Experimental search of nuclear fusion reactions in the ptμ system

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Muon catalyzed fusion in ptμ

$$\mu \rightarrow H/T \xrightarrow{\lambda_a} p\mu \xrightarrow{\lambda_{pt}} t\mu \xrightarrow{\lambda_{pt\mu}} pt\mu \xrightarrow{\lambda_f} {}^4He + \ldots$$

1. $pt\mu \rightarrow {}^4He\mu + \gamma + 19.8$ MeV,
2. $pt\mu \rightarrow {}^4He + \mu + 19.2$ MeV,
3. $pt\mu \rightarrow {}^4He\mu + e^+ + e^- + 18.8$ MeV,
4. $pt\mu \rightarrow {}^4He\mu + \gamma + \gamma + 19.8$ MeV.

Motivation to observe **ptμ** fusion:

2,3,4 – one can not observe in a beam-target [Phys.Rev. 75(1950)1361]

1,2 - the only previous observation [Phys. Rev. Lett. 70(1993)3720]

3,4 – not observed previously

1, 3,4 – yield is most critical for primordial nucleosynthesis in astrophysics [Phys.Part.Nucl. 33(2002)915]

1, 3,4 – perfect probe for developing four-body problem in nuclear physics

TRITON installation

The experimental complex TRITON **[Prib.Techn.Eksp. 6(1999)17]** was created in cooperation between the Russian Federal Nuclear Center (Sarov) and the Laboratory of Nuclear Problems (JINR, Dubna).

Since 1996 the comprehensive measurements of muon catalysis (MC) parameters in **D/T** and **H/D/T** mixtures have been carried out by use of TRITON at the Phasotron in Dubna and were awarded the JINR First Prize **[JETP 100(2005)663]**.

The most recent published results are the experiments with muons in pure tritium (**t + t** $\rightarrow$ **^{4}He + n + n**) and pure deuterium (**d + d** $\rightarrow$ **^{4}He + γ**) **[JETP 108(2009)216, JETP 113(2011)68].**

Liquid tritium target:

1-- cryorefrigerator;

2 – vacuum chamber;

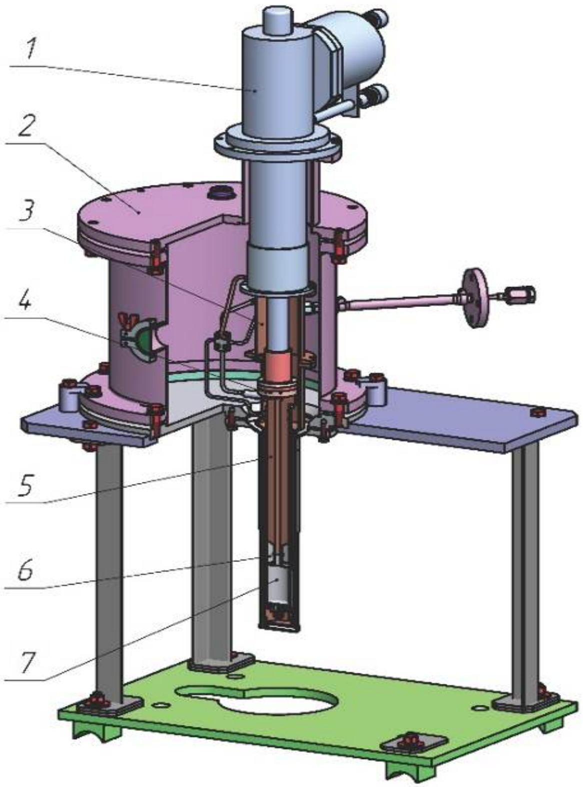
3 – vacuum insulation;

4 – heater;

5 – cold duct;

6 – container;

7 – liquid H/T mix



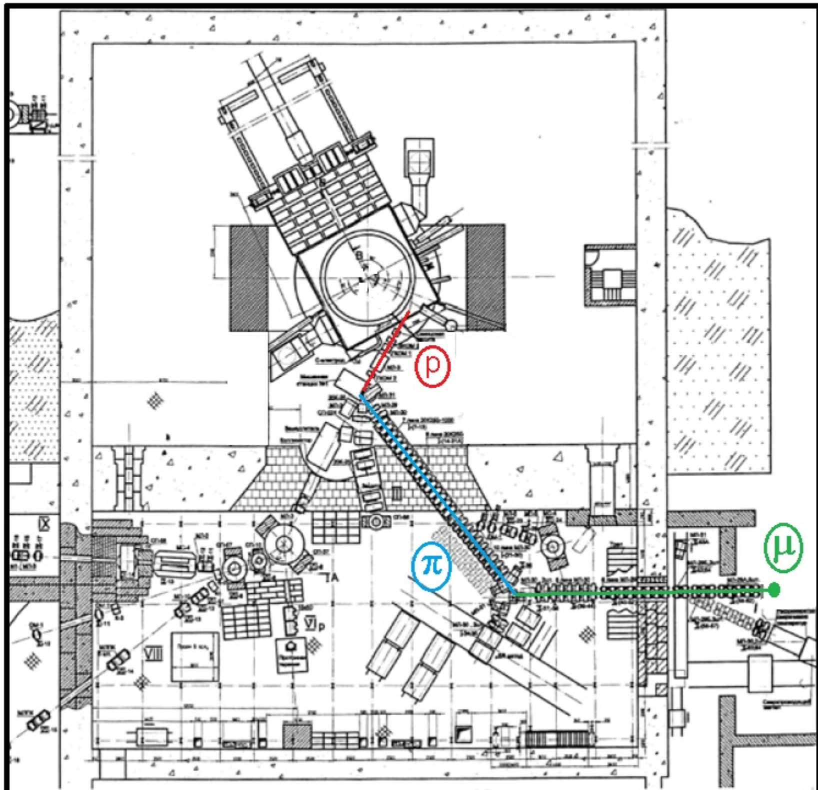
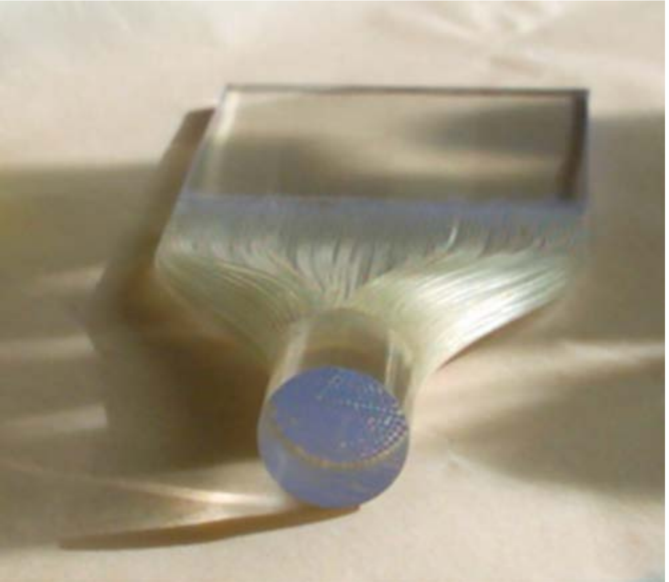


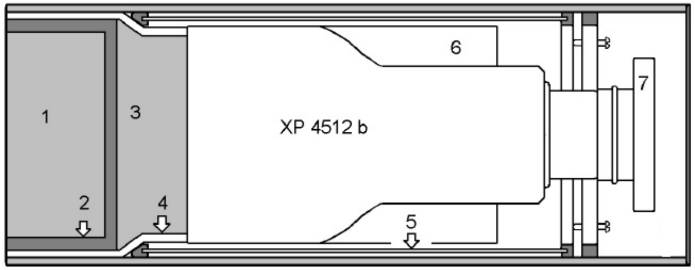
Fig.1. JINR Phasotron:
- proton channel,
- pion channel,
- muon cnannel

“ЖИДКОТРИТИЕВАЯ МИШЕНЬ ДЛЯ ИССЛЕДОВАНИЯ РЕАКЦИЙ ptμ-СИНТЕЗА”
А.А. Юхимчук и др, ПТЭ. in press

Detectors:

- Compact design,
- Electrons, muons, gamma-particles,
- and pairs
- Linearity to 20 MeV,
- High efficiency,
- Spectrometric quality





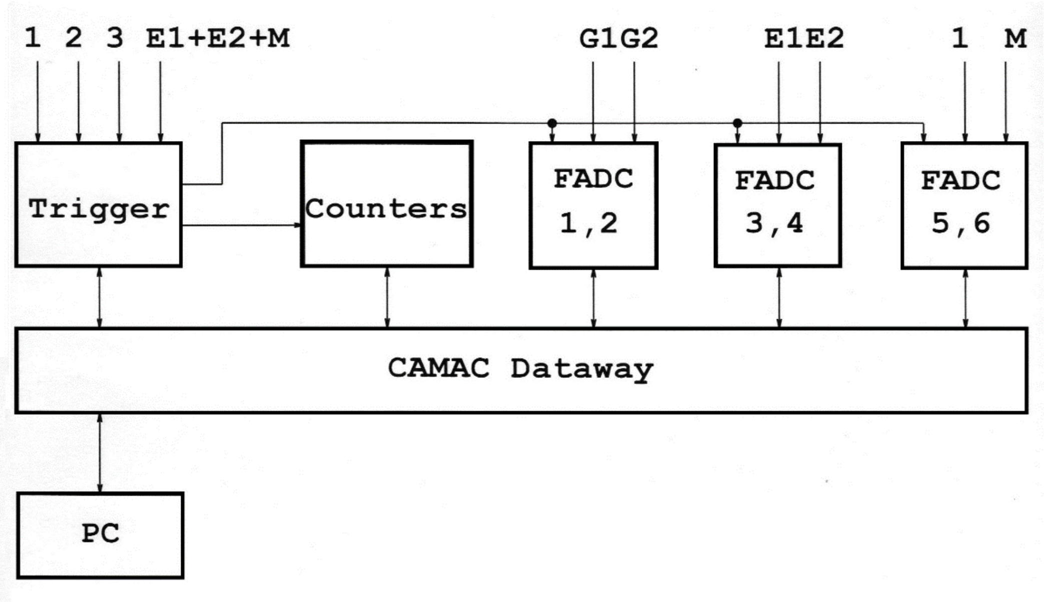
The gamma detector: 1 - BGO-crystal, 2 - plastic scintillator shell, 3 - light-guide, 4 - teflon, 5 - iron magnetic shield, 6 - permalloy magnetic shield, 7 - electronics

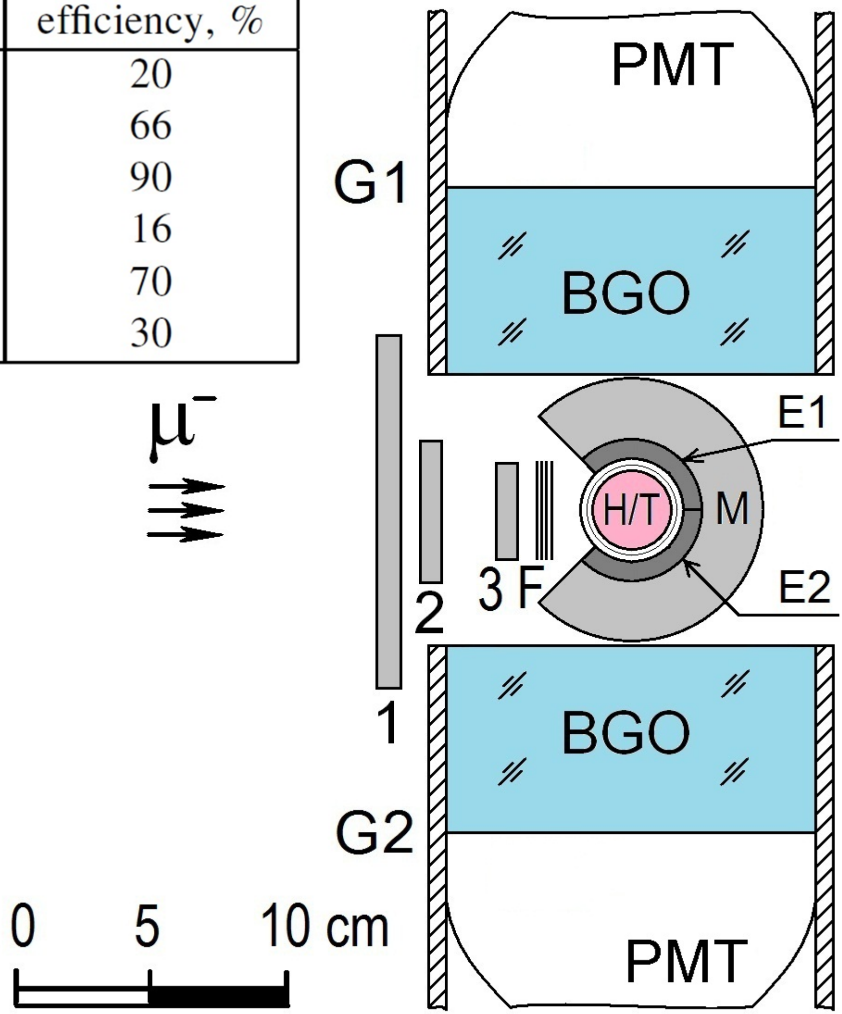
L. N. Generalov, B. L. Lebedev, K. L. Mikhailyukov, Yu. I. Vinogradov, and A. V. Livke, Preprint 104-2009, VNIIEF (Russian Federal Nuclear Center—The All-Russian Research Institute of Experimental Physics, Sarov, Russia, 2009).

Experimental installation:

1-3 – plastic counters,
BGO – crystal,
E1-E2 – electron telescope,
F – copper degrader,
G1-G2 – gamma-detector,
H/T – target,
M – muon detector (full absorption)

Particles	Registration efficiency, %
$\epsilon(\gamma)$	20
$\epsilon(\mu)$	66
ϵ (pairs 1)	90
ϵ (pairs 2)	16
$\epsilon(e_d 1)$	70
$\epsilon(e_d 2)$	30





There were 3 runs in the experiment, each approx. 100 hours

Run No.	Tritium content	Deuterium content	Gamma-detectors' angle	Triggers	Time
Dec'13	0%	10^{-4}	180 grad.	10^{6}	20 h
May'16 (1)	0.8%	10^{-4}	180 grad.	10^{7}	100 h
Nov.'16 (2)	0.08%	10^{-4}	180 grad.	10^{7}	100 h
Nov.'16 (3)	0.08%	10^{-4}	110 grad.	10^{7}	100 h

