Генерация нейтронов мюонами космических лучей в различных материалах

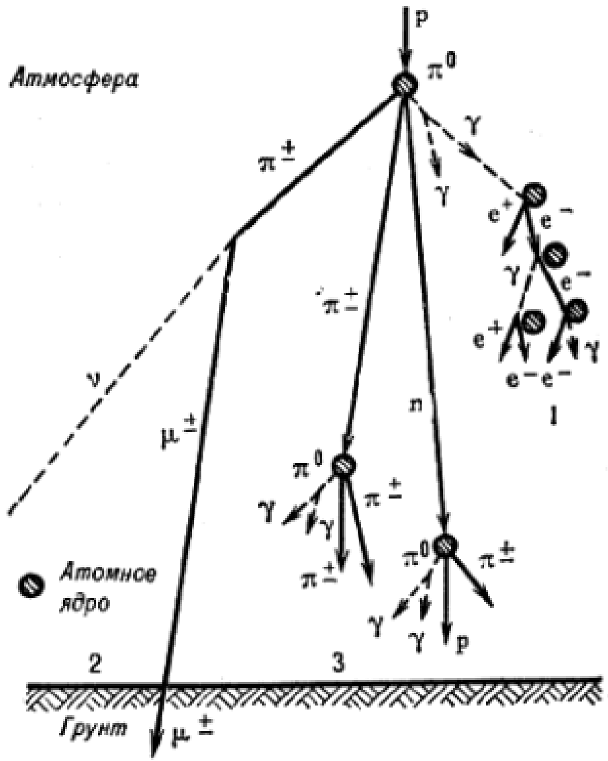
К.В. Мануковский, О.Г. Ряжская, Н.М. Соболевский А.В. Юдин[1]

33-я Всероссийская конференция по космическим лучам

[1] yudin@itep.ru (ITEP)

Motivation

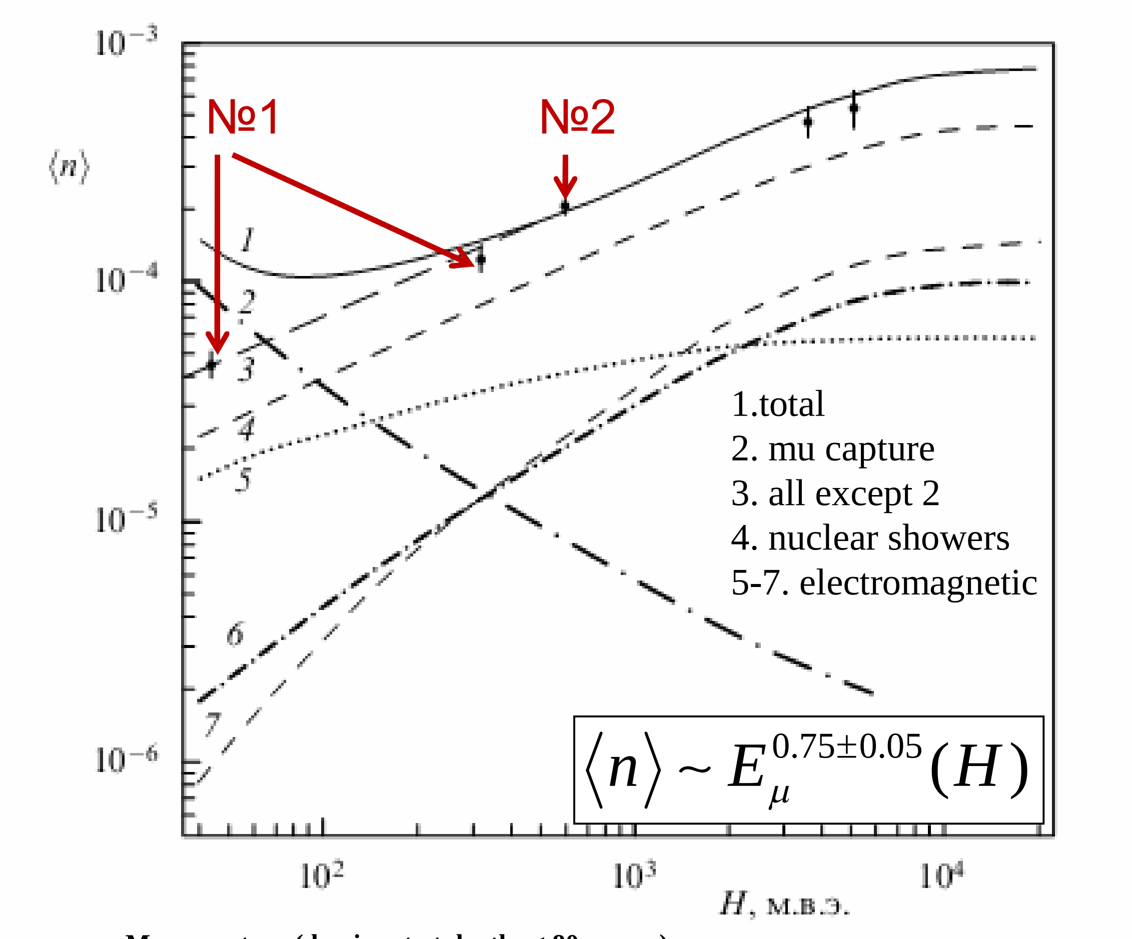
The key problem for all underground experiments looking for rare event physics, such as core-collapsing supernovae neutrinos, dark matter particles, low-energy neutrinos, etc., is the background due to natural radioactivity and cosmic-ray muons.



High energy cosmic-ray muons can easily penetrate the rock and reach an underground laboratory generating neutrons in hadronic and electromagnetic showers inside the surrounding soil, detector construction and shielding materials. These neutrons are the most undesired part of the background that can imitate sought events.

So it is ultimately important to estimate accurately the expected background neutron flux induced by cosmic rays for the operating and newly designed underground detecting facilities. And to optimize the suppression and shielding tools in order to increase the experimental sensitivity.

Muon-induced neutron production at various depths



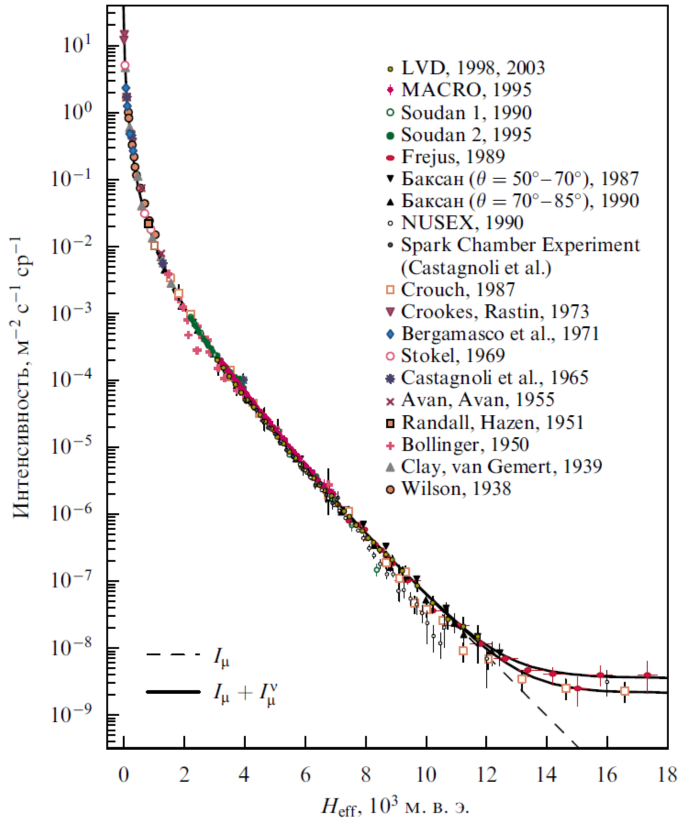


Рис. 3. Зависимость интенсивности мюонов от эффективной глубины грунта H_{eff} [44, 45].

