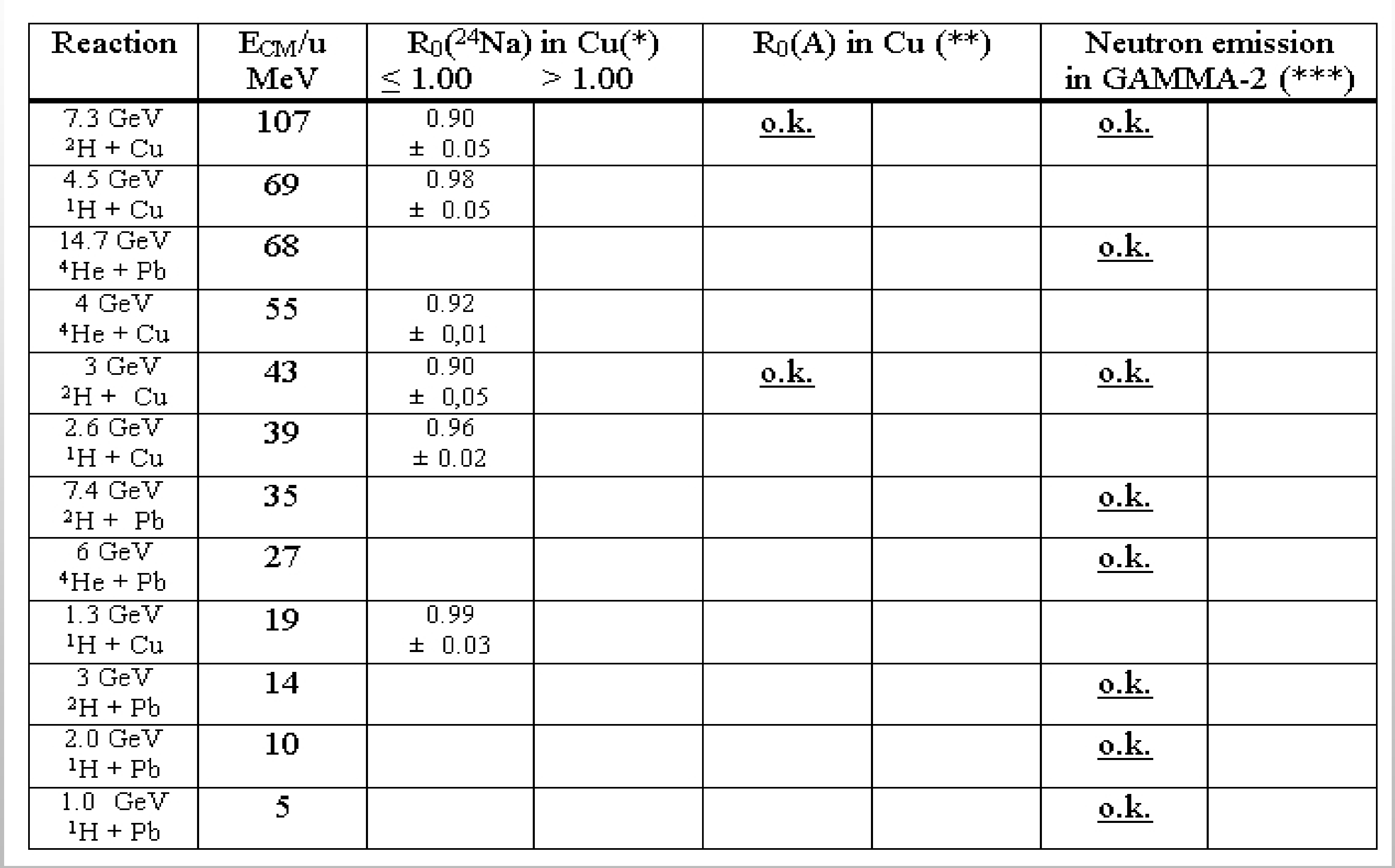
$$E_{CM}/u = E_{CM} / (A_P+A_T)$$



Reaction	E_{CM}/u MeV	$R_0(^{24}Na)$ in Cu(*)		$R_0(A)$ in Cu (**)		Neutron emission in GAMMA-2 (***)	
		≤ 1.00	> 1.00				
48 GeV ^4He + Cu	664		1.21 ± 0.02		**Problem**		
44 GeV ^{12}C + Cu	488		1,24 ± 0,02		**Problem**		**Problem**
72 GeV ^{40}Ar + Cu	426		1.50 ± 0,02		**Problem**		**Problem**
24 GeV ^1H + Cu	333		1.10 ± 0.02		**Problem**		
25.2 GeV ^{12}C + Cu	279		1.13 ± 0.03		**Problem**		
36 GeV ^{40}Ar + Cu	213		1.17 ± 0.02		**Problem**		
18 GeV ^{12}C + Cu	194		1.08 ± 0.10		**Problem**		
22.4 GeV ^{22}Ne + Cu	192		1.08 ± 0.02				
44 GeV ^{12}C + Pb	189						**Problem**
44 GeV ^{12}C + U	168						**Problem**

