Stopping of Muons in Helium-3 and Deuterium

V.M. Bystritsky, V.V. Gerasimov

Joint Institute for Nuclear Research, Dubna

J. Wozniak

AGH University of Science and Technology, Cracow

Abstract. Stopping power ratio of helium-3 and deuterium atoms for muons slowed down in D/^{3}He gas mixture was measured using 34.0 MeV/c muon beam at PSI meson factory. We present the measurement method and the analysis of experimental data.

Collaboration Dubna-Fribourg-Cracow-PSI

MUON INDUCED PROCESSES IN HELIUM AND HELIUM-DEUTERIUM MIXTURES

Experiments performed at PSI, μ-E4 muon channel

V.F. Boreiko V.M. Bystritsky W. Czapliński A. Del Rosso M. Filipowicz V.V. Gerasimov O. Huot P.E. Knowles F. Mulhauser V.N. Pavlov F.M. Penkov C. Petitjean N.P. Popov V.G. Sandukovsky L.A. Schaller H. Schneuwly V.A. Stolupin V.P. Volnykh J. Woźniak

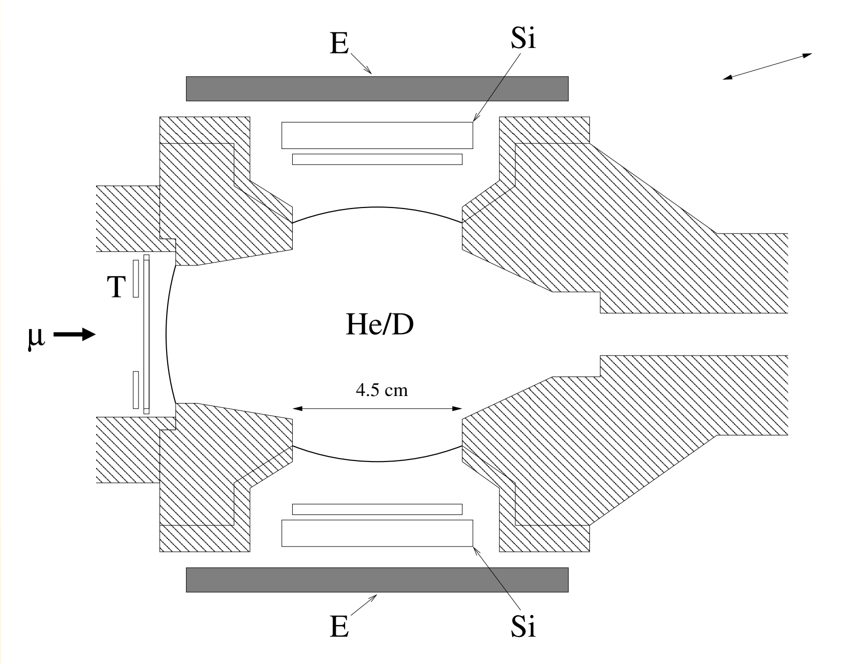
- measuring μd^3He fusion
- nuclear muon capture by ^{3}He
- various μ-atomic, μ-molecular characteristics
- muon stopping

Introduction

- Spatial distribution of muon stops gives an information on the distribution of formatted μ-atoms
- decay electrons are used as the markers of the muon stops:

μ^- slowing-down $\longrightarrow$ formation of μ-atom $\longrightarrow$ μ-decay $\longrightarrow$ $e^- + \nu_\mu + \tilde{\nu}_e$

- experimental set-up



- ▷ *muon beam momentum $P_\mu = 34.0$ MeV/c, spread 1.23 FWHM*
- ▷ *gas targets: pure ^{3}He, D/^{3}He mixture (0.0496 He concentration)*
- ▷ *different gas densities (0.034 - 0.058 LHD)*
- ▷ *pressure 5.1 - 6.9 atm*
- ▷ *temperature ∼33 K*