- **Muon capture (dominant at depths < 80 m.w.e.)**
- **Muon-nuclear interaction (via the exchange of virtual photon)**
- **Electromagnetic showers**
- **Hadronic showers**

О.Г. Ряжская, УФН, 183, №3, 2013

А.С. Мальгин, О.Г. Ряжская, Ядерная физика, **71**, №10, 2008

GEANT4 simulation

- GEANT4 version 9.4.
- Detailed geometry.
- Physics list (essentials for muon-induced neutrons):

Electromagnetic

mu-	G4QCaptureAtRest	

Photonuclear

mu+/-		1 GeV < E
gamma	CHIPS	E < 3.5 GeV
	QGSC	3 GeV < E < 100 TeV
e+/-	CHIPS	E < 10 TeV

Hadronics

HP	n	0 < E < 19.9 MeV
BiC	n	19.5 MeV < E < 6.1 GeV
BiC	p	0 < E < 6.1 GeV
LEP	p, n	6.1 GeV < E < 12 GeV
QGSP	p, n	12 GeV < E < 100 TeV
BiC	pi	0 < E < 1.5 GeV
LEP	pi	1.4 GeV < E < 12.1 GeV
QGSP	pi	12 GeV < E < 100 TeV
LEP	H2, H3, He4	0 < E < 100 MeV
BiC	He3, GenIon	0 < E < 10 GeV

Lindote A. et al., Astropart. Phys., **31**, p.366, 2009.

Evolution of the neutron yield in GEANT4

GEANT4 version	physics list	muon-induced neutron yield [neutrons/muon/(g/cm^2)]
8.2	custom list	$(2.846\pm0.006)\times10^{-3}$
9.4	custom list	$(3.304\pm0.003)\times10^{-3}$
9.4	QGSP_BIC_HP	$(3.376\pm0.003)\times10^{-3}$
9.4	Shielding	$(3.682\pm0.003)\times10^{-3}$
9.5	QGSP_BIC_HP	$(3.993\pm0.004)\times10^{-3}$
9.5	QGSP_BERT_HP	$(4.369\pm0.004)\times10^{-3}$
9.5	FTFP_BERT	$(4.467\pm0.004)\times10^{-3}$
9.5	Shielding	$(4.594\pm0.004)\times10^{-3}$

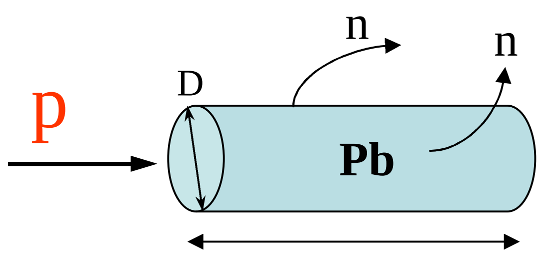
Reichhart L. et al., Astropart. Phys., **47**, p.67, 2013.

Proton-induced neutron production

«ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА», 1978, том 9, вып. 5

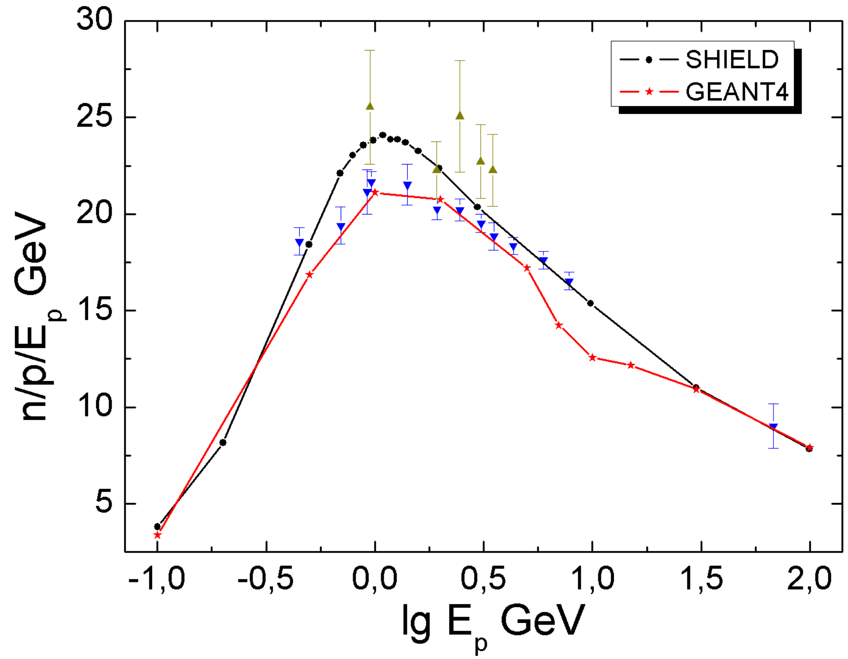
ЯДЕРНО-ФИЗИЧЕСКИЕ АСПЕКТЫ ЭЛЕКТРОЯДЕРНОГО МЕТОДА

В. С. Барашенков
Объединенный институт ядерных исследований, Дубна



D=20 cm, L=60 cm

D, cm	L, cm	E_p, GeV	neutrons escaped per proton		
			Calc, Barash.	Exp.	Geant
10.2	61	0.47	7.8±0.3	8±0.4 6.4±0.3	6.97
10.2	61	0.96	17.8±0.6	16.6±0.8 16.8±0.5 17.7	16.65
10.2	61	1.47	25.1±0.1	26.4±1.3 27.5±0.6 29.4	25.1
20.4	61	0.47	8.1±0.3 9.2	8.7±0.4	7.92
20.4	61	0.96	21.7±0.8 22.2	20.3±1.1	20.36
20.4	61	1.47	31.5±1.2	31.5±1.6	31.84



R.G. Vassil'kov and V.I. Yurevich, Proc. 11th Meeting of Int. Collaboration on Advanced Neutron Sources ICANS-11 KEK, Tsukuba, Japan, October 22–26, 1990, KEK Report 90-25 (1991) vol. 1, p. 340.

SHIELD transport code:
A.V. Dementyev, N.M. Sobolevsky,
Radiation Measurements, **30**, №5, p.553, 1999.