Transition is between E_{CM}/u = 168 MeV …..

…… and 107 MeV



Reaction	E_{CM}/u MeV	R_0(^{24}Na) in Cu(*)		R_0(A) in Cu (**)		Neutron emission in GAMMA-2 (***)	
		≤ 1.00	> 1.00				
7.3 GeV ^{2}H + Cu	**107**	0.90 ± 0.05		<u>o.k.</u>		<u>o.k.</u>	
4.5 GeV ^{1}H + Cu	**69**	0.98 ± 0.05					
14.7 GeV ^{4}He + Pb	**68**					<u>o.k.</u>	
4 GeV ^{4}He + Cu	**55**	0.92 ± 0,01					
3 GeV ^{2}H + Cu	**43**	0.90 ± 0,05		<u>o.k.</u>		<u>o.k.</u>	
2.6 GeV ^{1}H + Cu	**39**	0.96 ± 0.02					
7.4 GeV ^{2}H + Pb	**35**					<u>o.k.</u>	
6 GeV ^{4}He + Pb	**27**					<u>o.k.</u>	
1.3 GeV ^{1}H + Cu	**19**	0.99 ± 0.03					
3 GeV ^{2}H + Pb	**14**					<u>o.k.</u>	
2.0 GeV ^{1}H + Pb	**10**					<u>o.k.</u>	
1.0 GeV ^{1}H + Pb	**5**					<u>o.k.</u>	

Unexplained experimental observables

Conclusion: there is a critical energy E_{CM}/u above which unexpected results are measured

- neutron multiplicity exceeds calculations
- „limiting fragmentation“ concept fails
- R_0 of distant fragmentation products (e.g. ^{24}Na from Cu) is >1

The critical energy Ě is around 107 MeV < Ě < 168 MeV

(This is NOT “cold fusion” or “poly-water” – it’s real)

n.b. in this energy range there is another (the same?) critical energy

the Hagedorn-limit

(R. Hagedorn, Supp. Al Nuovo Cimento 2 (1965) 147)

Hagedorn: There is a limit in nuclear temperature, T_0, above which it is easier to produce particles than to increase T

From elastic scattering : $\boldsymbol{T_0}$ **= 158 ± 3 MeV**

Proposed experiment:

- **irradiate 2 thick Cu-targets with ^{12}C, 2*10^{12} in each experiment**
- **energies : 0.6, 0.9, 1.1, 1.2, 1.3, 1.5 and 1.8 GeV/u**
- **γ-spectrometric measurement of products, determine $R_{(A)}$**
- **if possible, independent measurement of neutron densities**

If there is a critical energy (limiting temperature) then one should find a gradual transition from explained to unexplained results

How much is neutron density enhanced?

a) Experimental B-value of ^{140}La is a measure of neutron density

b) Calculate the number of neutrons N per projectile atom

Thus, V = B/N characterizes the neutron density in units of the expected (calculated) density

In „normal“ reactions : V = 0.319±0.017 [10^{-5} g^{-1} $neutron^{-1}$]

In “other” reactions: V = 0.963±0.043 [10^{-5} g^{-1} $neutron^{-1}$]
(all 44 GeV ^{12}C)

Factor 3.0 ± 0.2

- We do not know the physics behind
- But we do have a means of classification

This is NOT "cold fusion" or "poly-water" – it's real

Thank you!