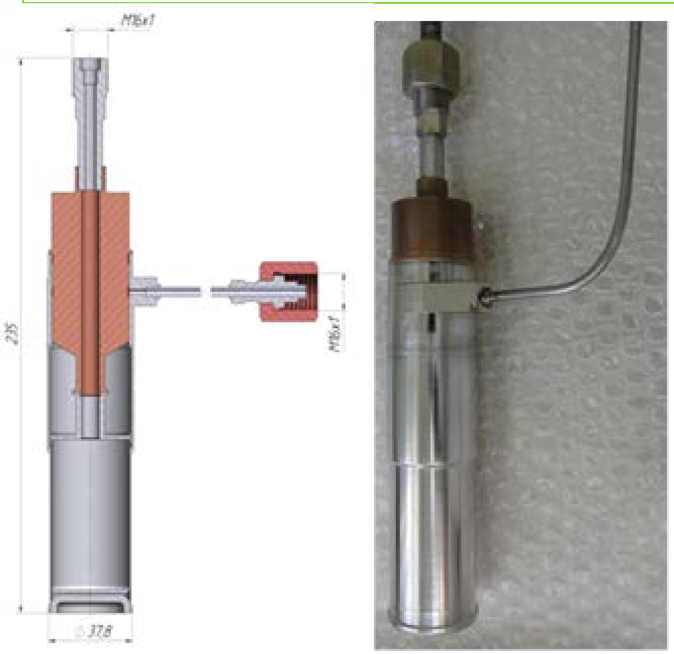


Рисунок 3 – Макет ампулы

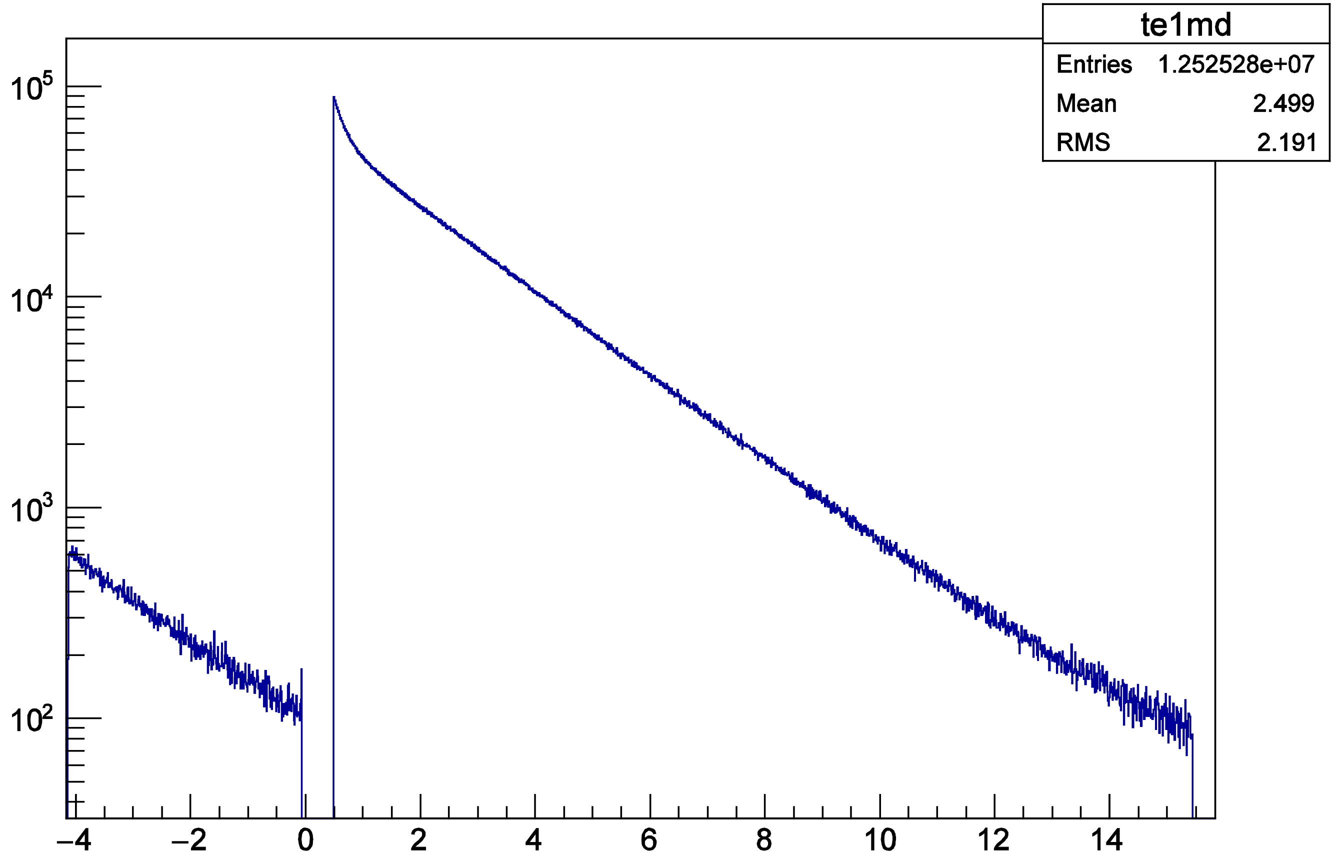
- The 50cc cryogenic target filled with liquid H/T mixture was exposed to the negative muon beam (10^{4} s^{-1}, 100 MeV/c) of JINR Phasotron in 2016.
- Run-time duration is 270 h.
- The experiment is aimed at measuring the product yields of the pt-reactions: γ-quanta, conversion muons and $e^{+}e^{-}$ pairs.

Experimental spectra:

Time spectrum of μ-decay electrons
(is used for MC normalization)

$$N_e^{\text{total}}(t) = A_e \exp(-\lambda_e t) + k\, B_{\text{empty}}(t) + F$$

N

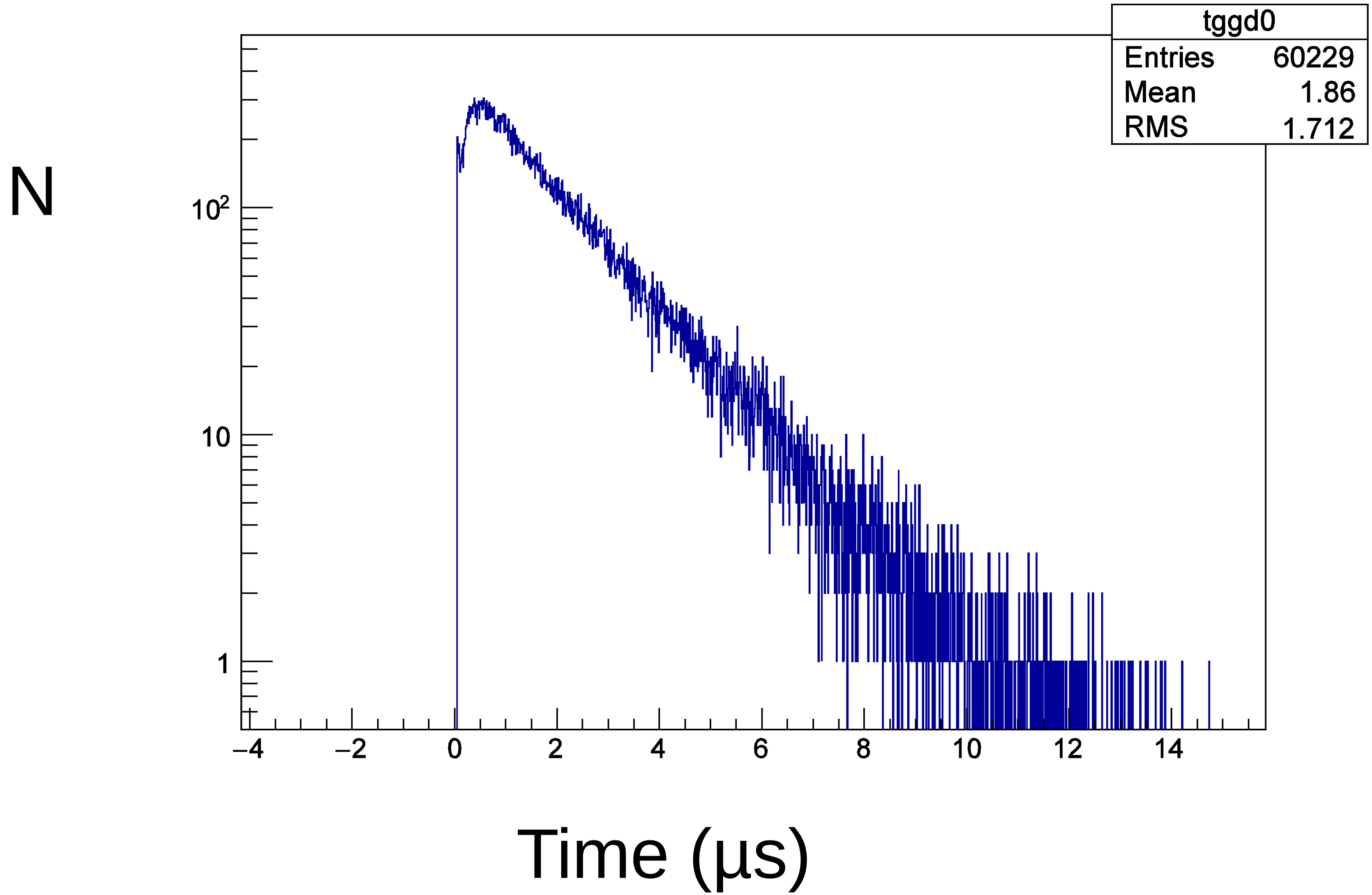


Time (μs)

Experimental spectra:

Time spectrum of gamma-quanta

- $pt\mu \rightarrow {}^4He\mu + \gamma + 19.8$ MeV

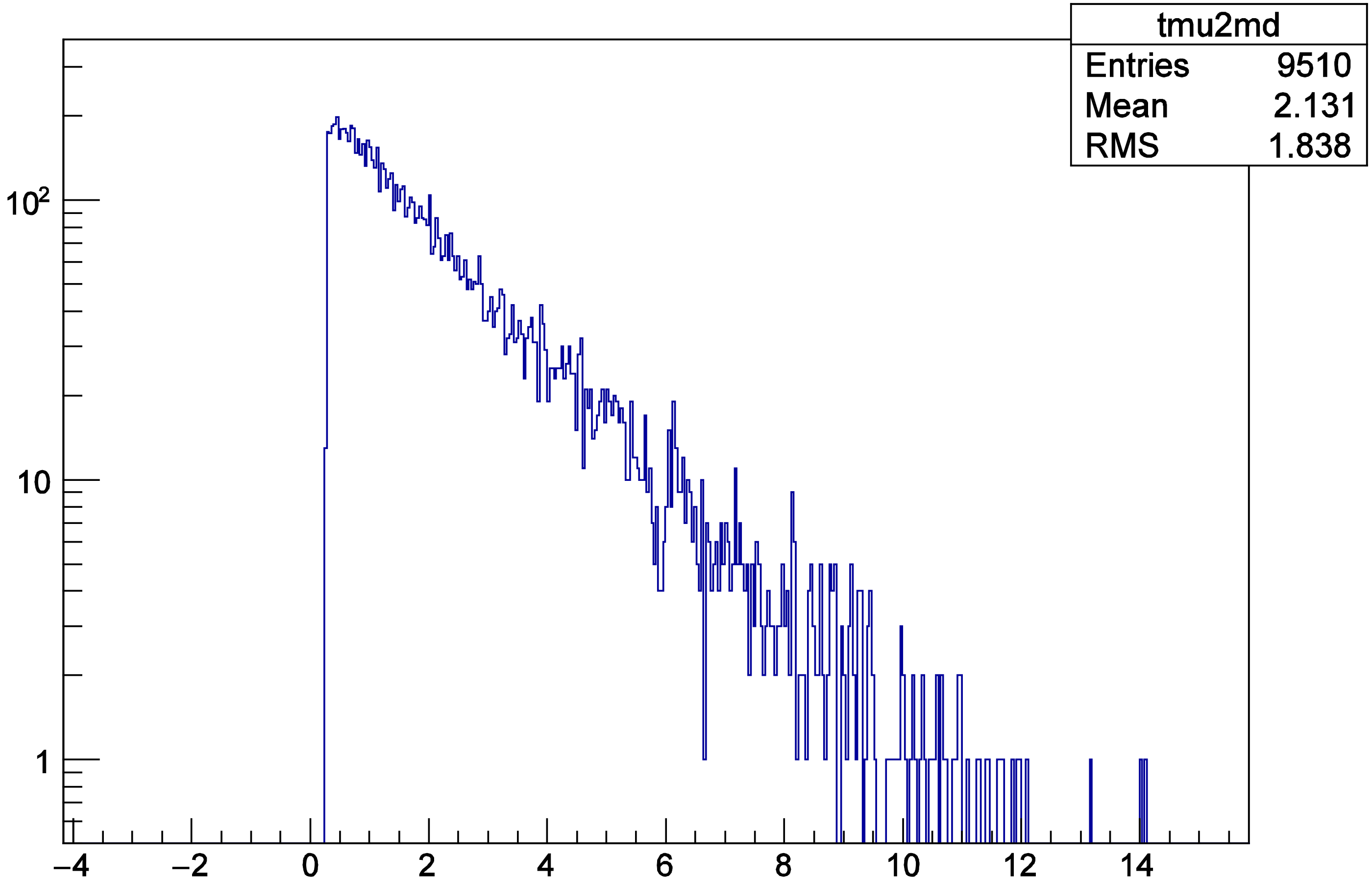


Experimental spectra:

Time spectrum of conversion muons

- ptμ → ^{4}He + μ+19.2 MeV

N



Time (μs)

Comparison of the rates of the nuclear reaction from the analysis of time spectra:

The preliminary results of **TRITON** experiment (2016)

λ_{pt}^{γ} (I_{pt}=1) = 0.065±0.004(stat) μs^{-1}(fusion rate)

λ_{pt}^{μ} (I_{pt}=0) = 0.11±0.01(stat) μs^{-1} (muon conversion rate)

PSI results [Phys. Rev. Lett. 70(1993)3720]

λ_{pt}^{γ} (I_{pt}=1) = $0.067 \pm 0.002_{-0.002}^{+0.005}$ μs^{-1}(fusion rate)

λ_{pt}^{μ} (I_{pt}=0) = 0.15±0.02 μs^{-1} (muon conversion rate)

Registration of yields of paired particles

One of the goals of our experiment was detecting the yield of $\mathbf{e^+e^-}$ pairs, which were not observed in the PSI-93 experiment with **ptμ** molecule

ptμ → **^{4}He + μ (conv),**

ptμ → **^{4}Heμ + e^+e^-.**

$$R = \frac{Y_\mu}{Y_{e^+e^-}} = 0.73 \quad \text{(theory)}$$

[PR 56(1939)1066] [MCF 4(1989)103]

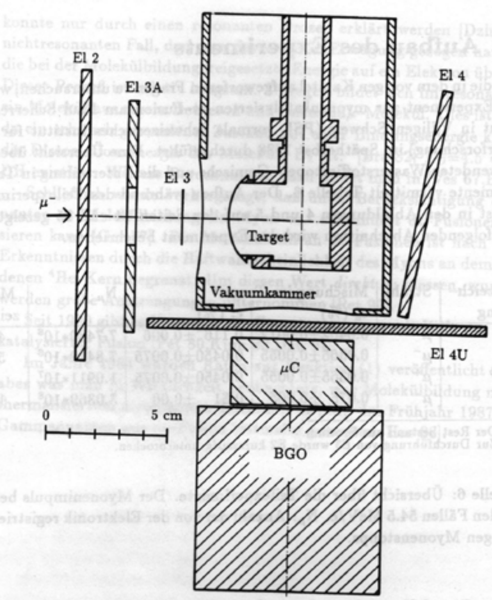


Abb. 4: Vertikalschnitt des Aufbaus (Teilexperiment E2). Angegeben sind Namen des Detektors, Meßzweck (Detektormaterial): μC, Zähler für Konversionsmyonen (Szintillator NE 102A); Ge(hp), Gammaquanten (Reinstgermanium); BGO, Gammaquanten (Szintillator Wismut Germanat); Ge(X), Röntgenstrahlung (Germanium); El 2, El 3, El 4, El 4R und El 4U, Elektronenzähler (Szintillator NE 102A); N1, Neutronen (Szintillator NE 213). Weitere Erklärungen siehe Text und Tabelle 8.

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[Phys. Rev. Lett. 70(1993)3720].