Muon-induced neutron production (Experiment №1)

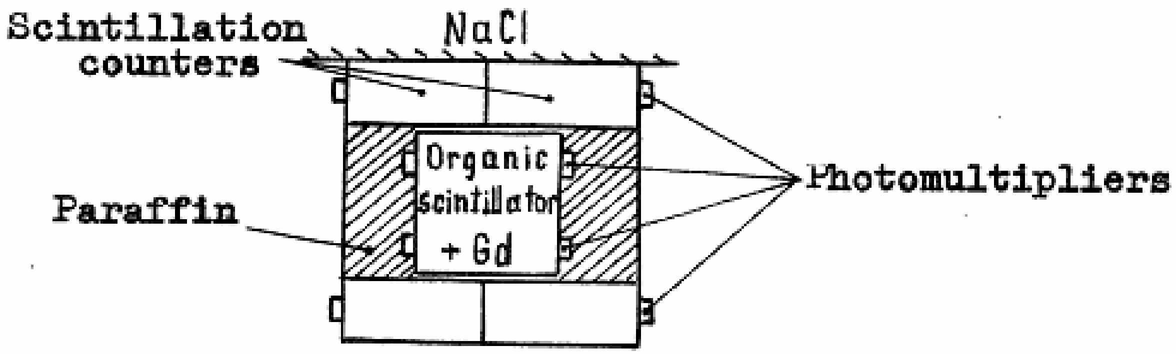
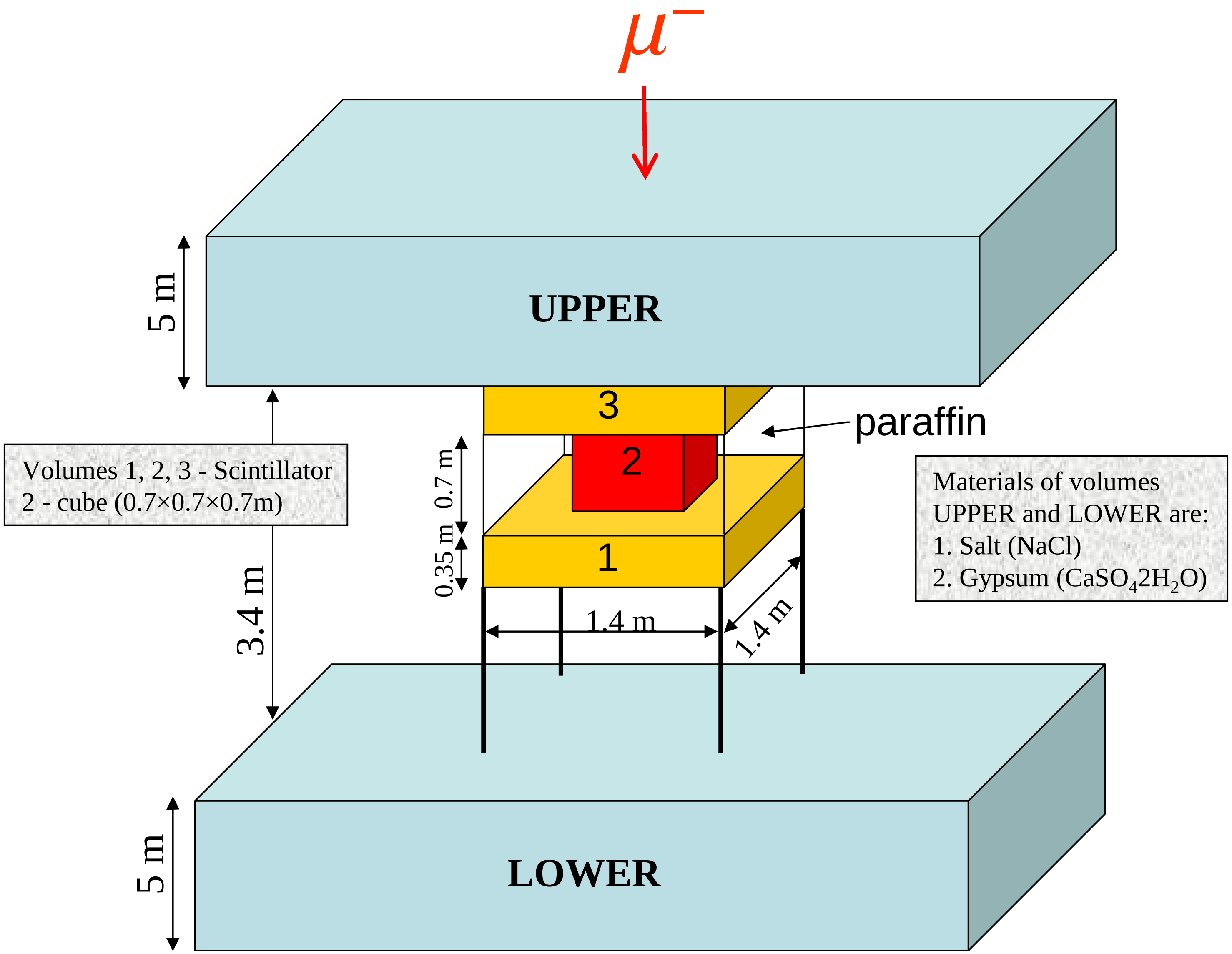


Fig.1 The experimental arrangement.

Neutrons produced by muons at the depth of 316 m.w.e. and 25 m.w.e. Experimental results.

L.B. Bezrukov et al., Soviet Journal Nucl. Phys., vol. 17, (1973) 98.

Experimental setup



Muon-induced neutrons (E_μ=16.8 and 86 *GeV*)

Definition

$Y=N_{nb}/N_\mu/l_\mu/\rho$,
N_{nb} – number of generated neutrons
N_μ – number of selected muons
l_μ – the length of muon's path inside the matter (cm)
ρ – density of the matter (g/ccm)

Muon selection

Passing muon must release at least 55 MeV in scintillators 1 and 3 and 110 MeV in scintillator 2 to be selected. Scintillator 2 is the sensitive volume for the measuring of quantities X and Y.