References:

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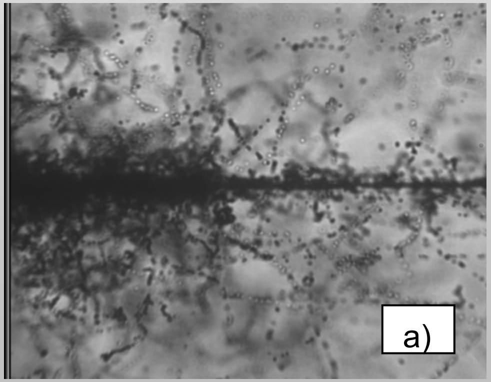
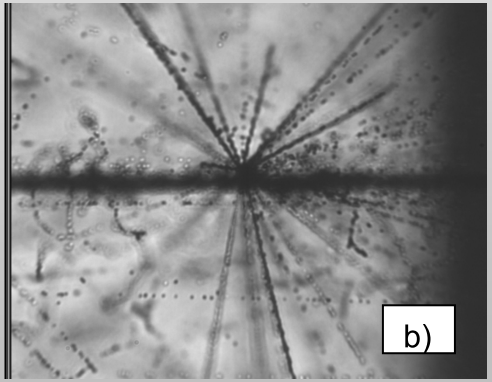
- R. Hagedorn, Supplemento Al Nuovo Cimento **2** (1965) 147
- R. Brandt et al., Phys. Rev. **C45** (1992) 1194
- O.V. Levitskaja, XVIII. ISHEPP (2006), personal communication

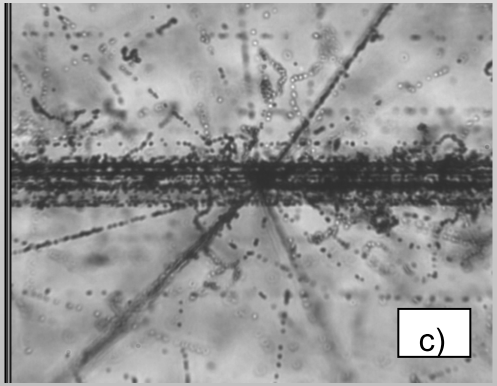
Experiments at very very high energies

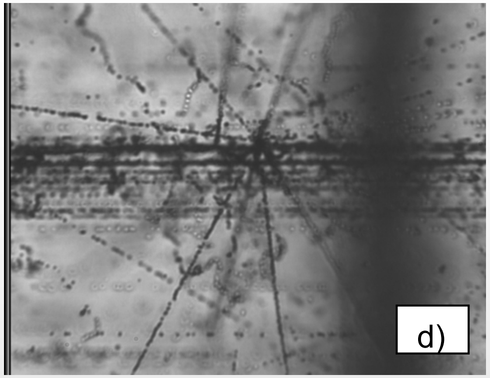
Brandt et al. (1992): R(^{24}Na) at 7000 GeV ^{32}S + Cu is 1.8 ± 0.1

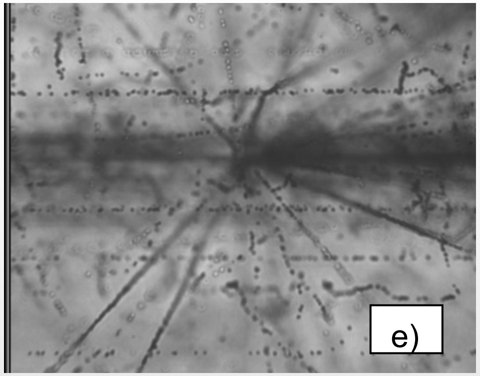
Levitskaja: very short mean free path at 32500 GeV ^{208}Pb in emulsion (H, C, N, O, Br, Ag)