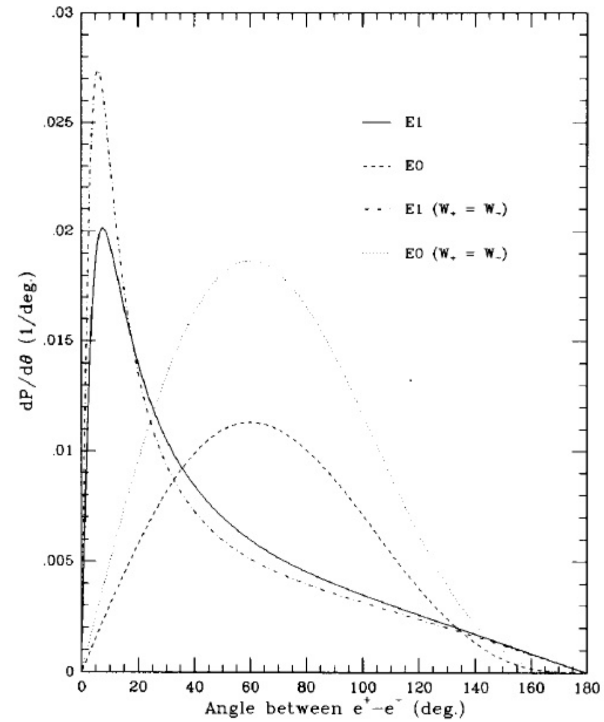


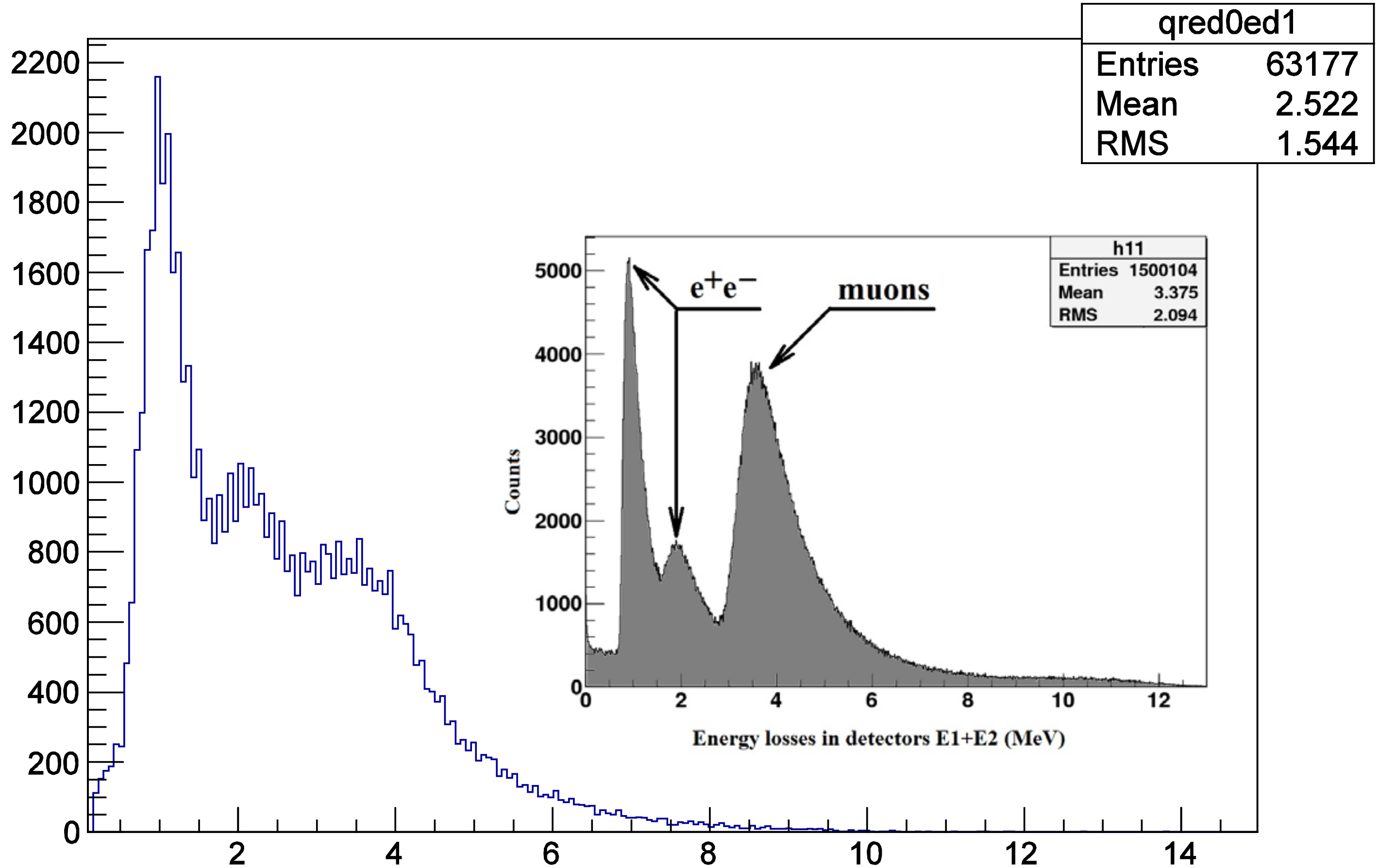
Fig. 4. The e^+-e^- angular correlation for a 15 MeV E0 and E1 transition. Also indicated is the strong effect which a requirement of equal energy sharing has on the angular correlations. The normalization of the curves is such that the two E1 curves have equal areas and the E0 curves are obtained assuming transition probabilities equal to the respective E1 transitions.

[NIM A 334(1993)437]

Experimental spectra (paired charged particles):

Sum energy spectrum of conversion muon and electron-positron pairs in electron telescope E1+E2

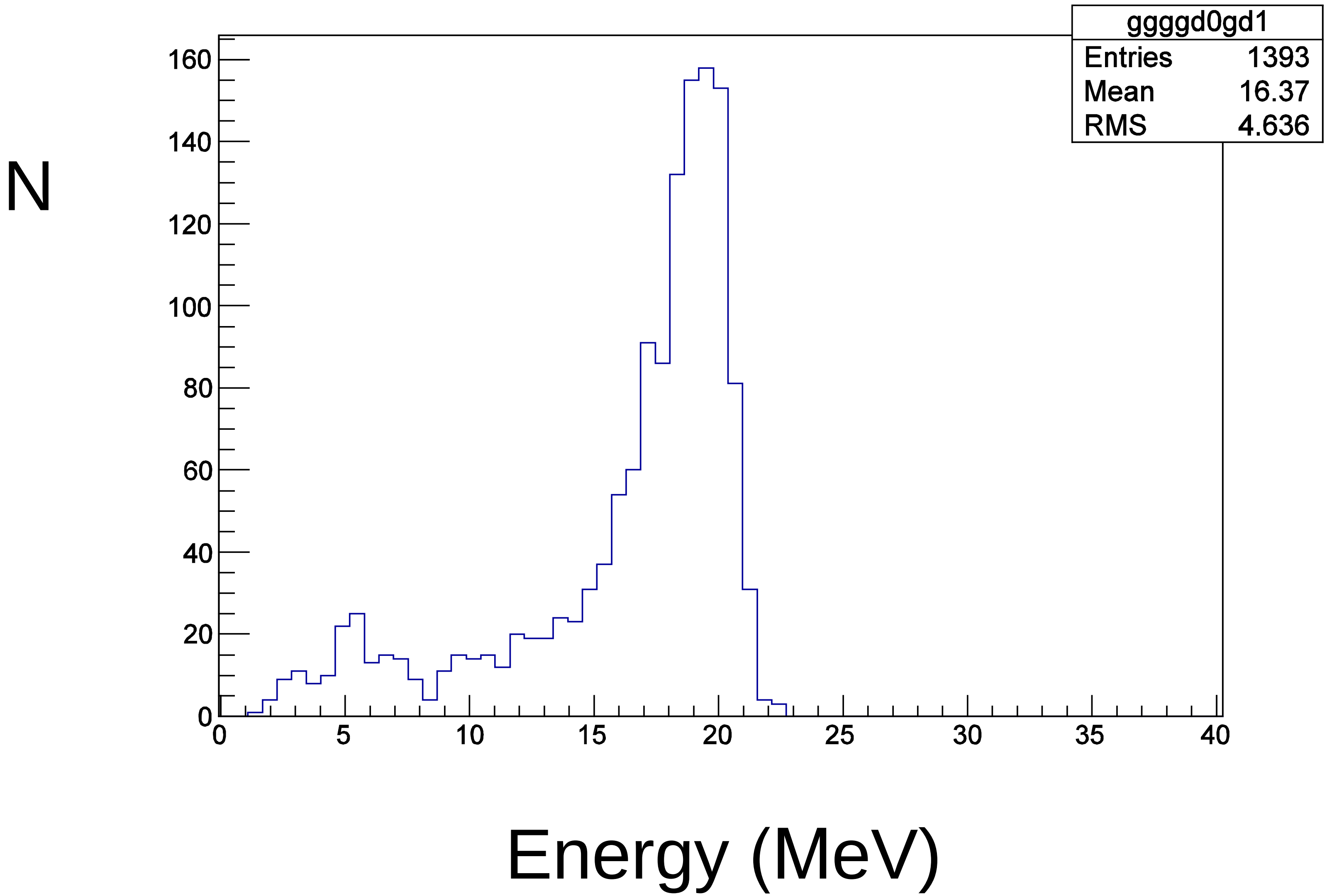
N

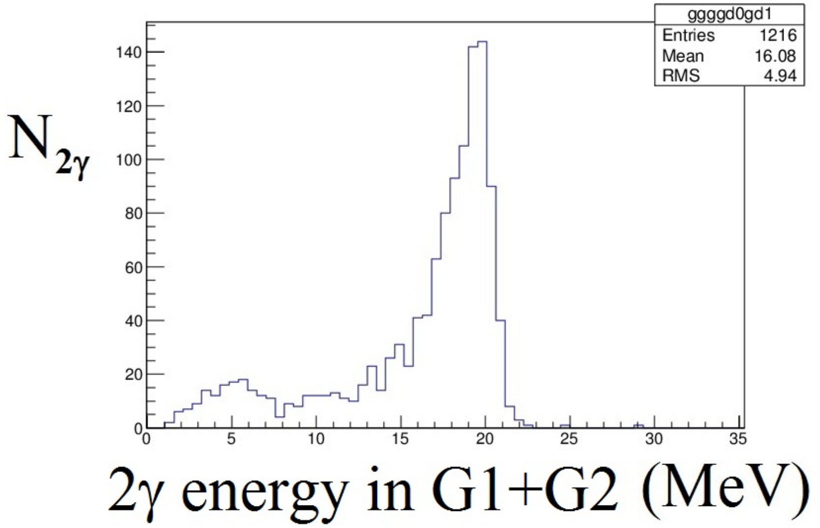


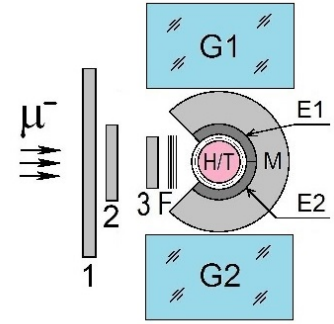
Energy (Mev)

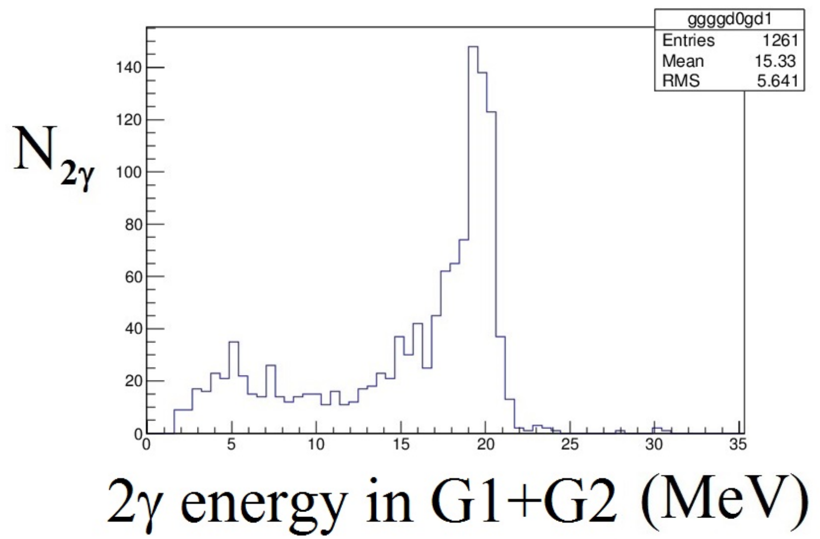
Experimental spectra (paired neutral particles):

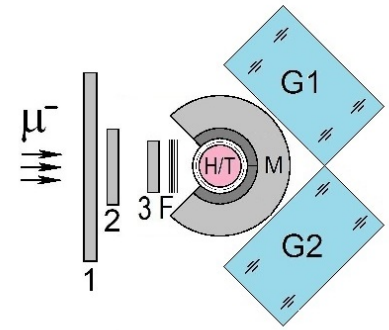
Sum energy spectrum of gamma-quanta pairs in detectors G1+G2 (May’16)











2γ-yield of pt-reaction at tritium concentration c_t = 0.08% on the same statistics for two different relative positions of gamma detectors: a relative angle of 180 degrees (top), 110 – (bottom). Nov’16.

Registration of e^+e^- pairs and pairs of gamma quanta

For the first time the channel of pt-reaction with electron-positron pair output

$$pt\mu \rightarrow {}^4He\mu + e^+ + e^- + 18.79\ MeV$$

was observed. The statistics collected on the TRITON installation in 2016

is **about 15 thousand** events.

For the first time the reaction channel with output of two gamma quanta

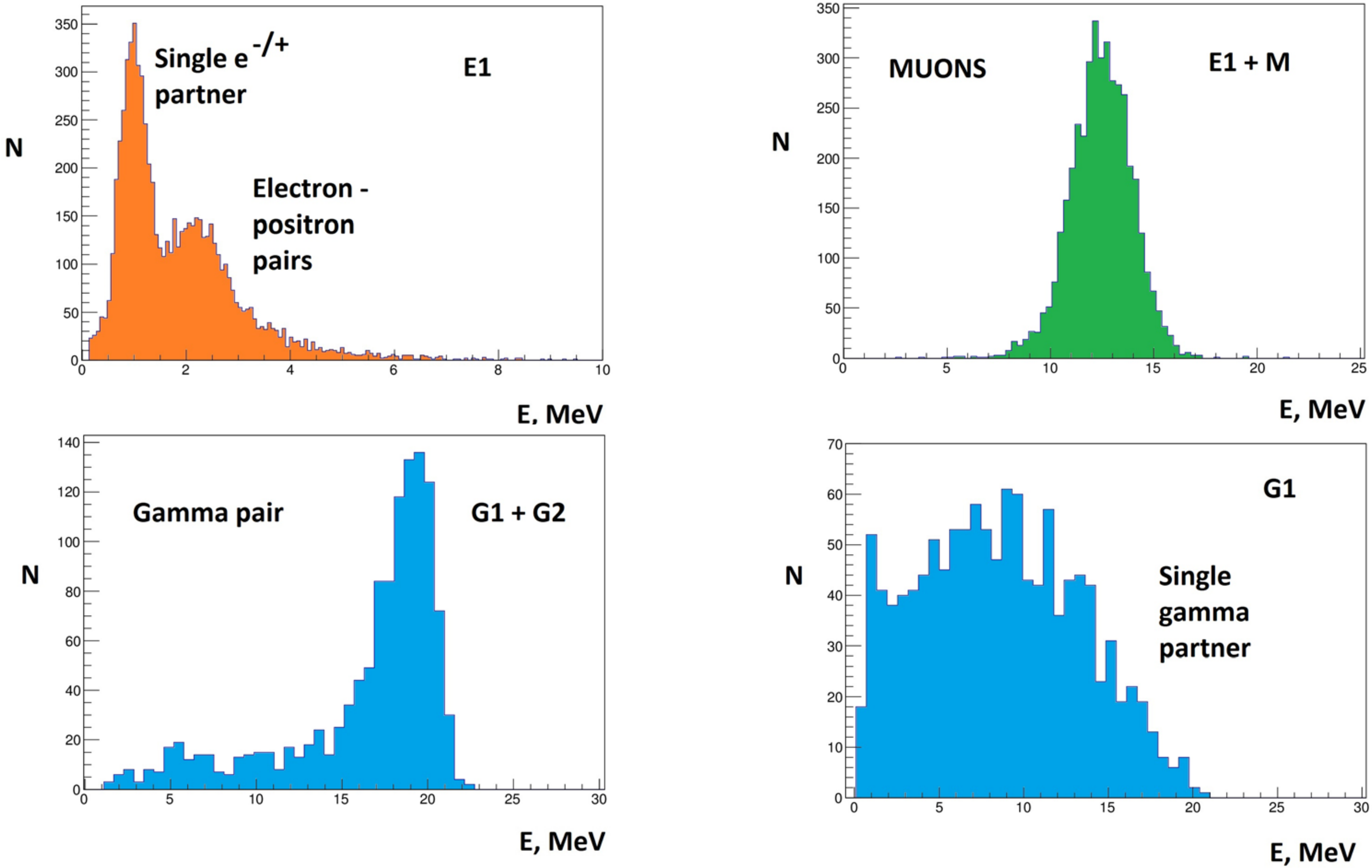
$$pt\mu \rightarrow {}^4He\mu + 2\gamma + 19.82\ MeV\ (E_{\gamma 1} + E_{\gamma 2} \geq 19.77\ MeV)$$

was observed. The statistics is **over 3 thousand registered** double events that satisfy the selection criteria for gamma quanta simultaneously recorded in each of two gamma detectors. Measurements with different geometry of the installation in November 2016 (gamma detectors were first set at a relative angle of 180, then 110 degrees) do not give a convincing evidence of the angular correlation between γ-quanta in 2γ-pair.

Also the reaction channel **(5)** with output of two gamma quanta has been given the **first indication** in our experiment (**about 100 events registered**).