Simulation

E_μ, GeV	Y, n/μ/g/cm^2
86 ± 18	1.2×10^{-4}
16.7 ± 8.2	3.92×10^{-5}

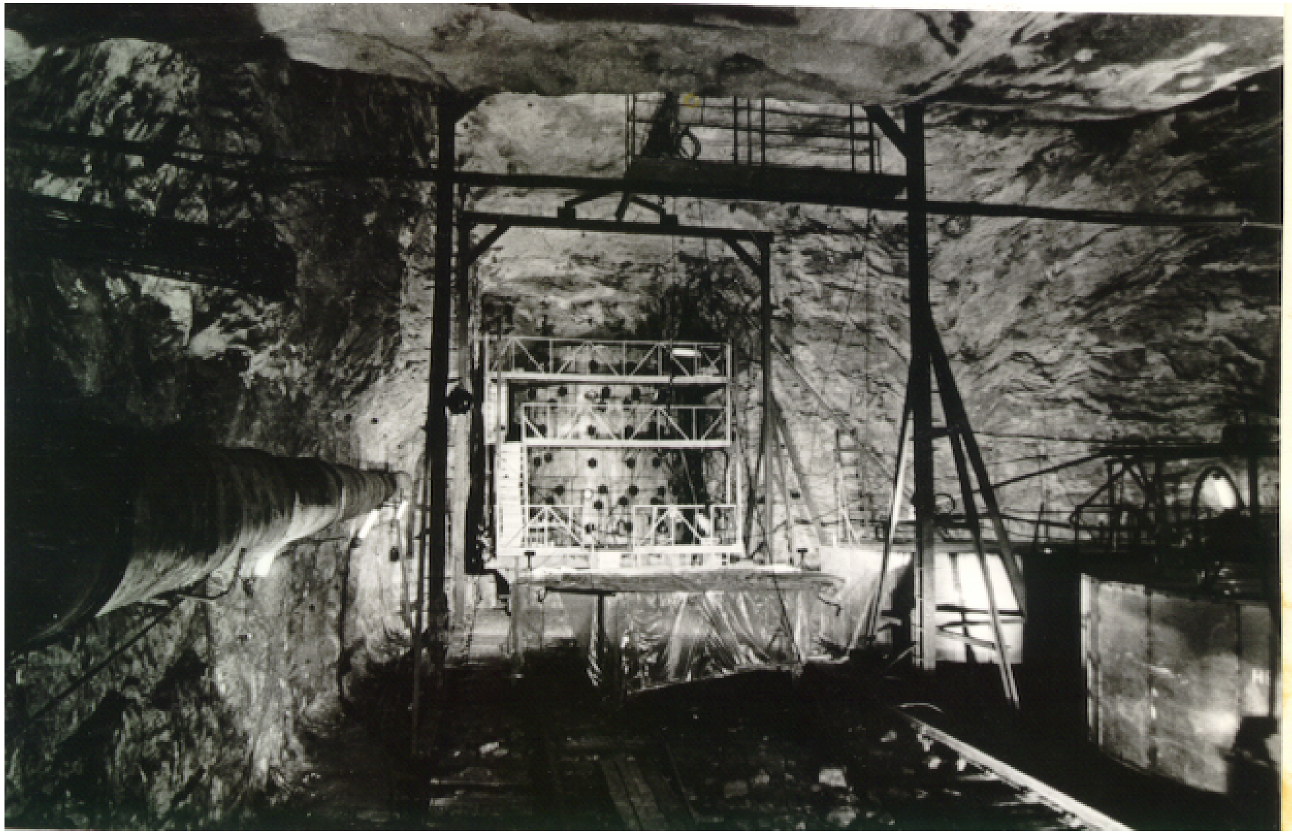
Experiment

E_μ, GeV	Y, n/μ/g/cm^2
86 ± 18	$(1.21 \pm 0.12)\times10^{-4}$
16.7 ± 8.2	$(4.7 \pm 0.5)\times10^{-5}$
16.5 ± 8.1	$(3.6 \pm 0.3)\times10^{-5}$

L.B. Bezrukov et al., Soviet Journal Nucl. Phys., vol. 17, (1973) 98.

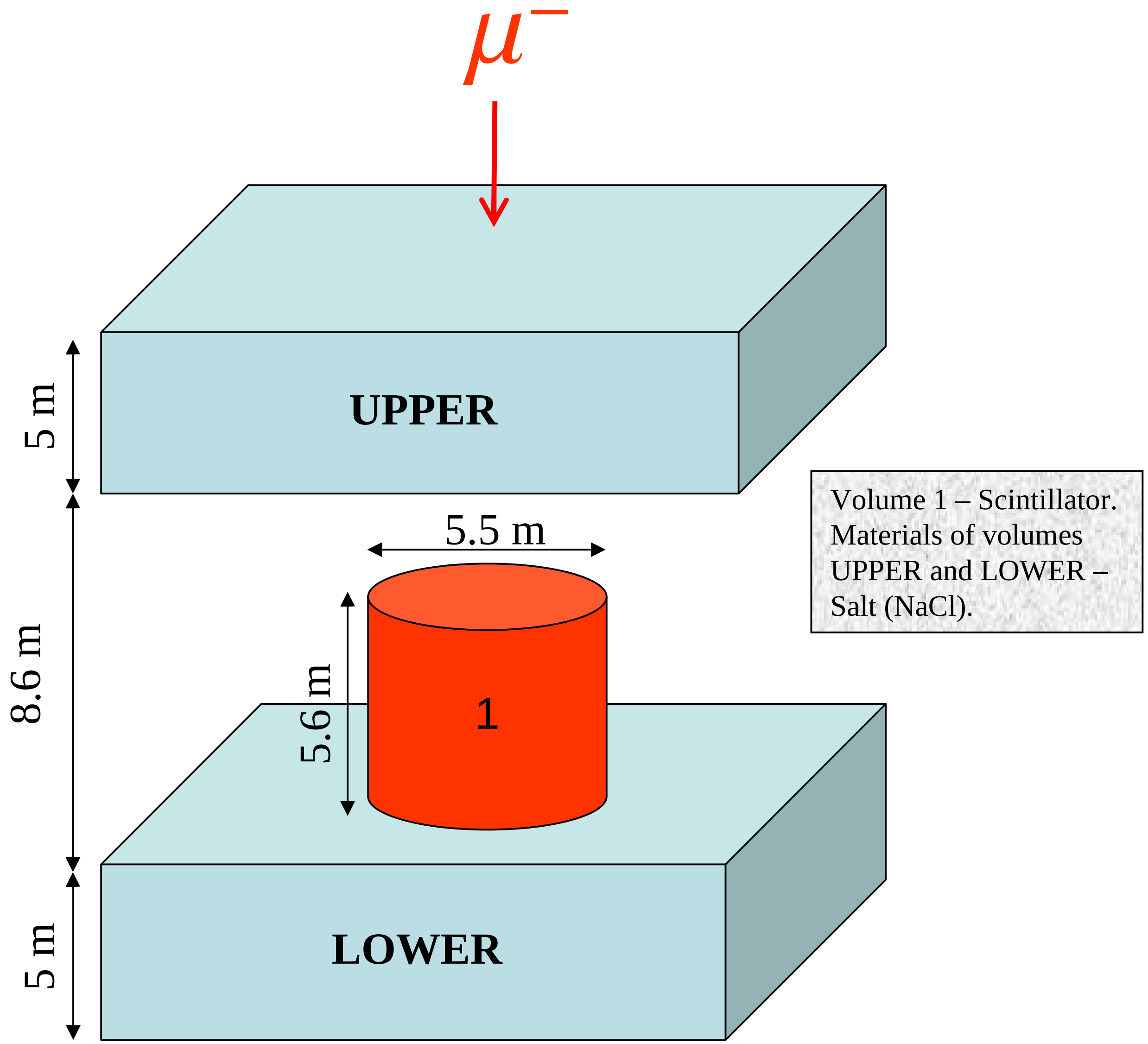
F. Boehm et al., Phys. Rev. D, **62**, 9, id. 092005, 2000.