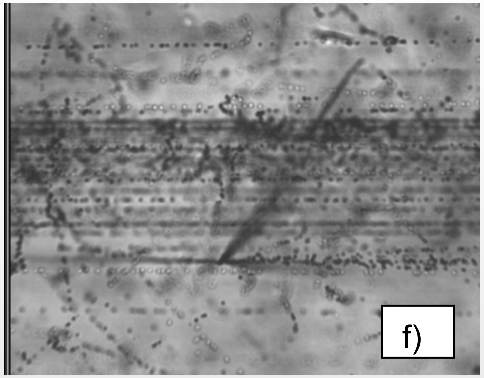


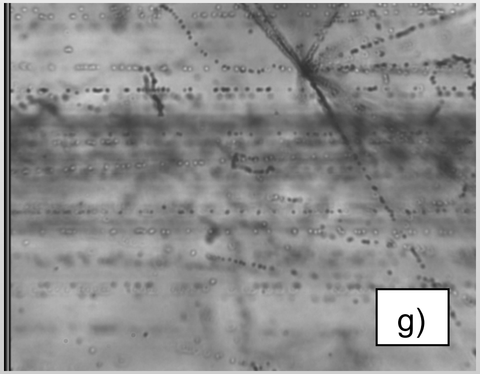






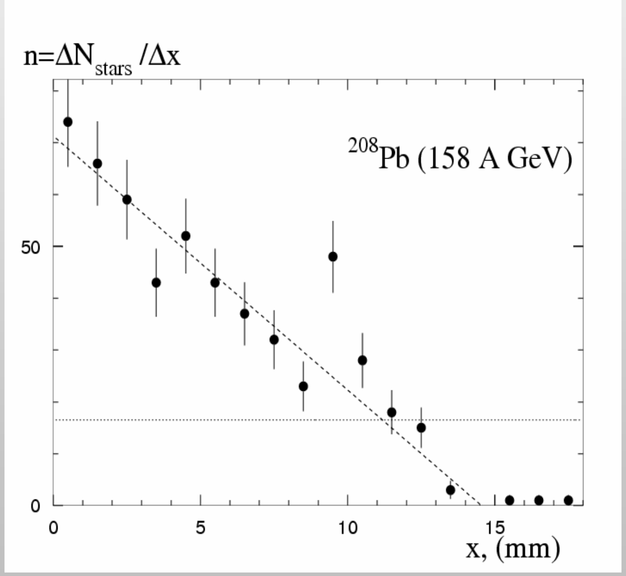






7 „stars“ in 19 mm

Analysis of 350 Pb-tracks yields this density distribution of „stars“



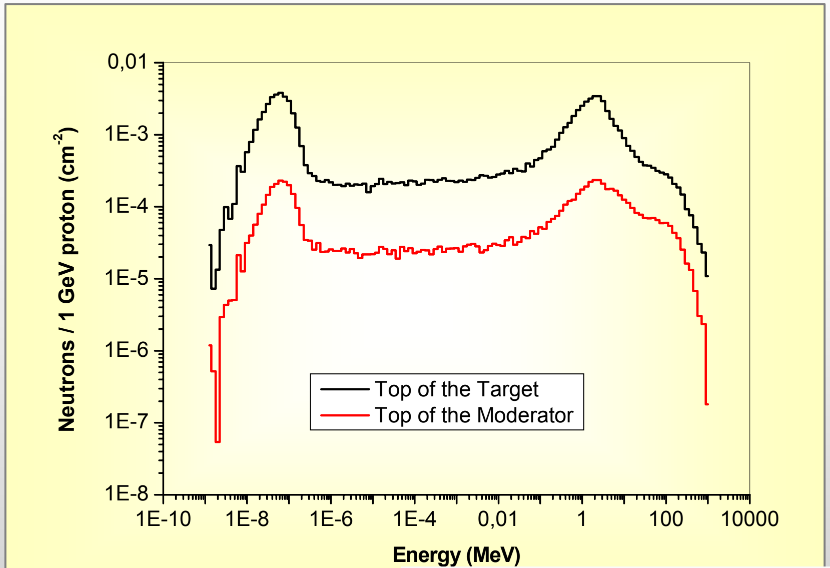
Mean free path = 0.62±0.24 cm

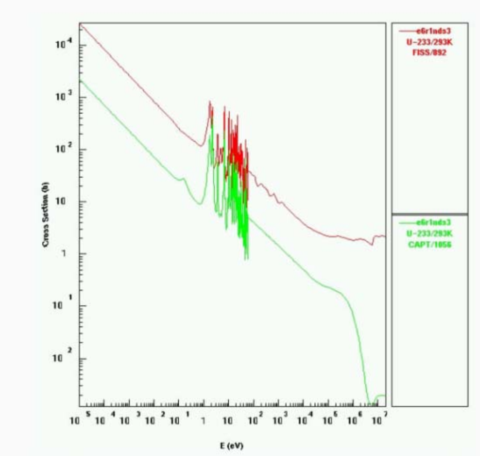
(Expected: ~ 30 cm)

(Alexander et al. (1957): MFP(π^+) 11 ± 2.4 cm; expected 31 ± 2 cm)

B-value of reactions with spallation neutrons

- Spallation neutrons have a very broad spectrum
- Cross-section depends strongly on E_n





$$\sigma_{tot} = \int_E \sigma_E \bullet I_E \, \partial E \qquad \textbf{(no way)}$$

B = Number of product atoms
per one projectile
per 1 gram of target material

B goes up with I (if spectrum unchanged)