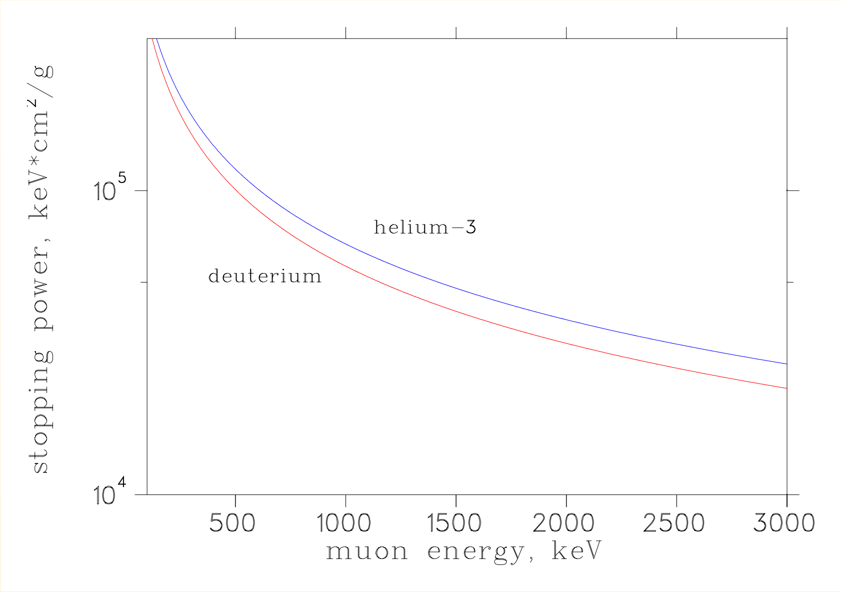
Stopping power

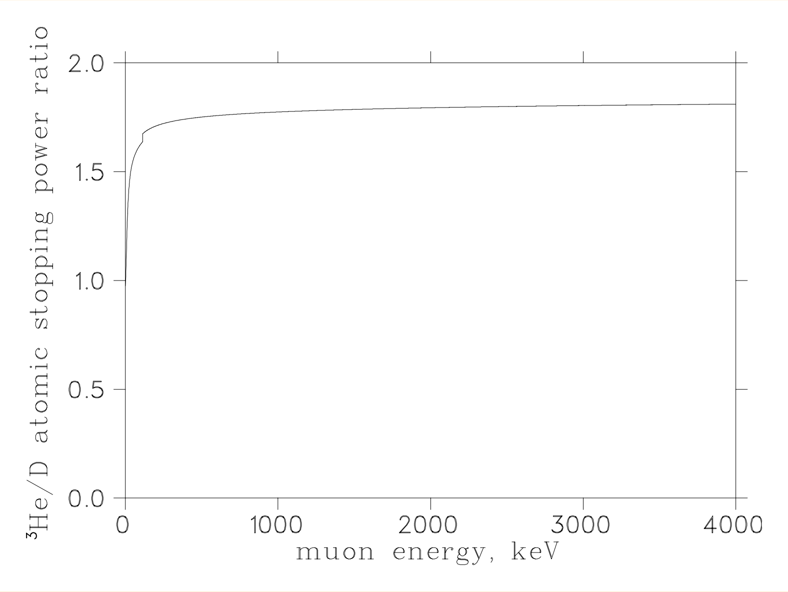
Per-atom stopping power [MeV·cm^2/atom]

$$S_i = \frac{1}{n_i}\left(-\frac{dE}{dx}\right)_i = A_i\left(-\frac{dE}{d\xi}\right)_i, \qquad S = \sum c_i S_i \qquad i = {}^3\mathrm{He}, \mathrm{D}$$

n_i - numeric density, A_i - atomic mass, c_i - atomic concentration, ξ - mass thickness.