Muon-induced neutron production (Experiment №2)



R.I. Enikeev et al., Soviet Journal Nucl. Phys., 46, p.1492, 1982.

Experimental setup



Muon-induced neutrons (E_μ=125 *GeV*)

Definition

$Y=N_{nb}/N_\mu/l_\mu/\rho$,
N_{nb} – number of generated neutrons
N_μ – number of selected muons
l_μ – the length of muon's path inside the matter (cm)
ρ – density of the matter (g/ccm)

Muon selection

Energy of incident muon is 125 GeV. Passing muon must release at least 1 GeV in scintillator 1 to be selected. Scintillator 1 is the sensitive volume for the measuring of quantities X and Y.

Simulation

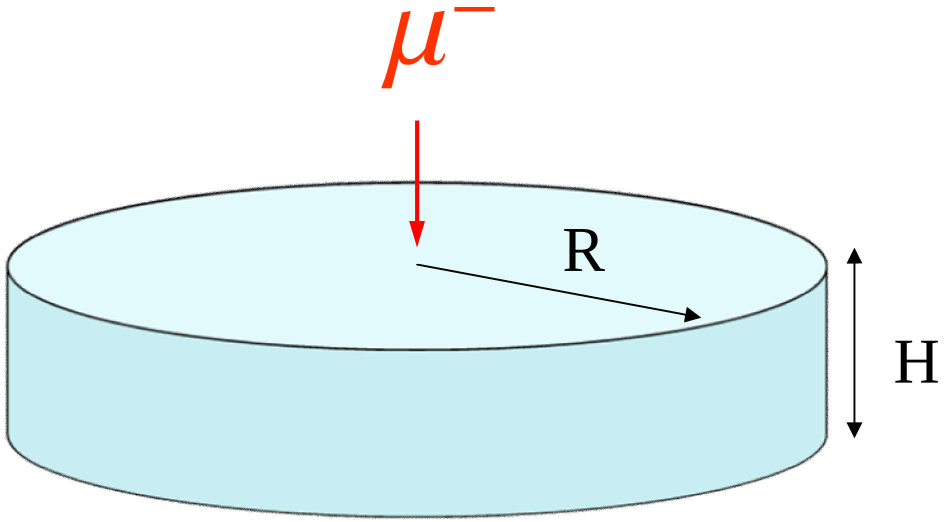
E_μ, GeV	Y, n/μ/g/cm^2
125	1.71×10^{-4}

Experiment

E_μ, GeV	Y, n/μ/g/cm^2
125 ± 22	$(2.04 \pm 0.24)\times10^{-4}$

O.G. Ryazhskaya, Doctoral thesis INR RAS, (1986).

Target setup (E_μ=100 and 280 *GeV*)



E_μ, GeV	H, g/cm^2
100	2000
280	4000

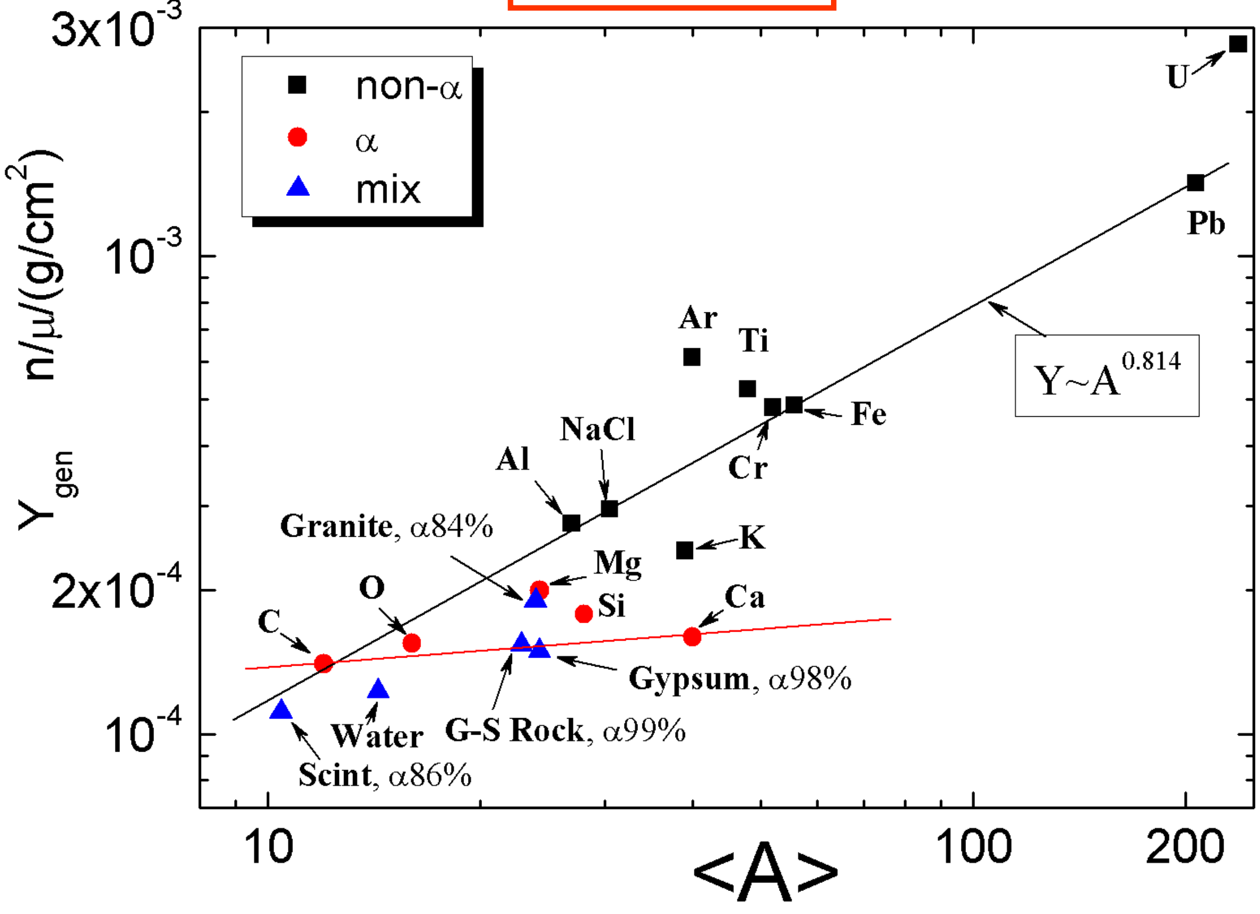
Muon energy losses:

$$-\frac{dE}{dx} = a + bE \ , \qquad a = 1.9 + 0.08 \ln \frac{E_\mu}{m_\mu} \frac{MeV}{g/cm^2} \ , \qquad b = 3.5 \cdot 10^{-6} \frac{1}{g/cm^2}$$

Neutron yield (E_μ=100 *GeV*).