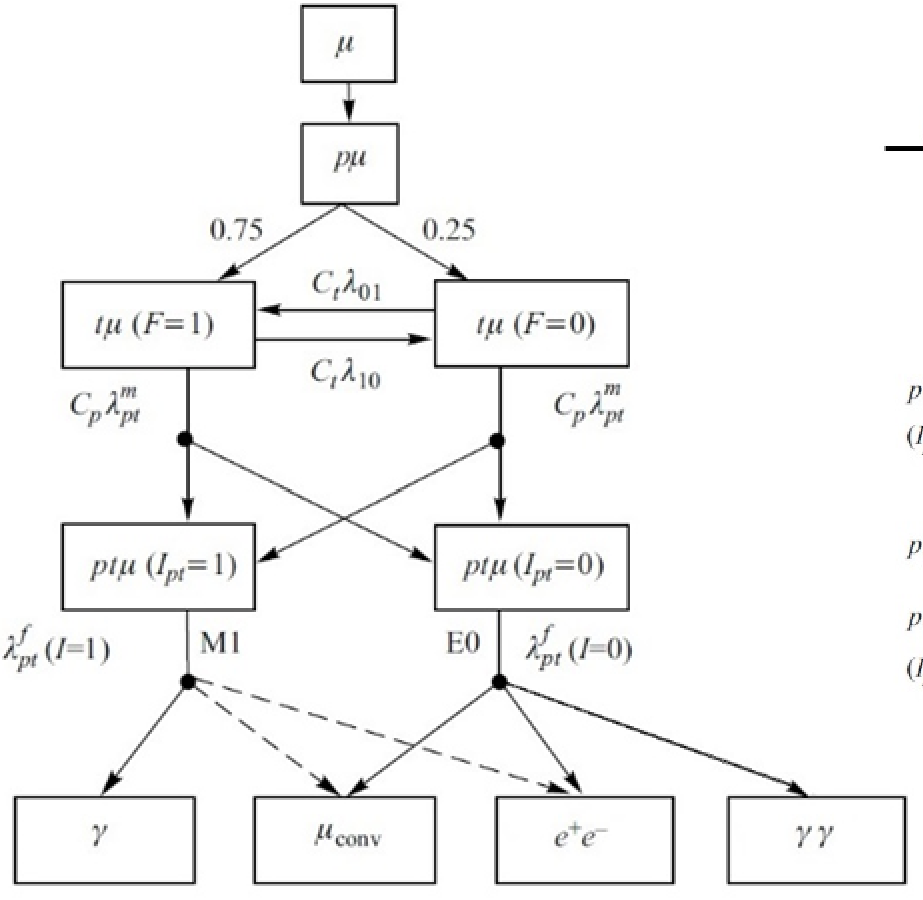
$$pd\mu \rightarrow {}^3He\mu + 2\gamma + 5.5\ MeV\ (E\gamma 1 + E\gamma 2 \geq 5.49\ MeV) \quad \mathbf{(5)}$$

Experimental spectra for E0 transition

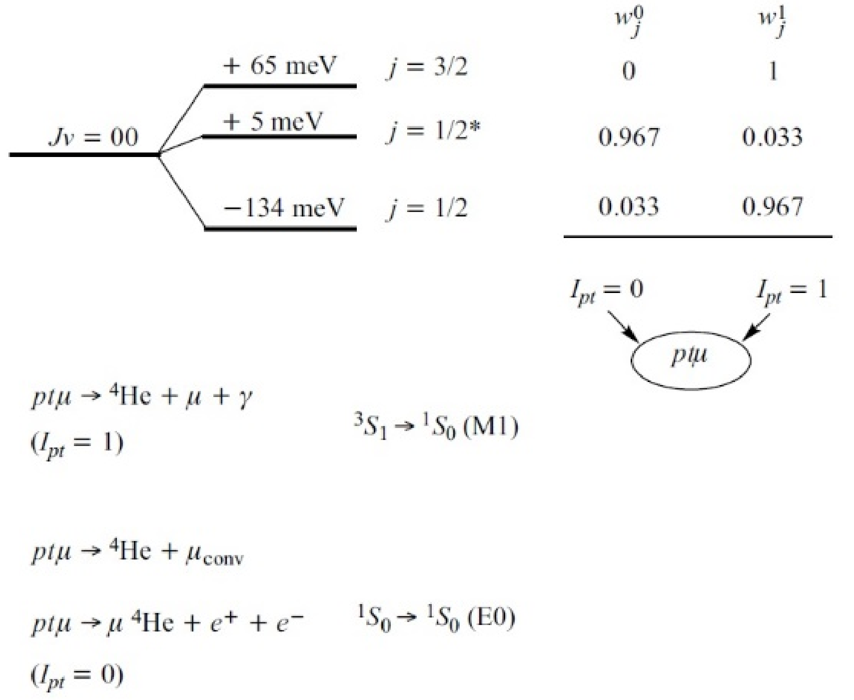


[Phys. Part. Nucl. Lett., 2012, Vol. 9, No. 8, pp. 605–614]

The package of computing programs on the basis of Monte Carlo method, allowing simulations of numerous muon atomic and molecular processes accompanying μCF was developed.

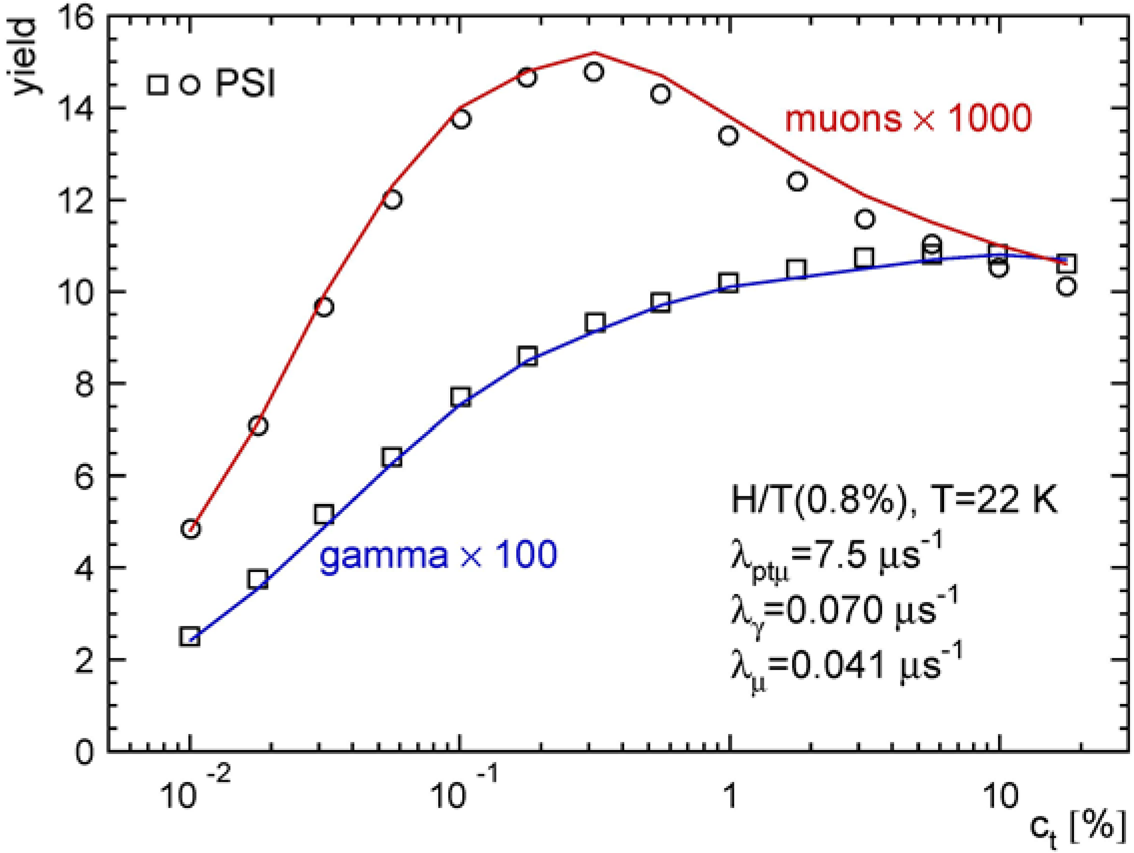


Scheme of the MC processes in H/T mixture



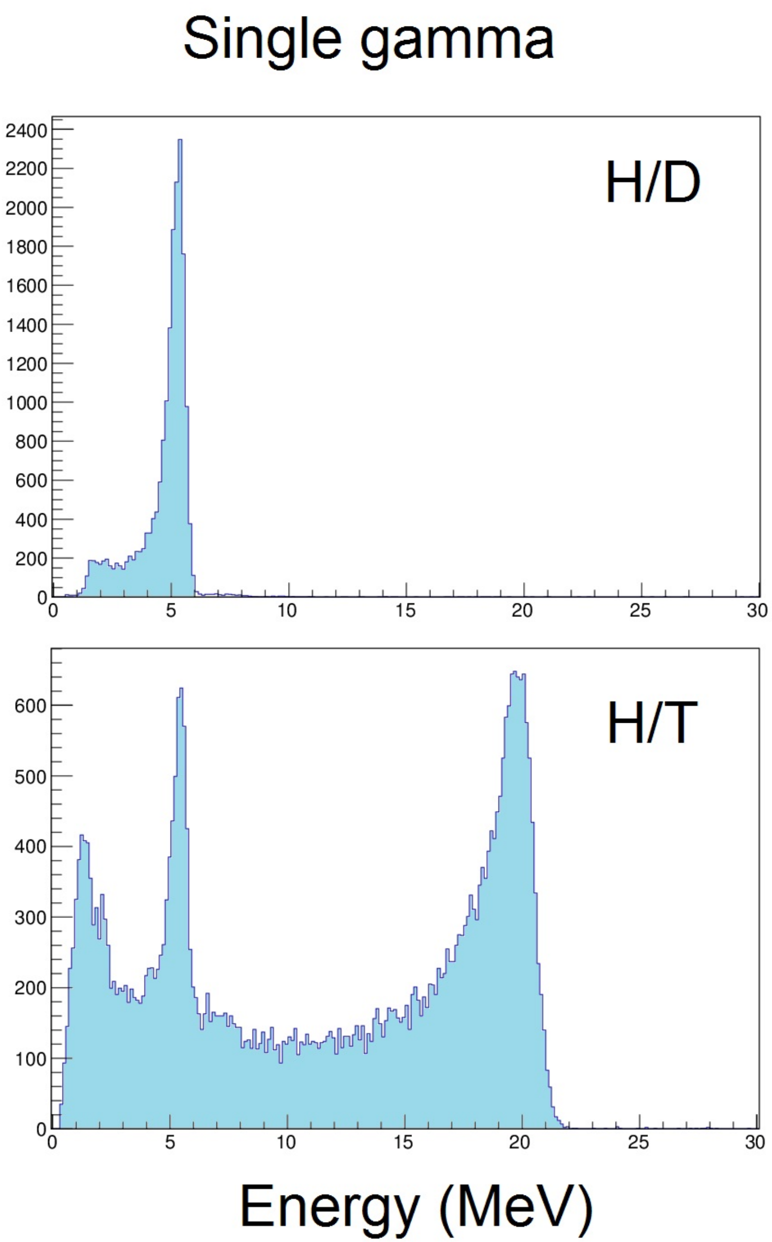
Hyperfine structure of $pt\mu$ ground state

The dependences, obtained by two different (PSI and our) calculating programs of kinetics modelling the μCF processes, are in quite good agreement.



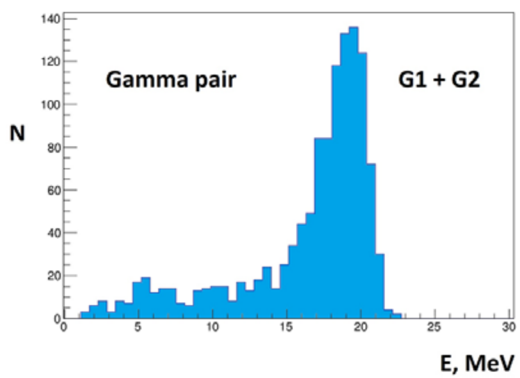
Yields for conversion muons (circles) and γ emissions (squares) in pt fusion as a function of tritium concentration c_t (PSI, 1993). Respectively, red and blue curves correspond to results of our MC simulations at fixed parameters (presented on plot).

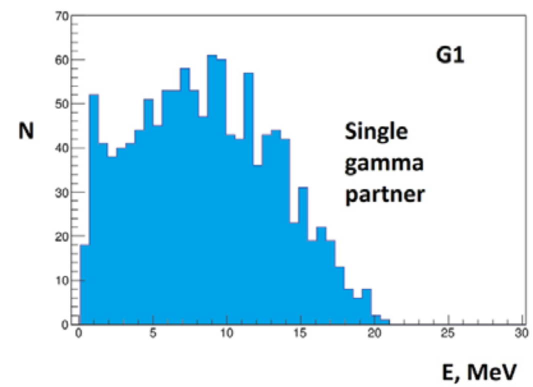
Experimental spectrum for **M1** transition



"The results of a measurement on **pd** fusion… agree with the results of several calculations. An attempt to extend the method to **pt** fusion was undertaken by the PSI group in 1988. The measurements suffered from **unexpectedly bad resolution of the detector**…"
[MCF 5/6(1990/91)277]

Now we know – there's an unavoidable systematic pile-up of 1-gamma and 2-gamma in the region E ~ 10 MeV

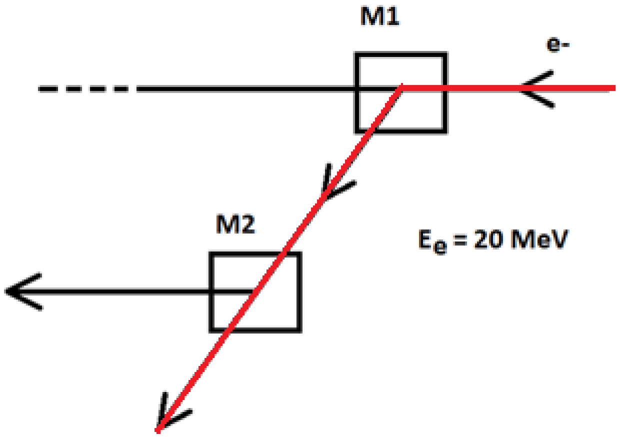




Study of Triton experimental equipment. Using electron beam of LINAC-200 [V.V.Kobets et al., LINAC2018, Beijing, 16-21 Sept. 2018] and Monte Carlo simulation for measurement calibration.