Stopping power ratio: $\tilde{s} = S_{^3\mathrm{He}}/S_\mathrm{D}$



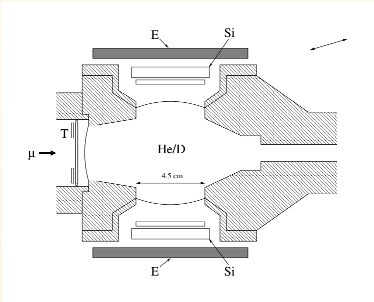


Calculated stopping powers (using data of J.F.Ziegler *et al.*, *The Stopping...*, Pergamon Press, N.Y., 1985)

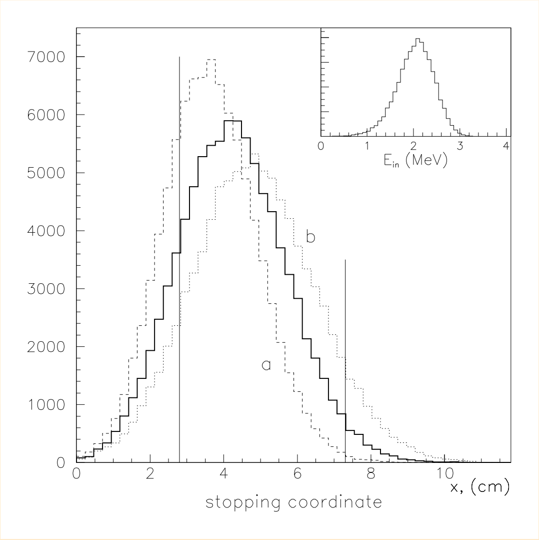
Measurement method

Muon slowing-down simulation via Monte Carlo; μ-stops distributions

- Monte Carlo code (R. Jacot-Guillarmod, Fribourg University); Ziegler's parametrisation of the stopping powers
- conditions of the experiment
  - ▷ *one target D + 0.05 ^{3}He, fixed density φ_{mix} = 0.0585*
  - ▷ *a set of pure ^{3}He targets, different densities φ_{He}*



- calculated stopping distributions for D/^{3}He target and ^{3}He target, example:



solid line: D/^{3}He mixture, $\varphi_{mix} = 0.0585$

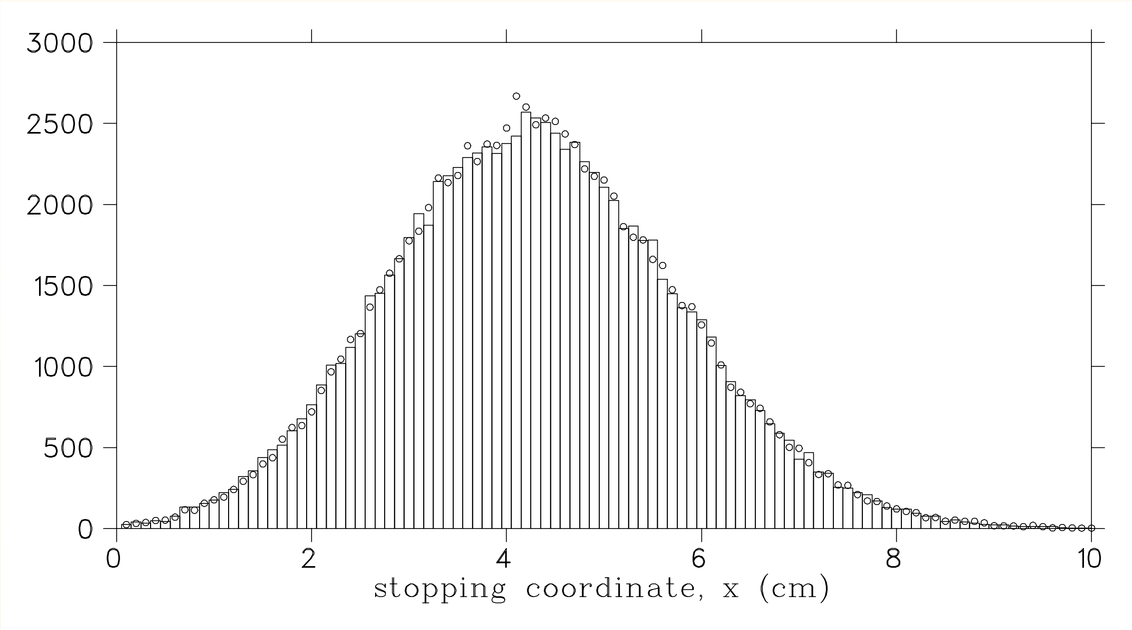
dotted,dashed lines: pure ^{3}He, densities:

(a) $\varphi_{He} = 0.0380$,
(b) $\varphi_{He} = 0.0320$

in the insert: energy spectrum of incident muons (E_{in})

Measurement method

Equivalence of the stopping distributions by Monte Carlo simulation



Histo: D/^{3}He mixture.

Circles: pure ^{3}He with equivalent density $\tilde{\varphi}_{He}$.

$\chi^2/df = 0.92$

Similar equivalency is also achieved in the plane perpendicular to the moun beam direction

Measurement method

The range of muon

- $$r_\mu = \int_0^{E_{in}} \frac{1}{-\left(\frac{dE}{dx}\right)} dE = \frac{N_a}{\varphi\, n_o} \int_0^{E_{in}} \frac{1}{\sum c_i S_i} dE \qquad (1)$$
- Keeping constant the beam momentum and changing the gas density in a given type of the target (^{3}He) one can obtain the same μ-stopping distribution as for another fixed-density target (D+^{3}He mixture)
- Such equivalence of muon ranges (for the whole initial energy spectrum of muons) is a key for the stopping power ratio measurement

Equivalence of the stopping distributions

- When the muon ranges are equal for both media then taking into account the similarity of the individual stopping powers of helium-3 and deuterium one obtains from (1) a formula for the mean stopping powers ratio:
- $$< \tilde{s} >= \tilde{s}(\overline{E}) = S_{^3\mathrm{He}}/S_{\mathrm{D}} = \frac{c_{\mathrm{D}}\varphi_{mix}}{\tilde{\varphi}_{\mathrm{He}} - c_{\mathrm{He}}\varphi_{mix}}. \qquad (2)$$
- $\tilde{\varphi}_{\mathrm{He}}$, φ_{mix} - equivalent densities of the pure ^{3}He target and the mixture D/^{3}He target.
- Equation (2) gives the receipe for the measurement of $< \tilde{s} >$ -value

Experiment

Experiment conditions

Run	Target	Temp. [K]	Presssure [atm]	φ [LHD]	C_{He} [%]	N_μ [10^9]
1	3He	32.9	6.92	0.0363	100	1.3625
2			6.85	0.0359		0.7043
3			6.78	0.0355		0.7507
4			6.43	0.0337		0.4136
5	D/^{3}He	32.8	5.11	0.0585	4.96	8.875

R-ratio measurement

Run	Target	φ [LHD]	N_μ [10^9]	N_e [10^6]	R [10^{-3}]
1	3He	0.0363	1.3625	0.5302 (14)	0.3891 (10)
2		0.0359	0.7043	0.2765 (10)	0.3926 (14)
3		0.0355	0.7507	0.2975 (10)	0.3963 (14)
4		0.0337	0.4136	0.1657 (8)	0.4007 (18)
5	D/^{3}He	0.0585	8.875	3.4635 (35)	0.3903 (4)

- *$P_\mu = 34.0$ MeV/c was chosen such to stop all entering muons inside the D/^{3}He target.*
- *electron time spectra analysis*
- $$R(\varphi) = \frac{N_e}{N_\mu}$$

$R_{mix}(\varphi = 0.0585) = R_{He}(\varphi_{He}) \quad \rightarrow \quad$ equivalent ^{3}He density $\tilde{\varphi}_{He}$