Atomic weight dependence.

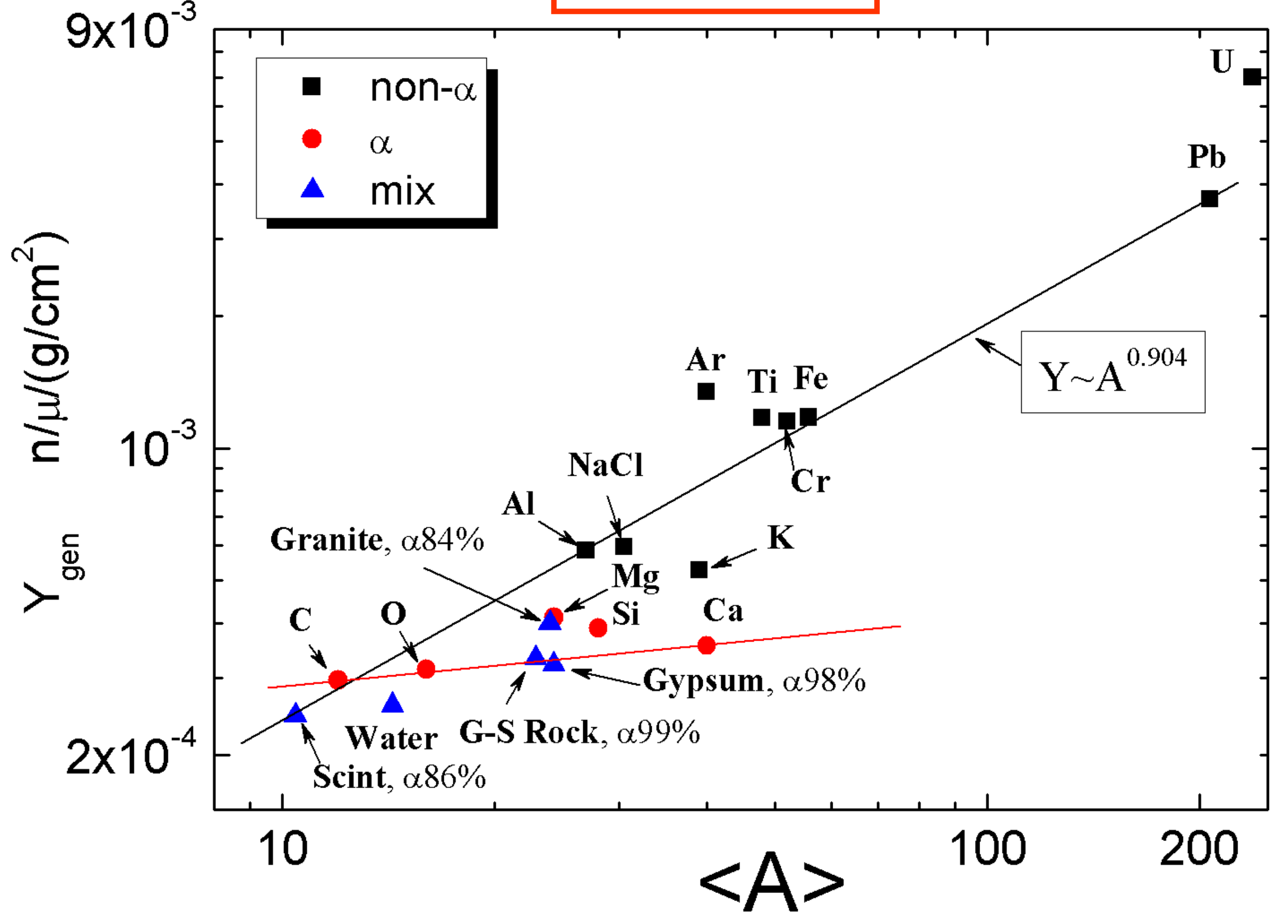
$$Y \sim A^{\alpha} E_{\mu}^{\beta}$$



Neutron yield (E_μ=280 *GeV*).

Atomic weight dependence.

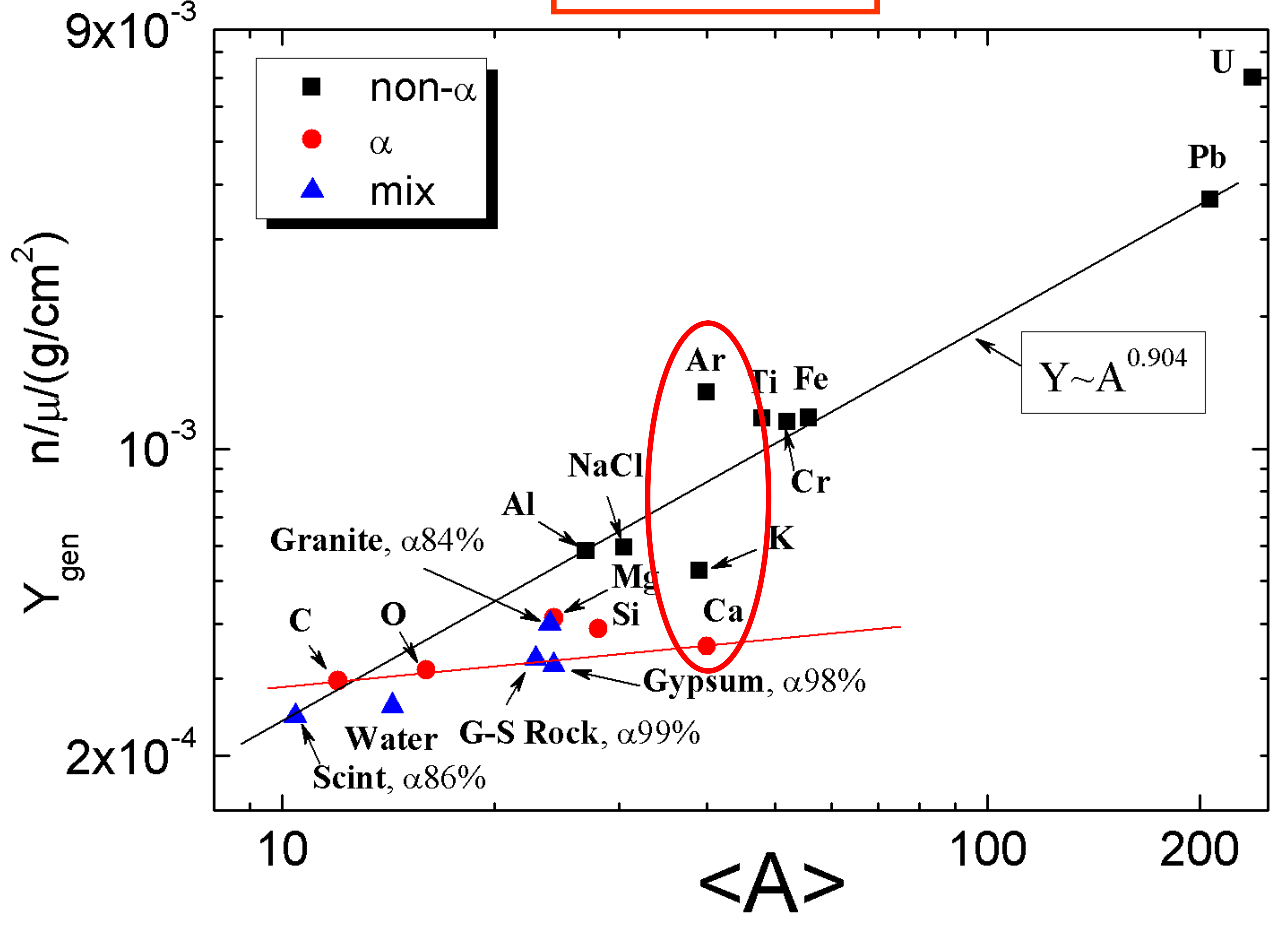
$$Y \sim A^{\alpha} E_{\mu}^{\beta}$$



Neutron yield (E_μ=280 GeV).