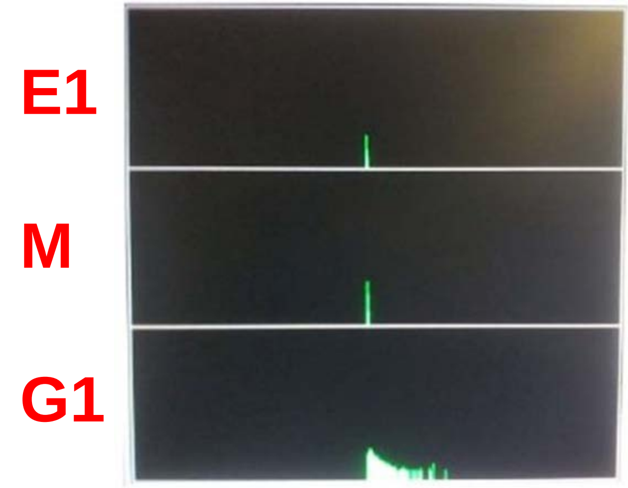
Joint Institute for Nuclear Research, Febrary 2018

Experimental setup:

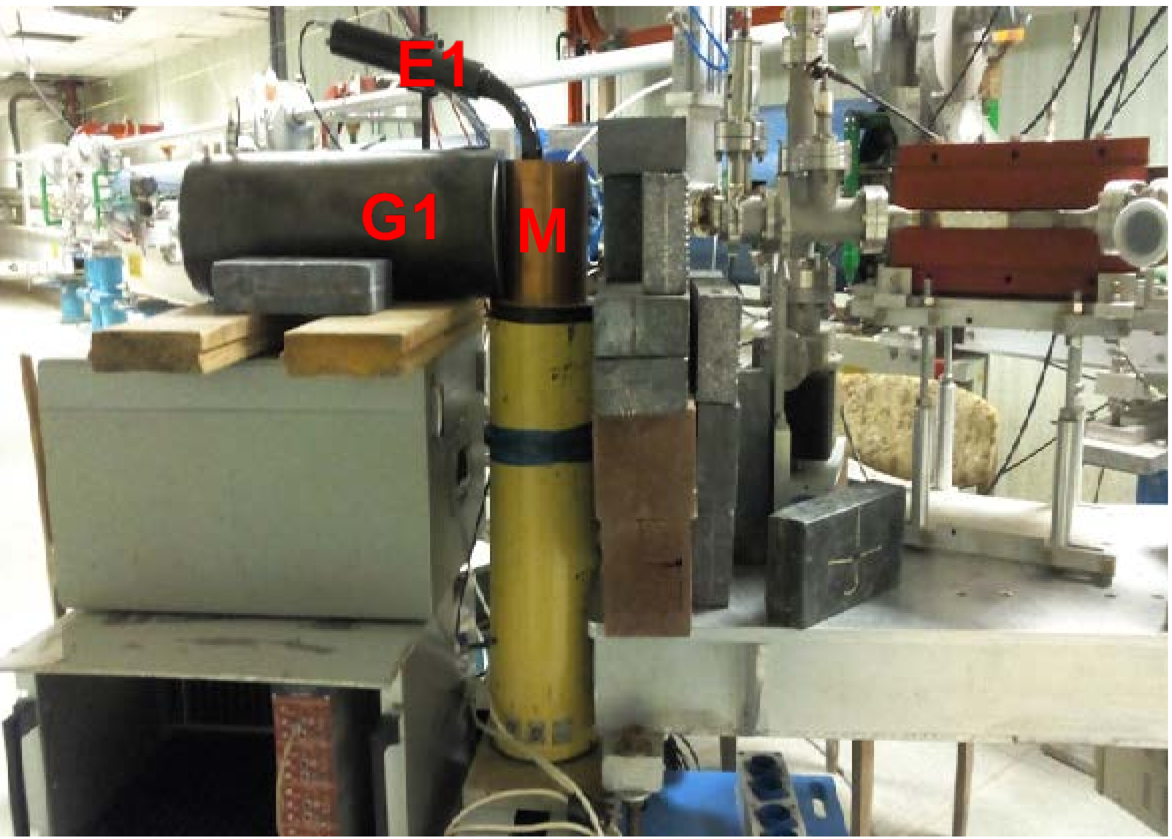


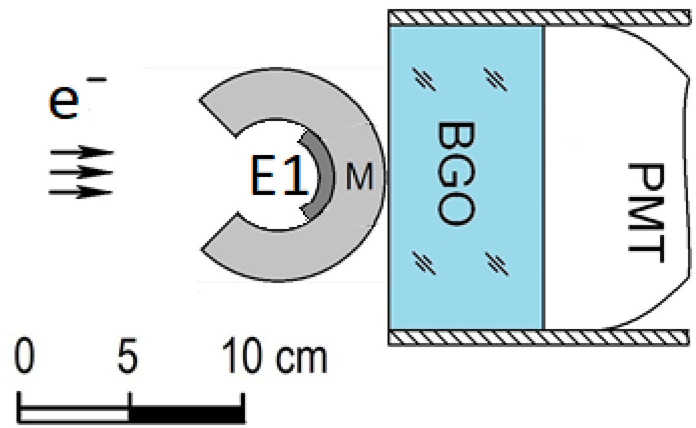
Triton detection system tested on electron beam of LINAC-200 :

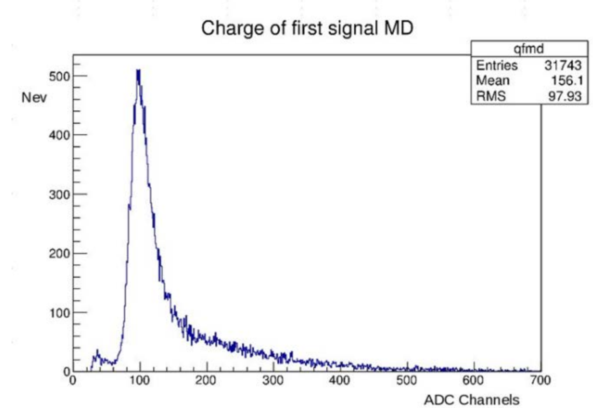
BGO – crystal BGO (Ø126 x 60 mm),
E1-E2 – electron telescope (5 mm),
M – conversion muon detector (19 mm)
G1-G2 – gamma-detector,



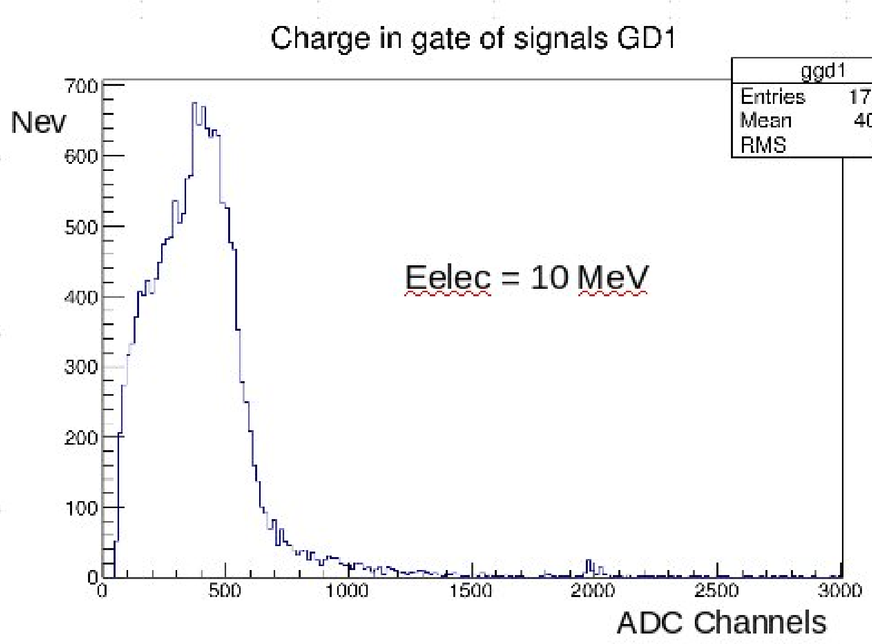
G1

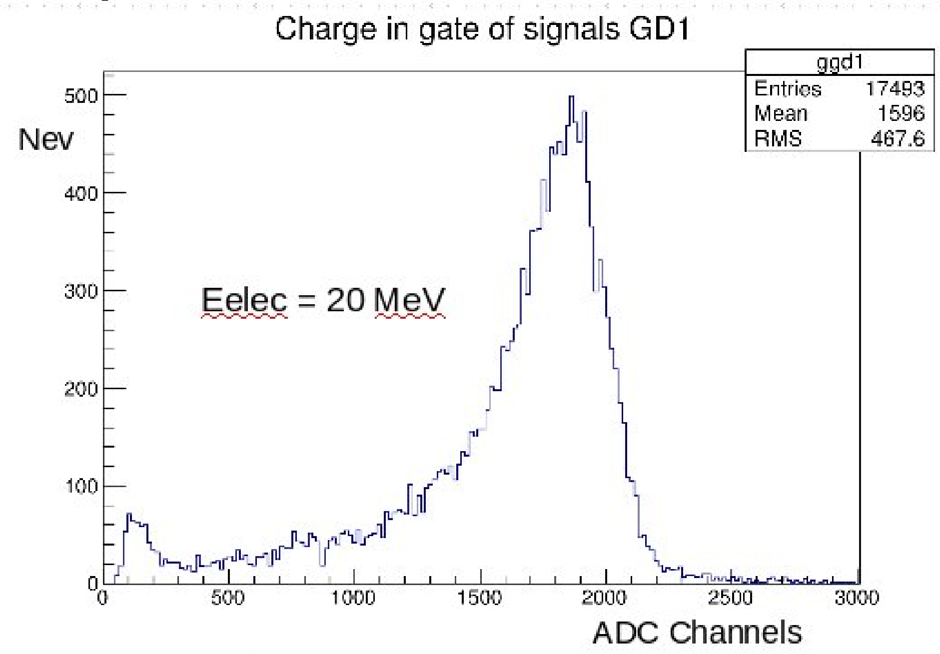






Experimental spectra (electrons):

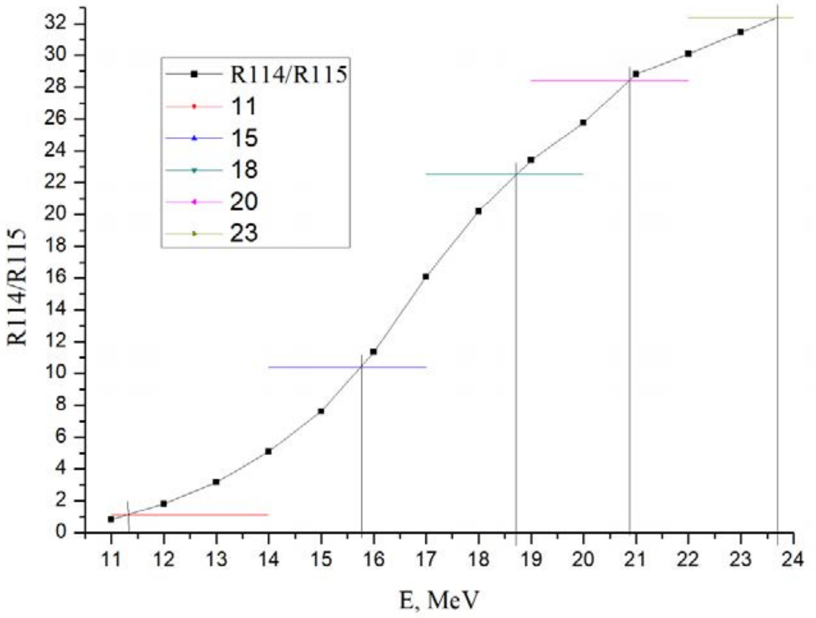




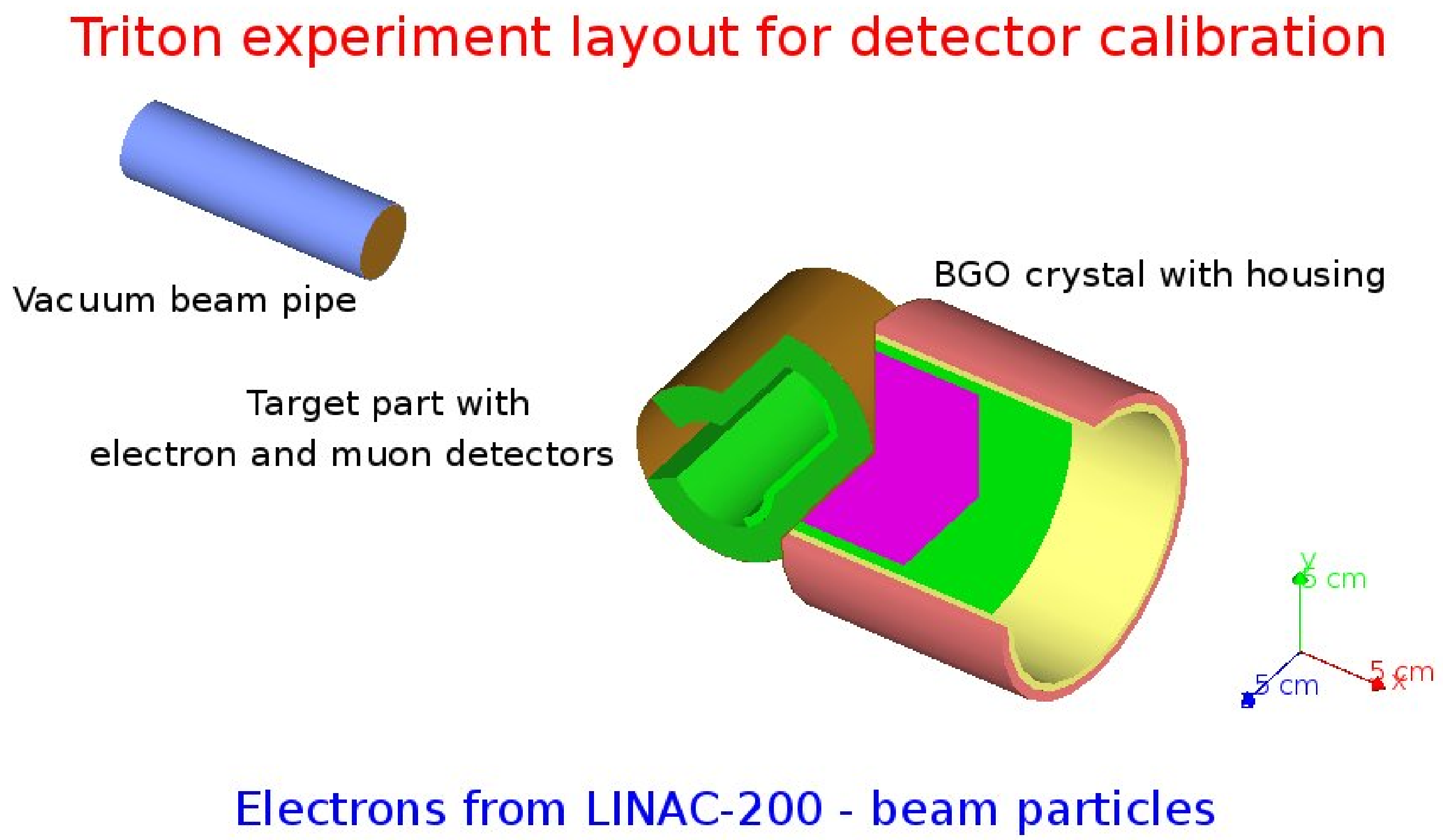
Beam calibration with the order of accuracy 1%):

[M.I.Gostkin, U.Kruchonak, A.S.Zhemchugov, to be published]

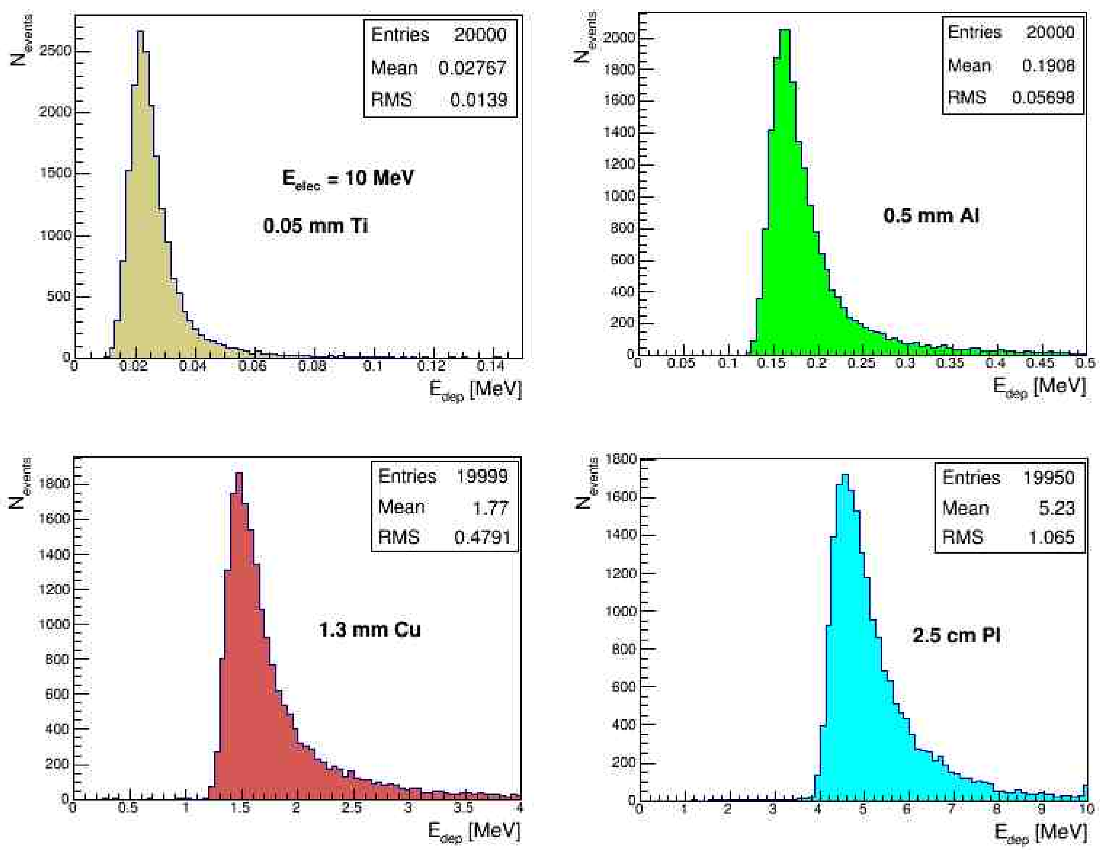
Method of calibration used - the ratio of photoactivation of ^{114}In-^{115}In isotopes: **[NIM A 901(2018)133]**