Experiment

When $\tilde{\varphi}_{He}$ is found (i.e. the muon stops numbers[1] are equal for both target gases, ^{3}He and D/^{3}He) it has been also observed experimentally that

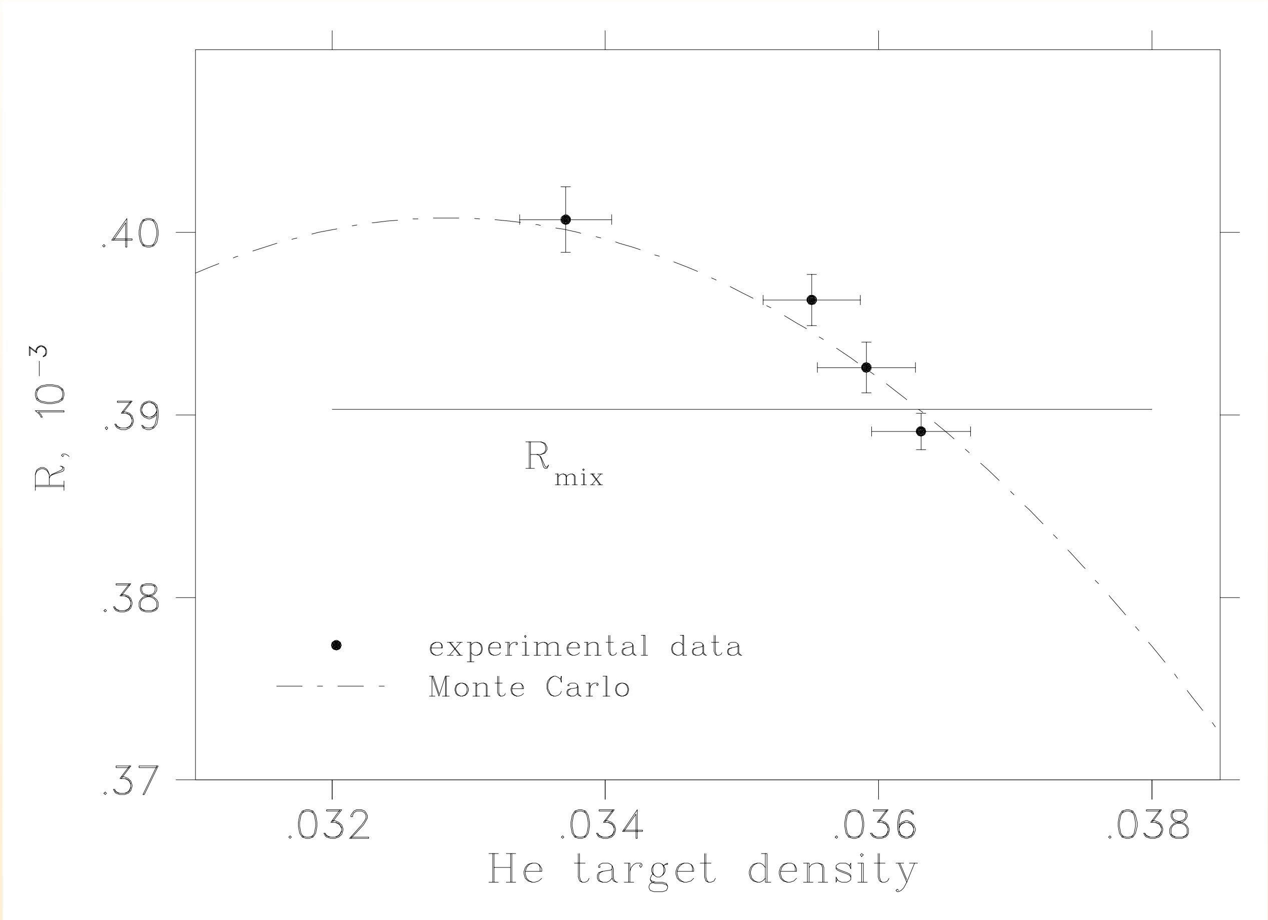
- R_{Al} *(the number of stops in the target walls),*
- R_{Au} *(the number of stops in the entrance gold ring)*

not change if D/^{3}He is replaced by ^{3}He($\tilde{\varphi}$).