Atomic weight dependence.

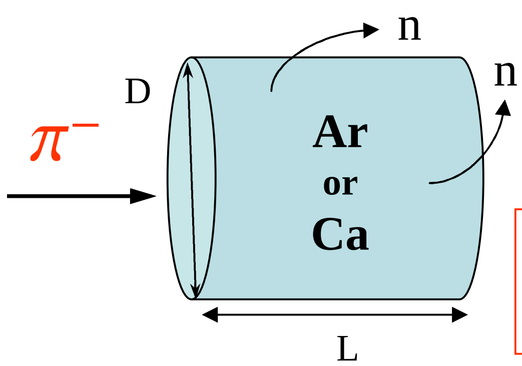
$$Y \sim A^{\alpha} E_{\mu}^{\beta}$$



Pion-induced neutron production with *SHIELD*

$E_n \leq 14.5 MeV$

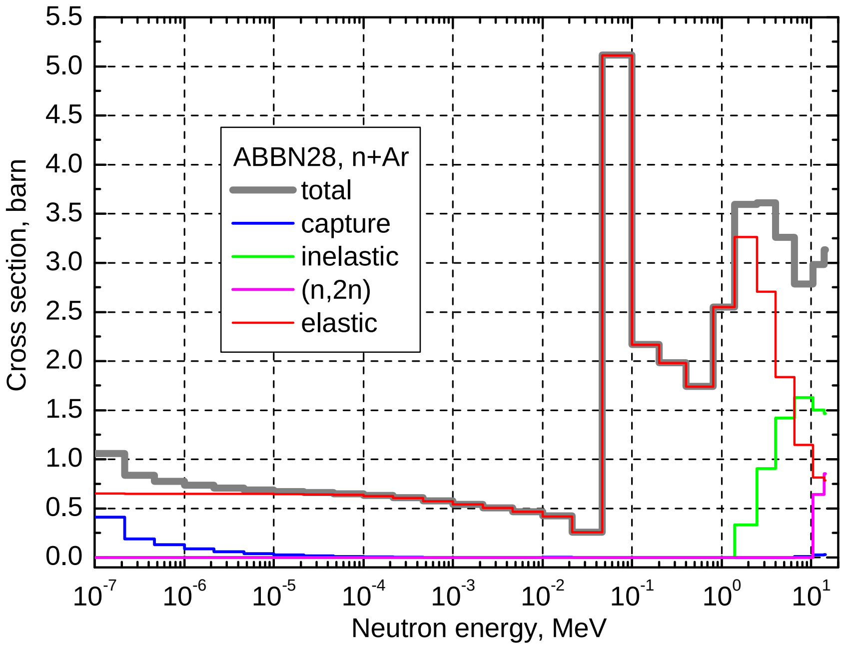
Eπ (GeV)	Ar		Ca	
	Source	Leakage	Source	Leakage
1	16.7	17.1	7.47	4.69
10	77.0	78.8	33.6	20.7
100	381	390	161	99.1