Using Monte Carlo simulation for Triton measurement calibration

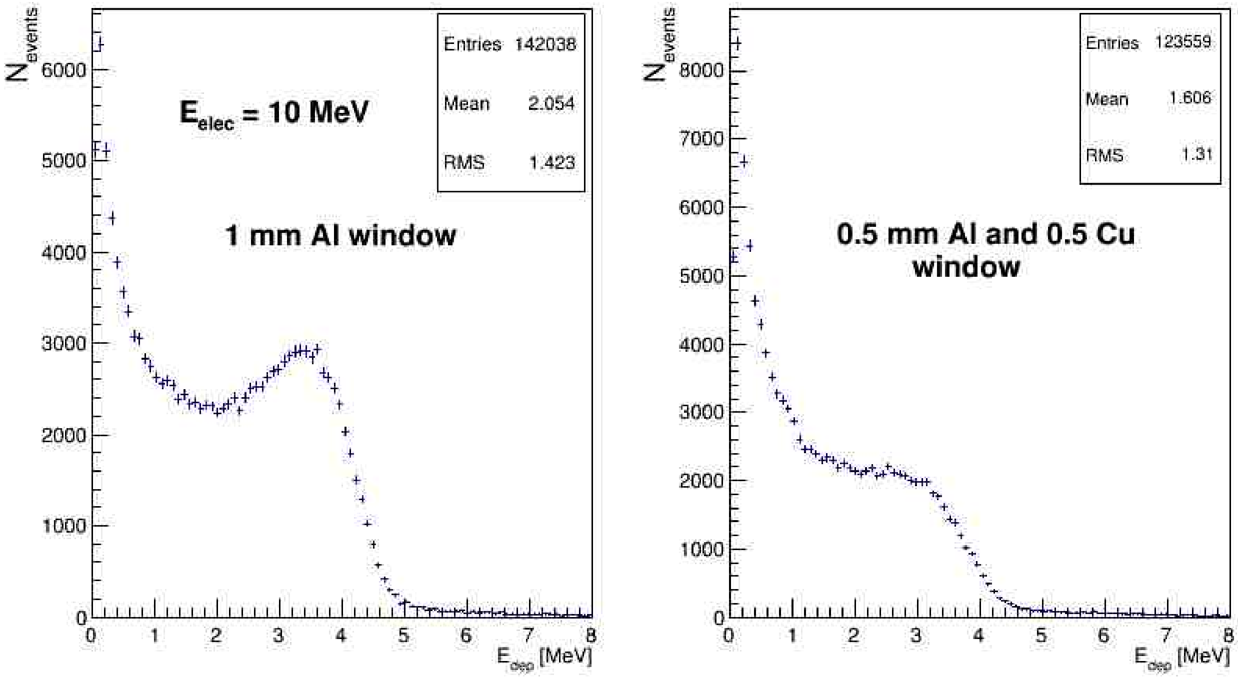


Energy deposition in matter in front of gamma detect



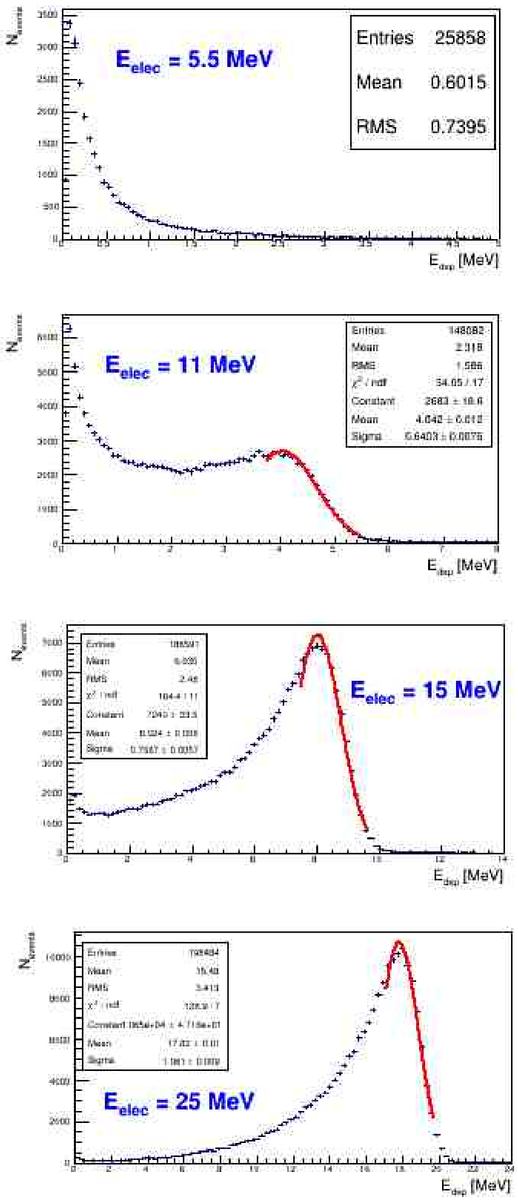
The effect of the gamma detector window on the energy deposited

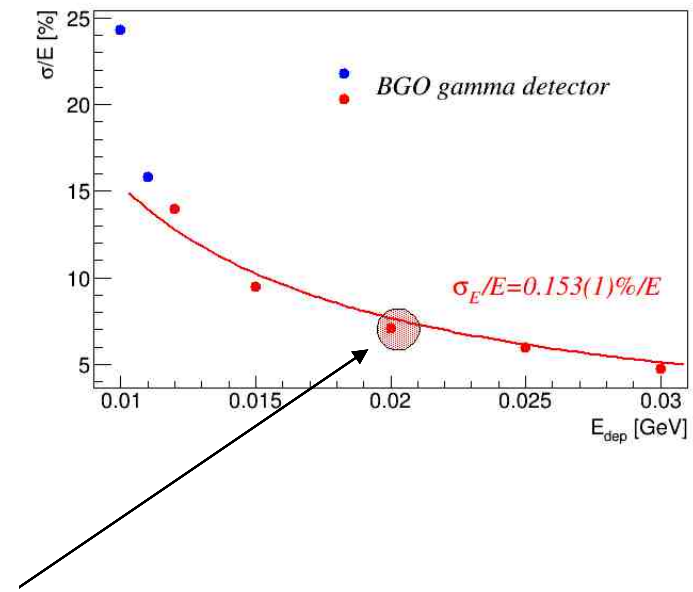
in the BGO crystal



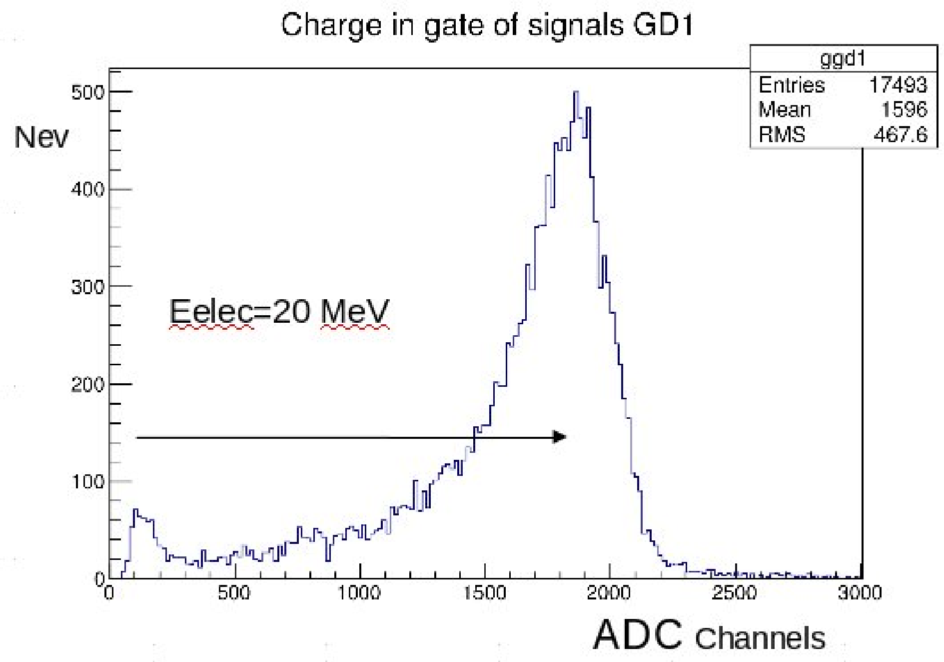
For Cu we have ~16.6 MeV/cm, for Al – 4.6 MeV/cm energy deposited

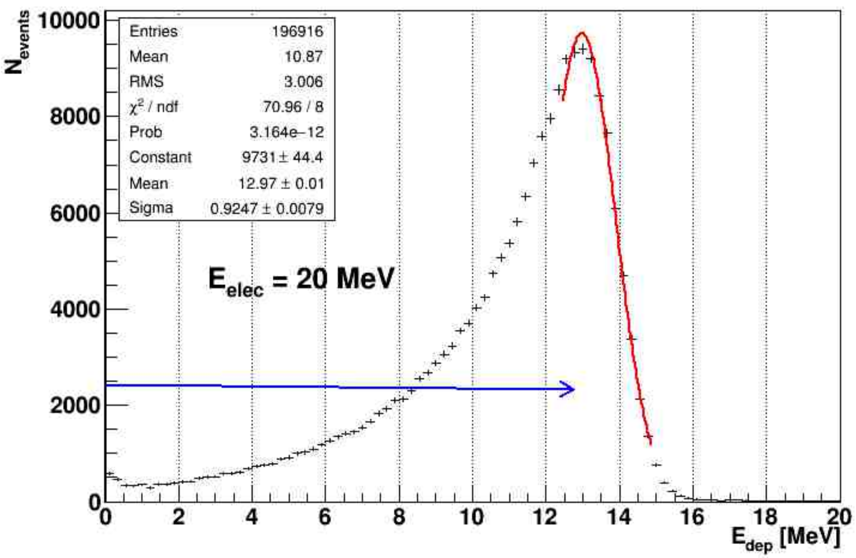
For scintillator, which widely used in setup - ~2 MeV/cm





The calibration of gamma detector in this case was made using data at E = 20 MeV





We found that each ADC channel corresponds to an energy of 7.4 keV

Applying this value to the measured data for Eelec=10 and 15 MeV, we obtained for the peak values ~3 and 7.7 MeV. When modelling for these values of electron energies, we have ~8 and 3 MeV, respectively.

CONCLUSIONS

1. **The obtained results confirm theoretical predictions** of Ya.B. Zel'dovich and S.S. Gershtein (1960) on the output products of nuclear reactions in cold hydrogen isotope mixtures caused by muons.

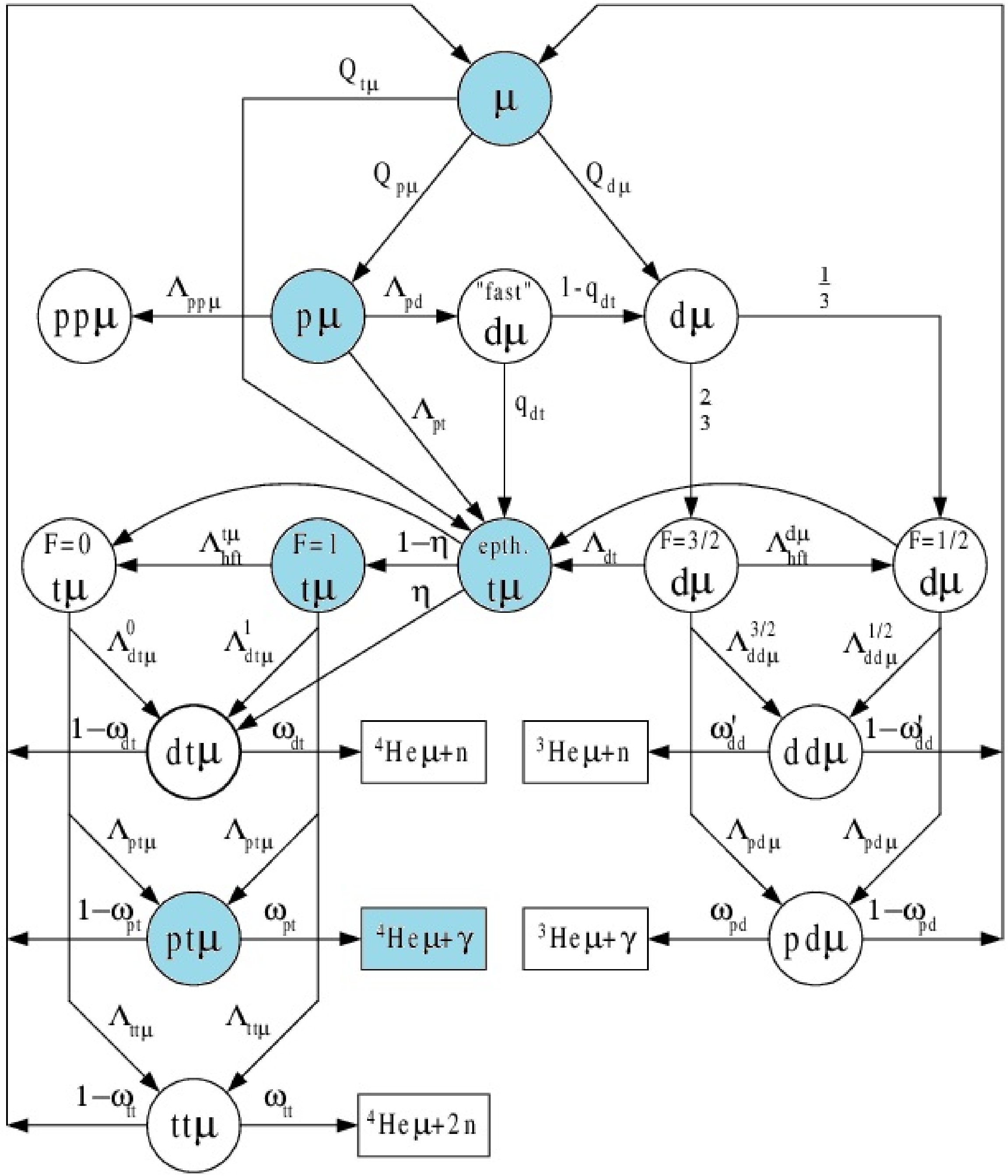
2. The preliminary analysis of data and obtained rates of previously observed pt-fusion channels with the yield of single gamma quanta and conversion muon **agree well with results of PSI experiment** [Phys. Rev. Lett. 70(1993)3720].

3. The pt-fusion channel with the output of electron-positron pairs as well as the channel with the output of a pair of gamma quanta were registered in our experiment **for the first time**.