It's an additional argument for the spatial equivalency of muon stops distributions in ^{3}He($\tilde{\varphi}$) and D/^{3}He) targets.

[1] per incident muon

Analysis



$$\tilde{\varphi}_{He} = 0.0363 \pm 0.0005 \rightarrow \boxed{< \tilde{s} >= S_{^3\mathrm{He}}/S_{\mathrm{D}} = 1.66 \pm 0.04}$$ [2]

[2] V.M. Bystritsky *et al.*, Eur.Phys.J. D, **42** (2007) 79

Mean ratio of the stopping powers

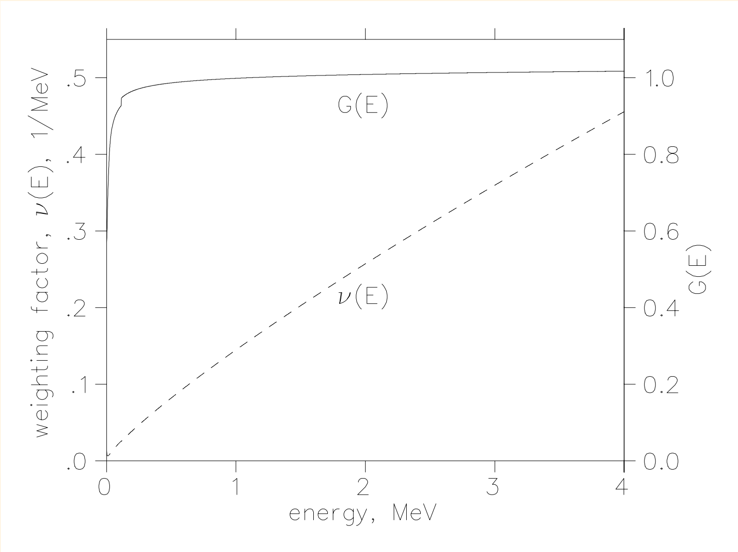
Equality of ranges $\int_0^{E_{in}} \frac{dE}{-\left(\frac{dE}{dx}\right)_{mix}} = \int_0^{E_{in}} \frac{dE}{-\left(\frac{dE}{dx}\right)_{He}}$ can be rewritten as

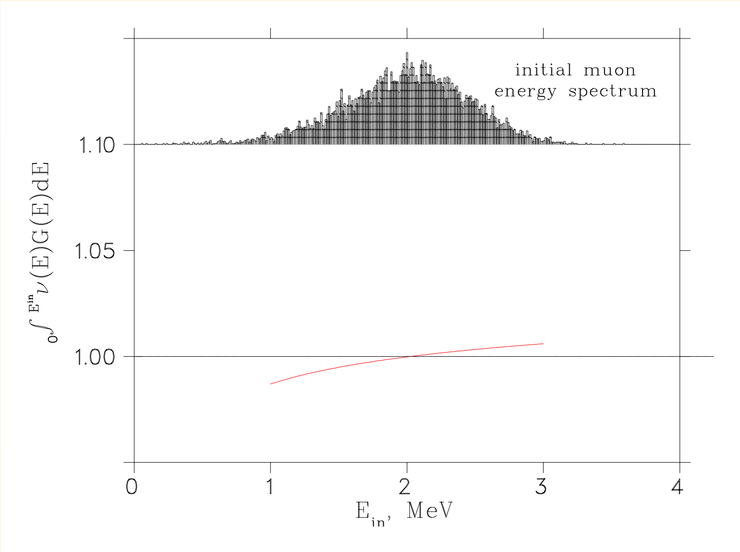
$\int_0^{E_{in}} G(E)\,\nu(E)\,dE = 1,$

where

$\nu(E) = \frac{1/S_{He}}{\int_0^{E_{in}} 1/S_{He}\,dE}$ is a weight function, $\int_0^{E_{in}} \nu(E)\,dE = 1,$