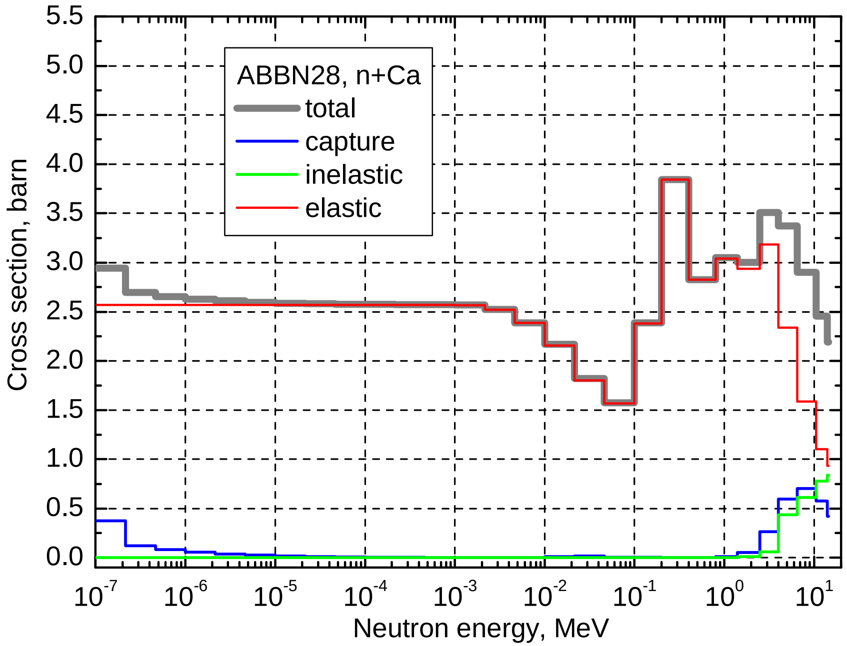


D=3 m, L=3 m

$\rho_{Ar} = 1.65\, g\, cm^{-3}$

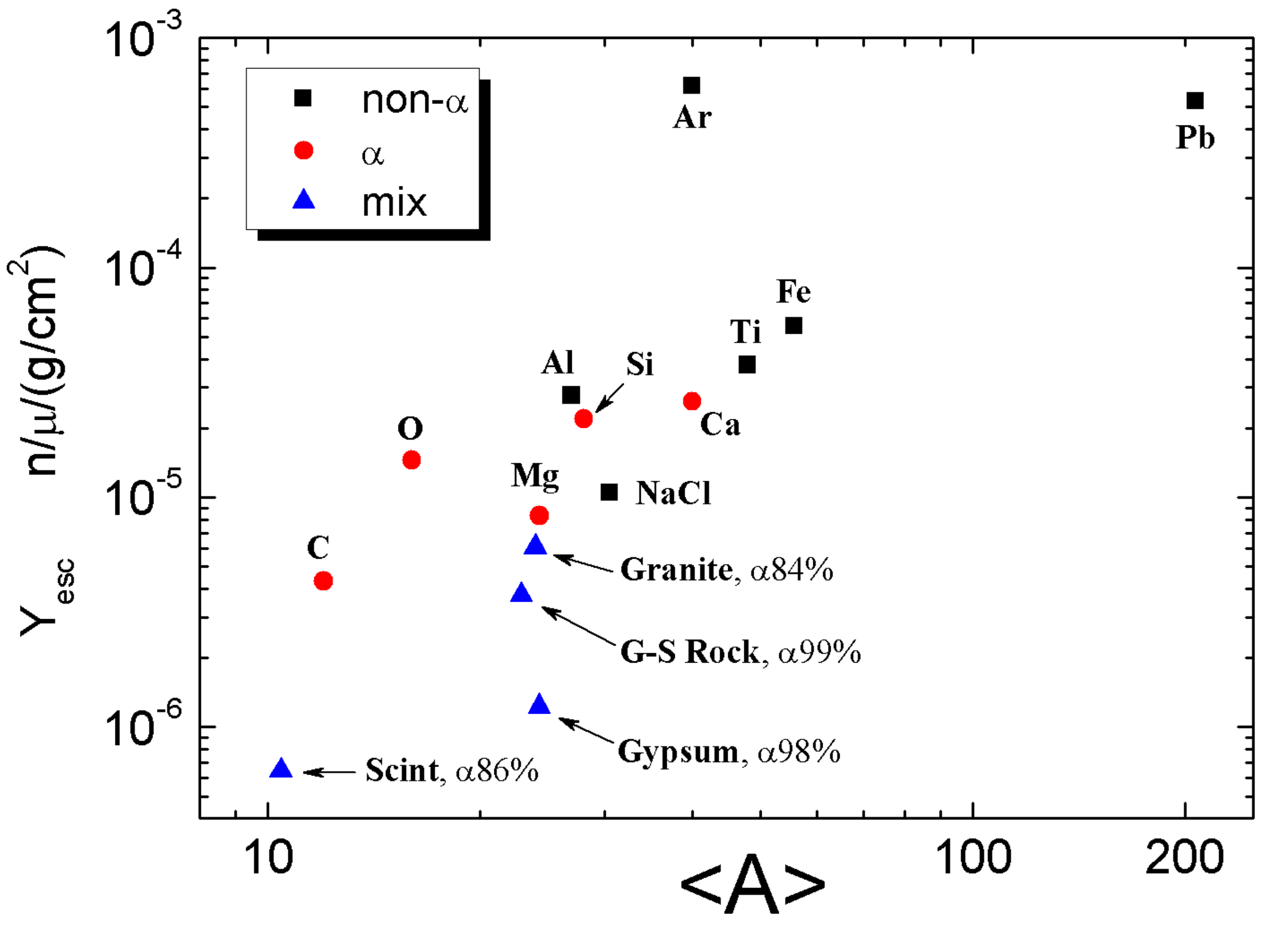
$\rho_{Ca} = 1.55\, g\, cm^{-3}$





Neutron escape with sampling (E_μ=100 *GeV*).

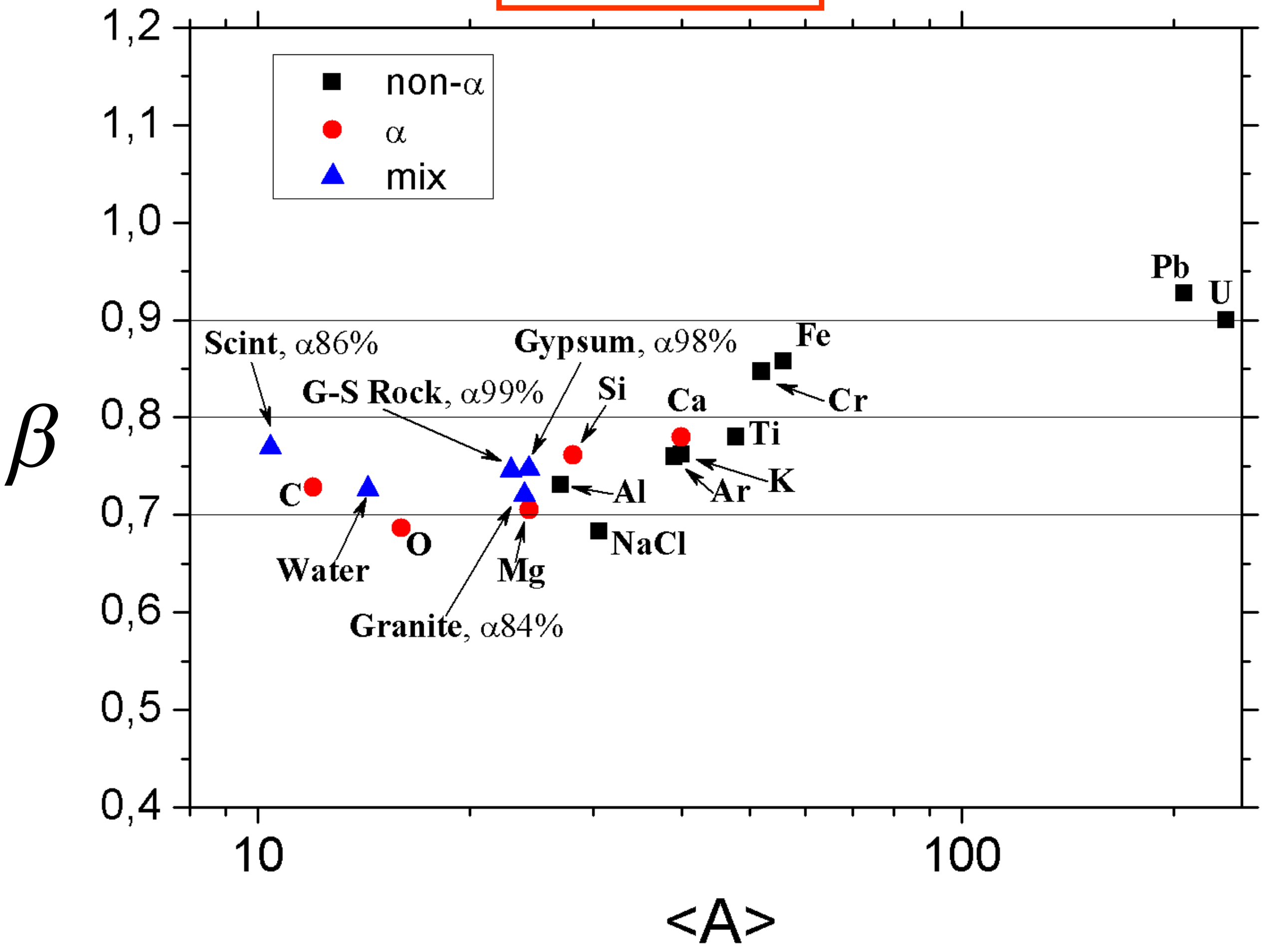
Atomic weight dependence.



Neutron yield.

Mean muon energy dependence.

$$Y \sim A^{\alpha} E_{\mu}^{\beta}$$



Neutron yield with sampling (E_μ=100 *GeV*).

Atomic weight dependence.