4. The **first indication is made** for the output channel with a pair of gamma quanta in pd-fusion.

Thanks for attention

Additional slides below



μ
Q tμ
Q pμ
Q dμ
ppμ
Λ ppμ
pμ
Λ pd
"fast" dμ
1-q dt
dμ
1/3
Λ pt
q dt
2/3
F=0 tμ
Λ tμ hft
F=1 tμ
1−η
epth. tμ
η
Λ dt
F=3/2 dμ
Λ dμ hft
F=1/2 dμ
Λ 0 dtμ
Λ 1 dtμ
Λ 3/2 ddμ
Λ 1/2 ddμ
1−ω dt
dtμ
ω dt
4Heμ+n
3Heμ+n
ω′ dd
ddμ
1−ω′ dd
Λ ptμ
Λ ptμ
Λ pdμ
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3Heμ+γ
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ttμ
ω tt
4Heμ+2n

Programme Advisory Committee for Nuclear Physics 46th meeting, 14–15 June 2017 Recommendations

The PAC heard a report on the results obtained in the TRITON experiment presented by D. Demin. The PAC notes that the measured rates of the nuclear reaction p + t in the channels with the output of the gamma quantum and muon conversion **confirm the results of the only PSI experiment (1993) and are in substantial contradiction with the modern theory**. Taking into account the new data on previously not observed pt-fusion channels with the emission of an electron-positron pair and gamma-quantum pair, as well as the complexity of the method of investigation, the PAC recommends continuation of the activity in the TRITON experiment in order to carry out in particular:

– modeling of kinetics of mesoatomic and mesomolecular processes in the target;

– calibration of detectors on an electron beam with an energy up to 20 MeV;

– development of a technique for modeling the channel registration process with the emission of two gamma quanta from the pt-fusion reaction in the TRITON installation;

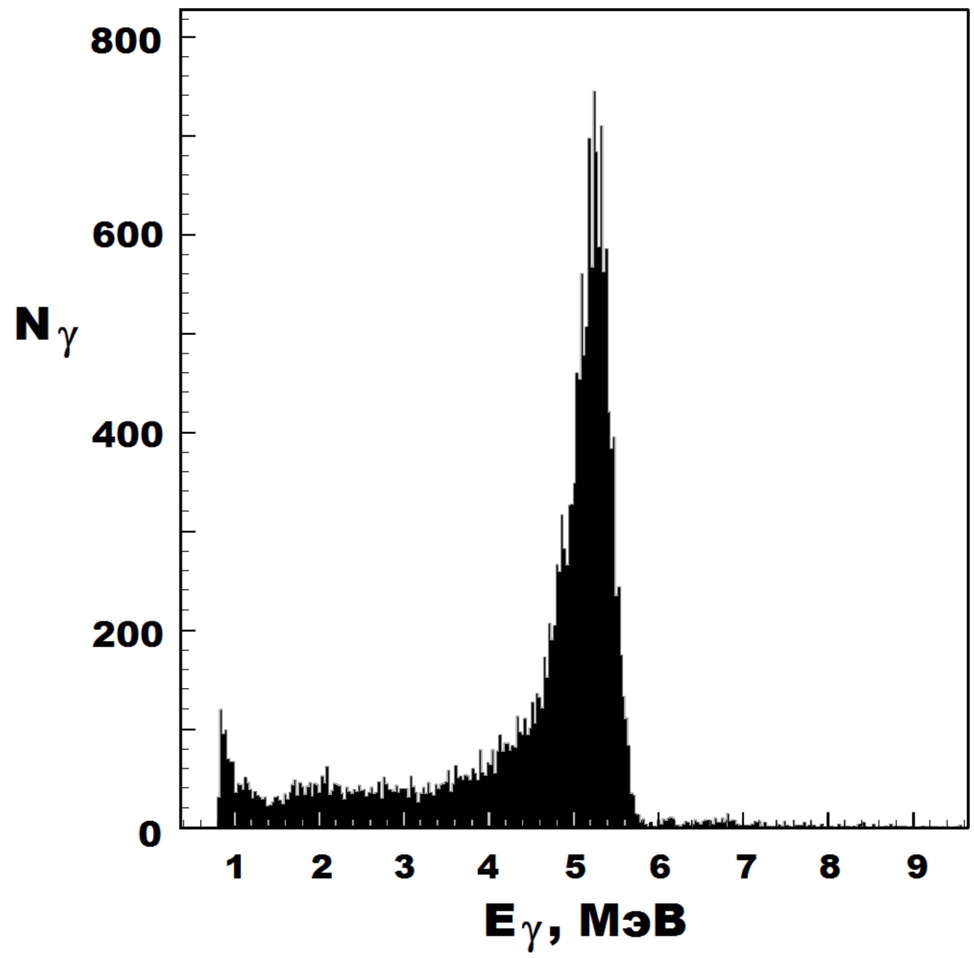
– in-depth analysis of the experimental data obtained, as well as the decommissioning of the TRITON installation from operation by 2020.

2013 - The experimental equipment was adjusted on a muon beam with a target filled with liquid hydrogen with a natural deuterium concentration

The experimental energy spectrum of gamma quanta from the reaction

pdμ → ^{3}Heμ+γ+5.5 MeV

was obtained.



Criteria for selecting experimental events:

- e_d1 is the coincidence signal $(E1+E2)\cdot M$, responsible for the muon stop in the target;
- $e_d2 = (\bar{E}1 + \bar{E}2)\cdot M \cdot (G1 + G2)$ means conversion muon decay in detector M.

Marker x notes the fusion reaction products: γ, e^-e^+ or conversion muon. The appropriate signals are the following:

- $x = \gamma$: $(\bar{E}1 + \bar{E}2)\cdot \bar{M} \cdot G$, the decay electron selected as e_d1;
- $x = \mu$: the coincidence signal $(E1 + E2)\cdot M$, and e_d2 for the electron from muon decay;
- $x = e^-e^+$: $(E1 + E2)\cdot M$, and e_d1 corresponds to detection of at least one particle of the pair;
- $E1 \cdot E2 \cdot M$, and the subsequent e_d1 corresponds to simultaneous detection of both particles of the pair with their coincidence in time.

For a more reliable identification of the registered experimental events and the background suppression, one should put certain timing limitations, usual in MC experiments:

$$t(e_d1) - t(\mu) > 0.5\ \mu\text{s}, \qquad t(e_d1,2) = t_x + (0.5\text{–}4.5)\ \mu\text{s}$$

Procedure for determining the yield in the reaction' channel

The number of detected events for each sort (y) of the fusion products is

$$N_y = N_\mu \cdot Y^0(y) \cdot \mathrm{eff}(y),$$

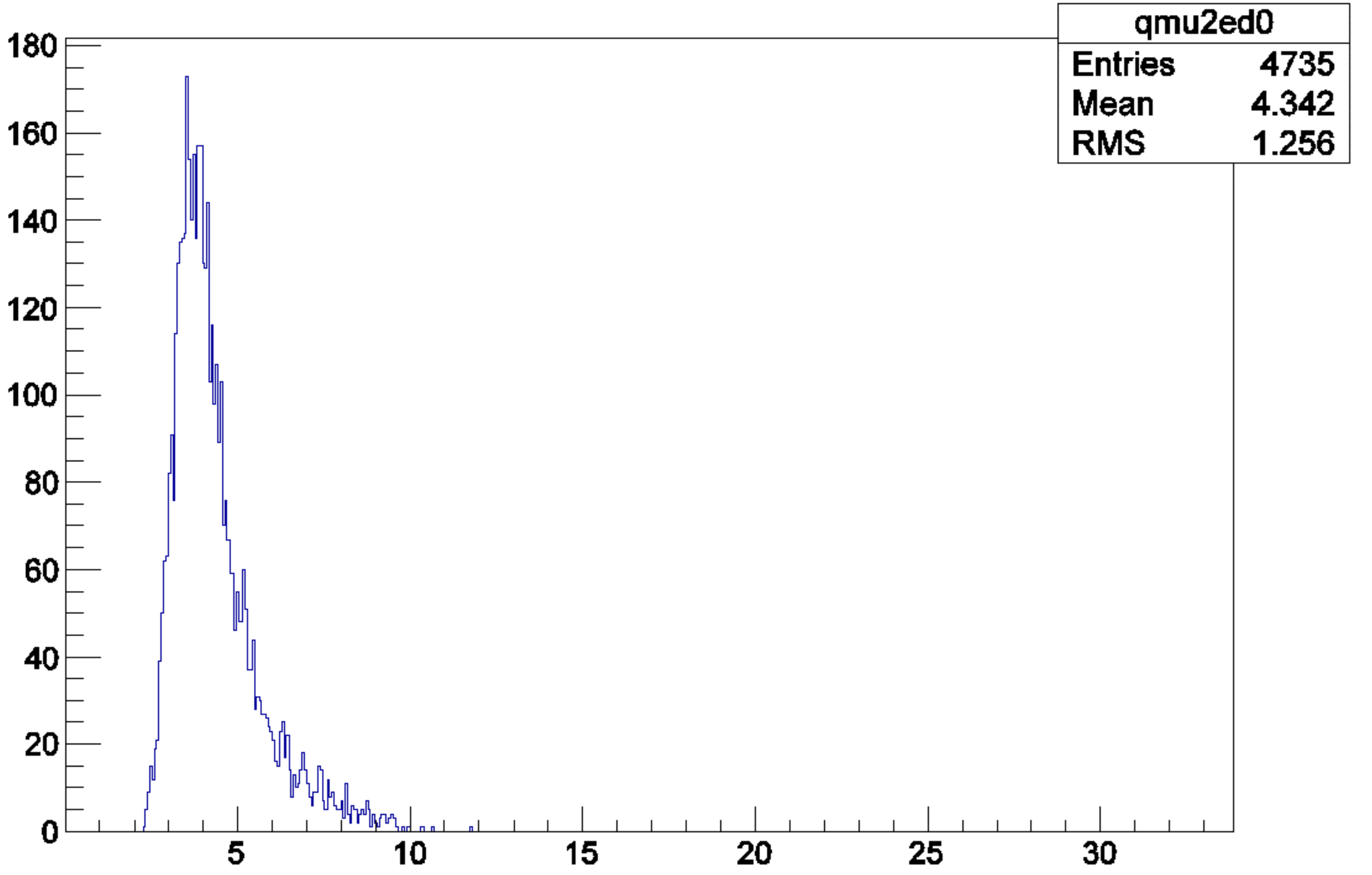
where $Y^0(y)$ is the absolute yield and $\mathrm{eff}(y)$ are the detection efficiencies:

$$\mathrm{eff}(\gamma) = \epsilon(\gamma) \cdot \epsilon(e_d 1) \cdot f_t, \quad \mathrm{eff}(\mu) = \epsilon(\mu) \cdot \epsilon(e_d 2) \cdot f_t,$$
$$\mathrm{eff}(\text{pairs } 1) = \epsilon(\text{pairs } 1) \cdot \epsilon(e_d 1) \cdot f_t, \quad \mathrm{eff}(\text{pairs } 2) = \epsilon(\text{pairs } 2) \cdot \epsilon(e_d 1) \cdot f_t.$$

A detailed description of the experimental procedure developed at the preparation stage is contained in the work: [L.N. Bogdanova, et al., "Experimental study of nuclear fusion reactions in a ptμ system", Physics of Particles and Nuclei Letters 9, No.8 (2012) 605].

Experimental spectra:

Conversion muon in E1



N

Energy (MeV)

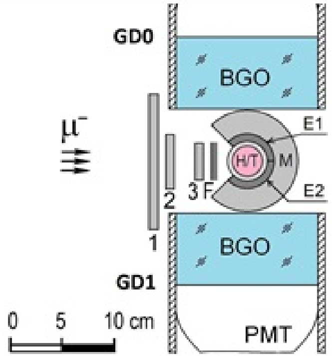


Рис.1. Схема установки

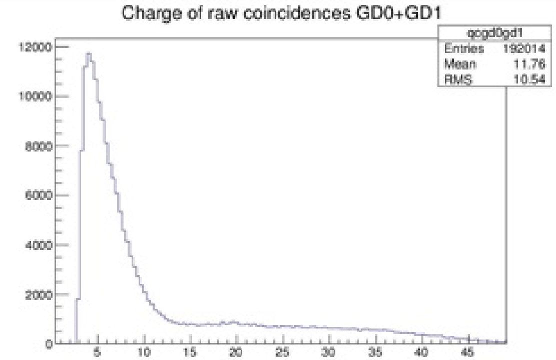


Рис. 2. Сырой спектр совпадений гамма-детекторов

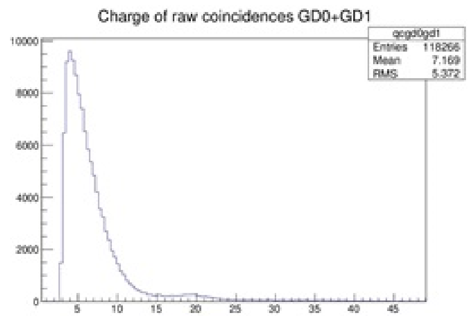


Рис. 3. Спектр совпадений гамма-детекторов

за вычетом отсчетов в детекторах E

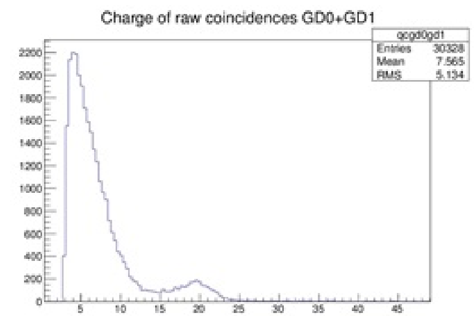


Рис. 4. Спектр совпадений гамма-детекторов

за вычетом отсчетов в детекторах E, M

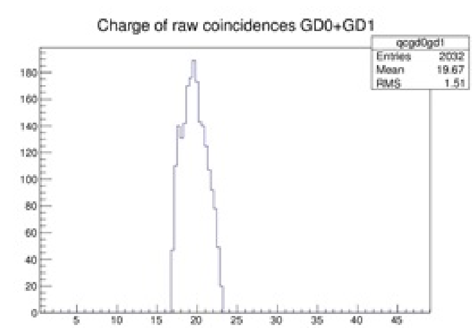


Рис. 5. Спектр совпадений гамма-детекторов

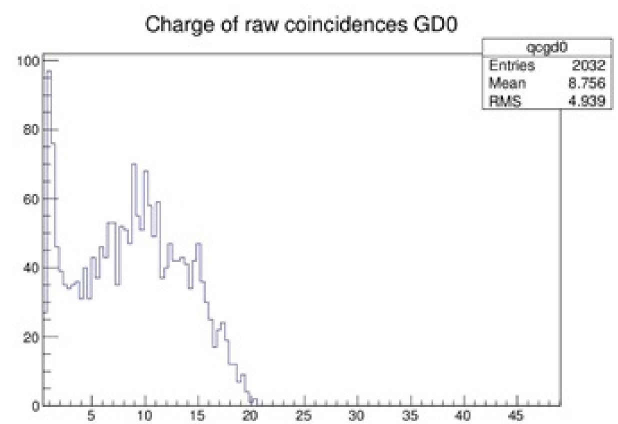


Рис. 6. Спектр энергии в GD0

Nuclear Instruments and Methods in Physics Research A 334 (1993) 437–446
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

An electron–positron pair spectrometer for high energy decays of nuclei

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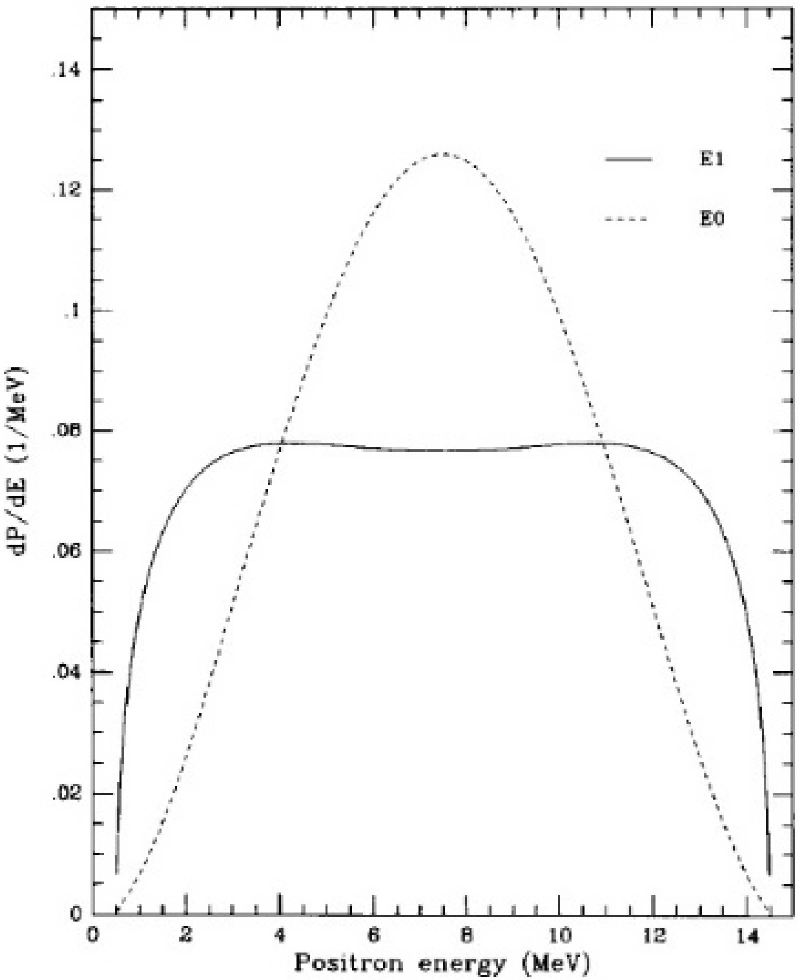


Fig. 3. Positron energy distribution for 15 MeV E0 and E1 transitions.