and $G(E) = \frac{\tilde{\varphi}_{He}}{\varphi_{mix}(\tilde{s}^{-1}(E)c_D + c_{He})}$ (energy dependent via $\tilde{s}(E)$).





finaly, $1 = \overline{G} \approx G(\overline{A(E)}) \approx G(A(\overline{E}))$ gives the formula for $< \tilde{s} >$.

Atomic capture in a binary mixture

- Atomic capture probability: $w_D = \frac{1}{1+Ac}, \qquad w_{He} = \frac{Ac}{1+Ac},$ (*)

  where $A = \frac{\sigma(He)}{\sigma(D)}$ - per-atom capture ratio (reduced ratio), $c = c_{He}/c_D$ - ratio of atomic concentrations

- "A" is usually energy dependent; $\overline{A} = \frac{\overline{\sigma(He)}}{\overline{\sigma(D)}}$ is more useful for experiments.

- The question of averaging.

- No simple relationship exists between the stopping power and the primary atomic capture; slowing down "is working" in MeV - keV region, capture occurs at low energies ($\sim< 100$ eV).

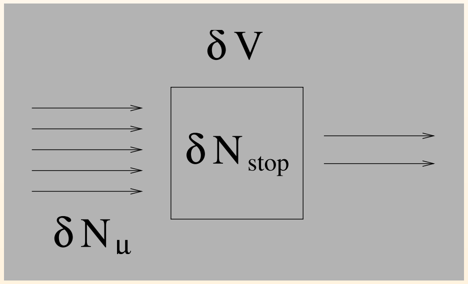
- Petrukhin's phenomenological model[3]: expressions (*) fit well the experimental data for H/He mixture when stopping power ratio $\tilde{s}$ is used instead of A

$$w_D = \frac{1}{1+\tilde{s}c}, \qquad w_{He} = \frac{\tilde{s}c}{1+\tilde{s}c}.$$

[3] V.I.Petrukhin and V.M.Suvorov, Zh. Eksp. Theor. Fiz. **70** (1976) 1145

reduced capture ratio

Let through a volume δV located in any given point in the target pass δN_μ muons



$\delta N_{stop} = \delta N_\mu n_o \varphi \overline{\sigma} \delta x$

- $\delta N^{He}_{stop} = \delta N_\mu n_o \varphi_{He} \overline{\sigma}_{He} \delta x$

  $\delta N^{mix}_{stop} = \delta N_\mu n_o \varphi_{mix} (c_D \overline{\sigma}_D + c_{He} \overline{\sigma}_{He}) \delta x$

- for the same stopping distributions in D/^{3}He and in ^{3}He targets:

  $\delta N^{He}_{stop}(\tilde{\varphi}_{He}) = \delta N^{mix}_{stop}(\varphi_{mix})$ for any volume element

- from this $\tilde{\varphi}_{He} \overline{A} = \varphi_{mix}(c_D + \overline{A} c_{He})$

  or $\overline{A} = \frac{\overline{\sigma}(He)}{\overline{\sigma}(D)} = \frac{c_D \varphi_{mix}}{\tilde{\varphi}_{He} - c_{He} \varphi_{mix}}$

- In general, the quantity $\overline{A}$ can be dependent on concentrations c_D, c_{He}. For a week dependency of the muon energy distribution on mixture composition at low energies, the $\overline{A}$-value is practically constant and can be interpreted as the mean reduced probability ratio for the muon capture by helium-3 and deuterium atoms.

- Above consideration can justify Petrukhin's model for the H/He mixture.