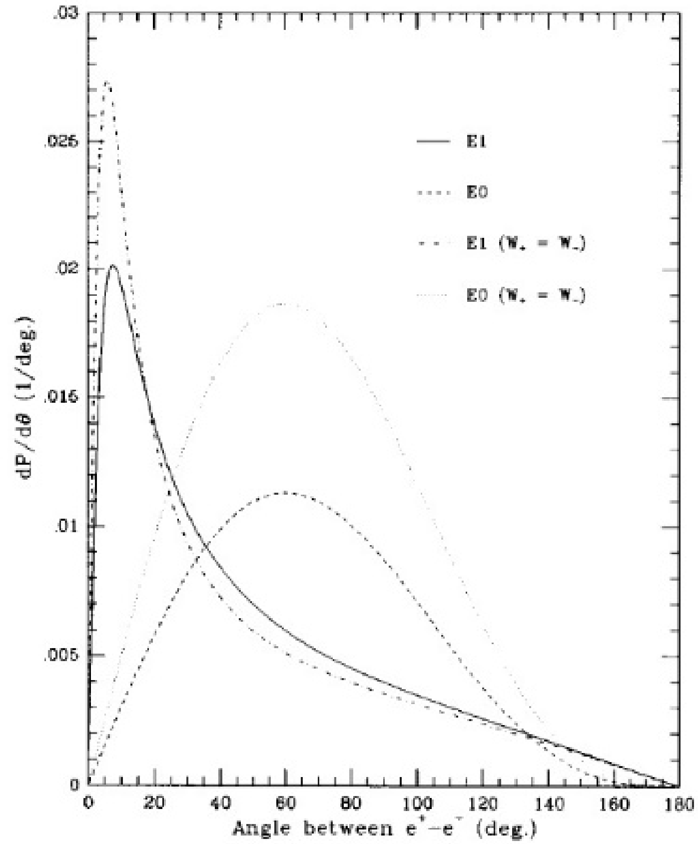
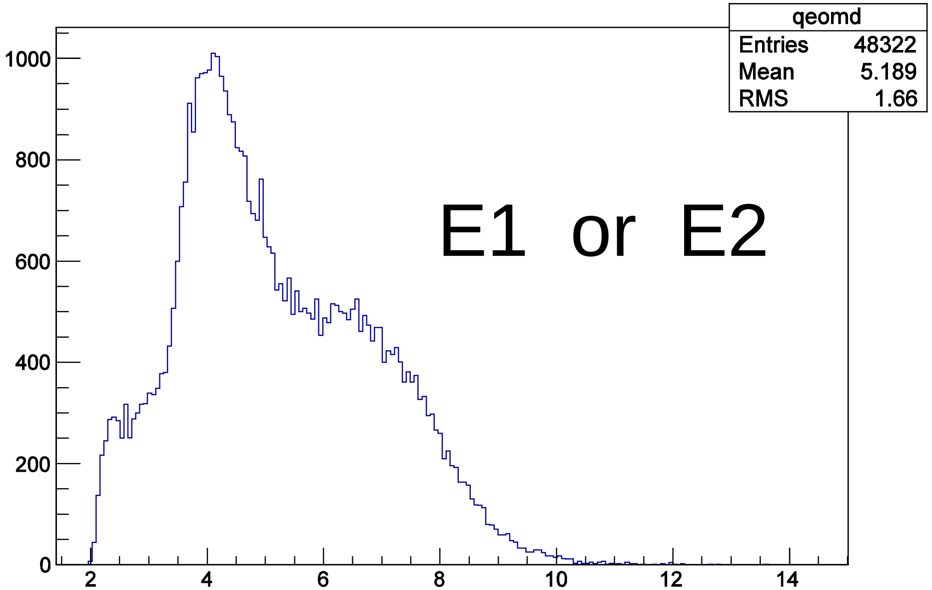
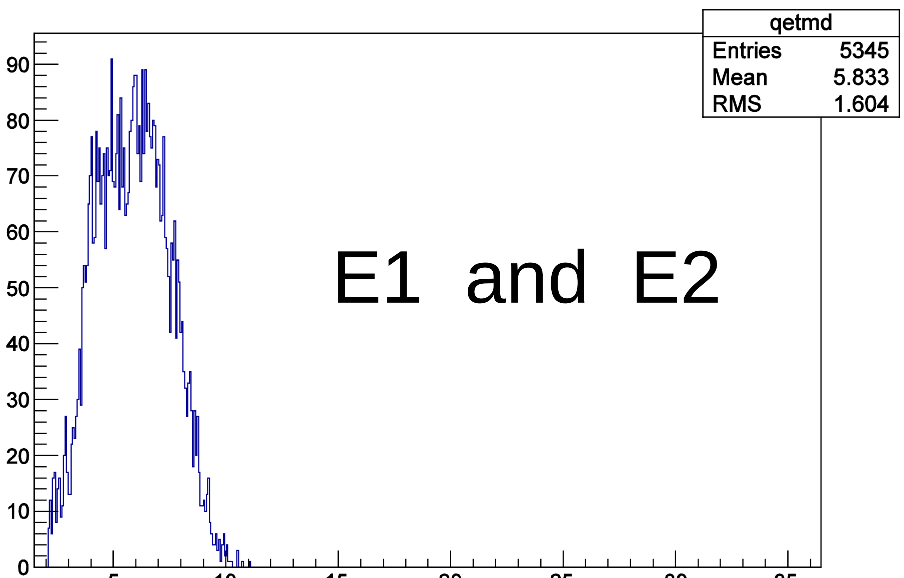
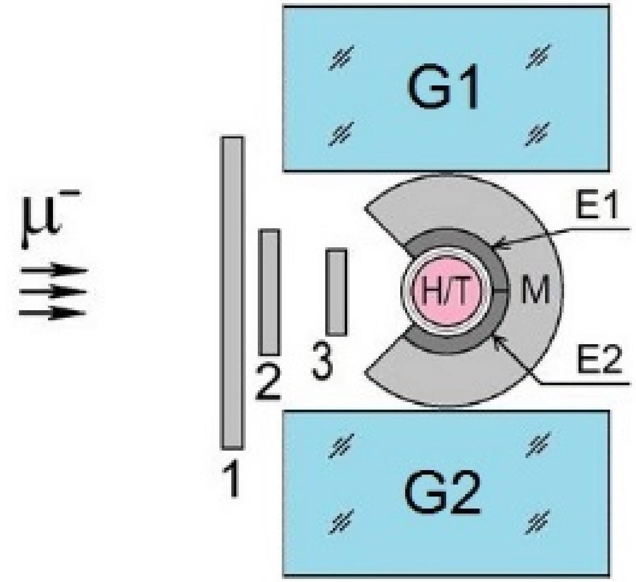


Fig. 4. The $e^+ - e^-$ angular correlation for a 15 MeV E0 and E1 transition. Also indicated is the strong effect which a requirement of equal energy sharing has on the angular correlations. The normalization of the curves is such that the two E1 curves have equal areas and the E0 curves are obtained assuming transition probabilities equal to the respective E1 transitions.

Spectra in M(E1,E2): pdμ, ptμ→ $e^+ + e^-$







C_t = 0

N (E1 or E2) = 4194

N (E1 and E2) = 53

C_t = 0,8

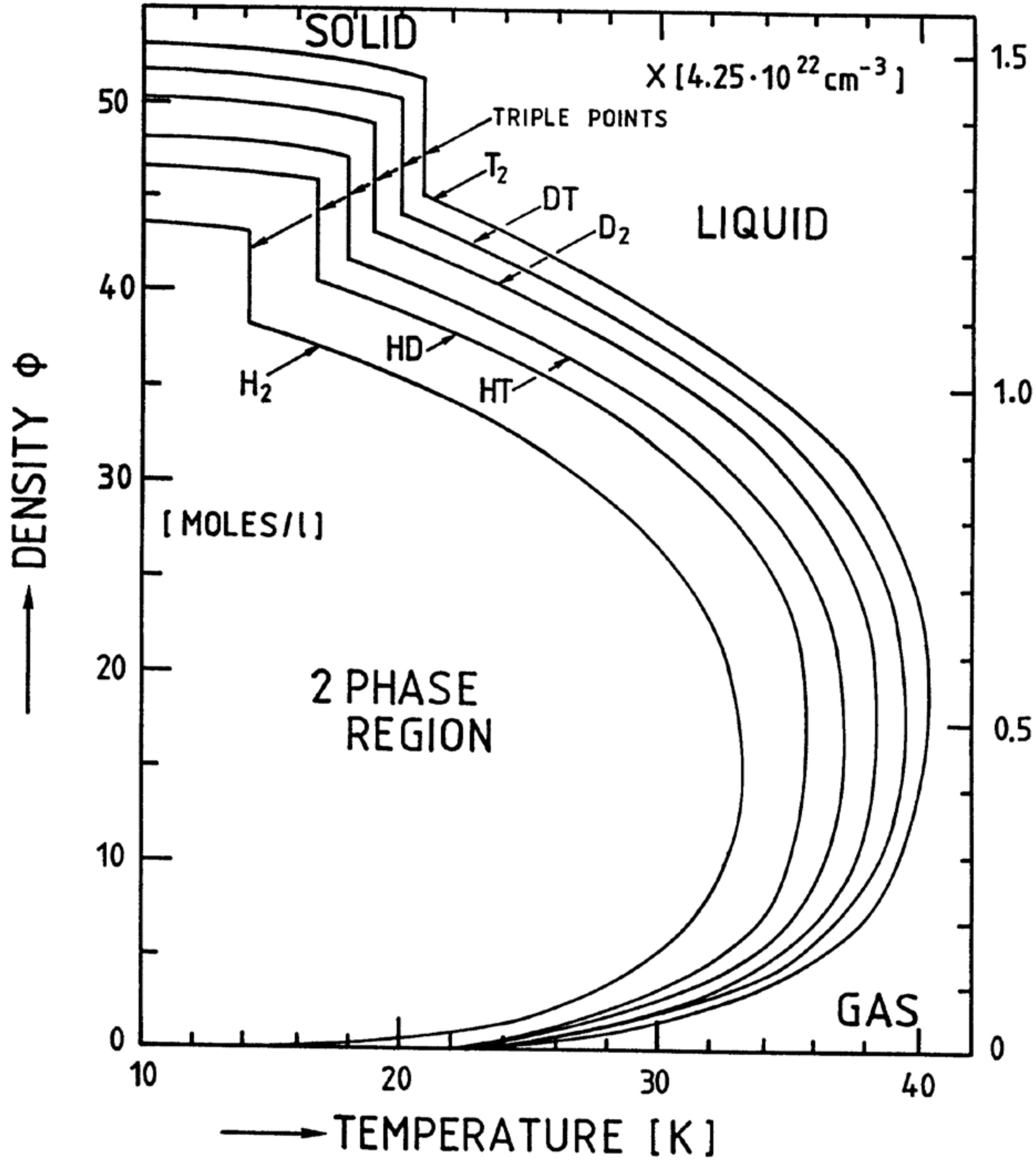
N (E1 or E2) = 48322

N (E1 and E2) = 5345

C_t=0,08

N (E1 or E2) = 46618

N (E1 and E2) = 4868



SOLID
X [4.25 · 10^22 cm^-3]
TRIPLE POINTS
T2
DT
D2
LIQUID
HD
H2
HT
2 PHASE
REGION
GAS
[MOLES/l]
DENSITY Φ
TEMPERATURE [K]
50
40
30
20
10
0
1.5
1.0
0.5
0
10
20
30
40

$$d+d = p+t$$

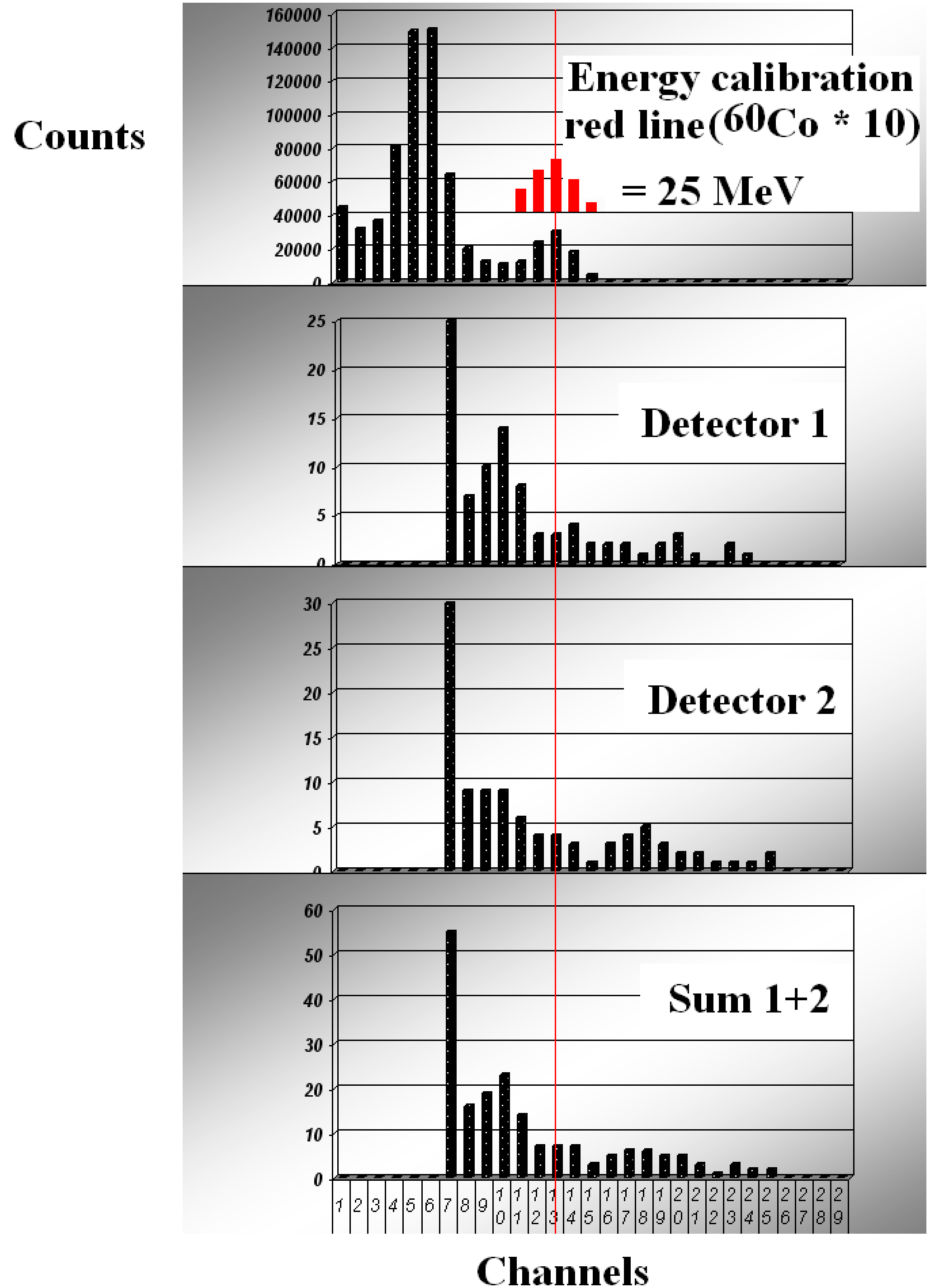

Counts
Energy calibration
red line(60Co * 10)
= 25 MeV
Detector 1
Detector 2
Sum 1+2
Channels

Table 2. Preliminary results. Y^{μ} denotes the yield for muon emission, Y^{γ} the gamma–ray yield. The ratio Y^{μ}/Y^{γ} is normalized to the best value of $(Y^{\mu}/Y^{\gamma})_0$ observed at $c_t * 10^3 = 8.1$ and $c_d * 10^3 = 0.76$. For further explanations see text.

	mixture		
concentration			
$c_t * 10^3$	8.1 ± 0.6	1.16 ± 0.06	0.45 ± 0.08
$c_d * 10^3$	0.76 ± 0.05	0.402 ± 0.012	0.37 ± 0.06
build–up rate (μs^{-1})	7.18 ± 0.44	7.11 ± 0.36	5.51 ± 0.30
pμt formation rate (μs^{-1}) [5]	6.5	6.5	6.5
disappearance rate (μs^{-1})	0.493 ± 0.004	0.518 ± 0.005	0.530 ± 0.006
fusion rate (γ) (μs^{-1}) [1]	0.06 ± 0.01	0.06 ± 0.01	0.06 ± 0.01
μ decay rate (μs^{-1})	0.455	0.455	0.455
$\frac{Y^{\mu}/Y^{\gamma}}{(Y^{\mu}/Y^{\gamma})_0}$	1.00 ± 0.02	1.20 ± 0.03	1.38 ± 0.04