INSTITUTE OF NUCLEAR PHYSICS
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MODIFICATED ACTIVATION METHOD FOR MEASUREMENT OF THE YIELD OF THE ASTROPHYSICAL REACTIONS

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Background

- Presently a great attention is drawn to renew the existing experimental database on the low-energy nuclear reactions of astrophysical importance.
- More precise values of reaction rates are demanded: absolute experimental errors not higher than 4–5% are frequently required for verification of astrophysical models.
- Major experimental predicament is the exponential drop of cross section with energy decrease, which results in impetuous increase of experimental errors.

Therefore, it is desirable

- to develop a new experimental methods

- to modify existing experimental technique;

- to apply different methods for obtaining the same data.

Experimental methods

Several methods are usually used for the direct experimental studies of the astrophysical important processes at very low energies to obtain total cross sections $\sigma(E)$ (or $S(E)$), yields $Y(E)$ and, finally, reaction rate $<\sigma v>(T)$.

☐ on-line detection of products formed directly in a reaction
(in-beam γ spectrometry, charge particle detection etc.)

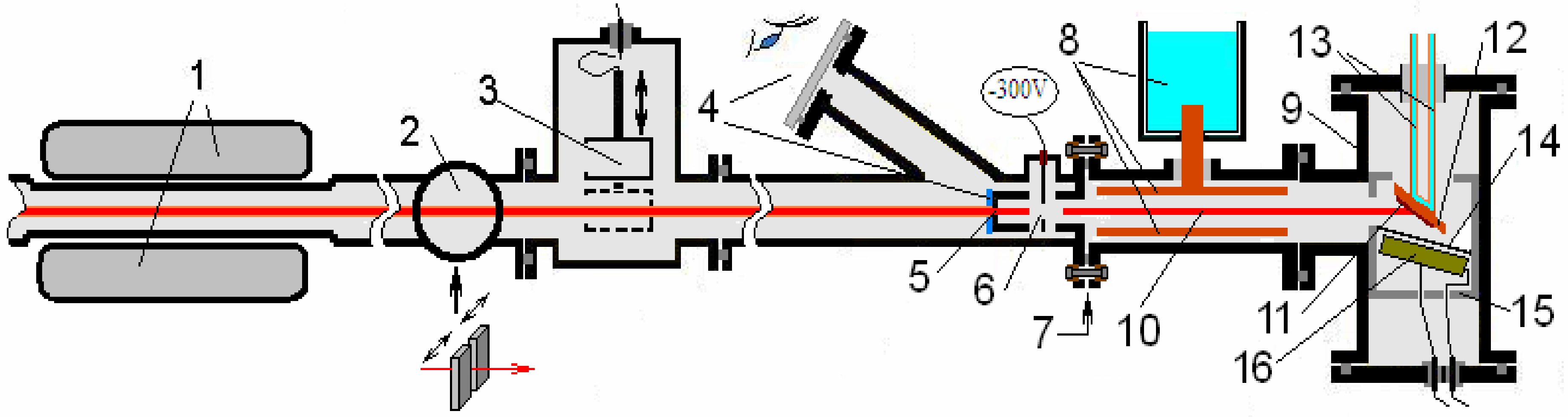
☐ off-line reaction product detection
(activation, mass-spectrometric or X-ray fluorescence etc.)

Experimental Set-up at the Electrostatic Accelerator EG-II (Tashkent, NUU)

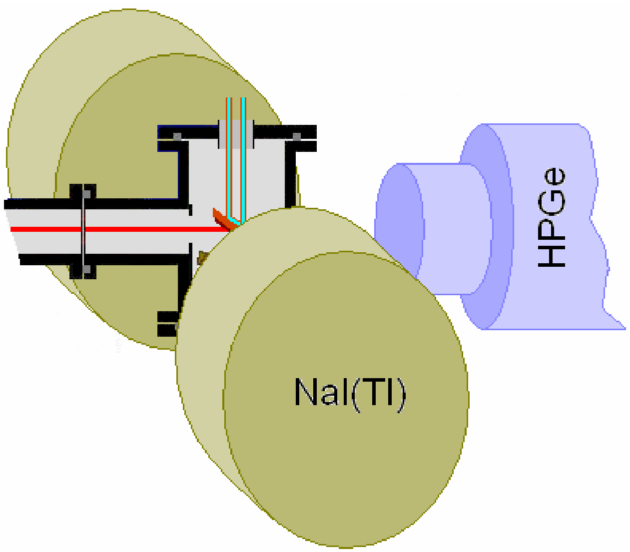
Accelerated particles: proton, Helium-4

Energy of the proton beams	**0.15 – 1.5 MeV**
Energy of the alpha beams	**0.2 - 3.5 MeV**
Beam currents (external)	**up to 25 мкА**
Monochromaticity	**~ 0.1%**

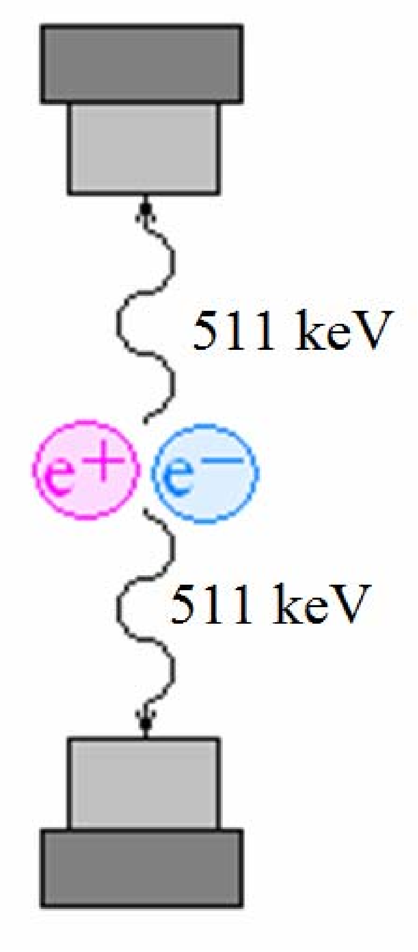
Beam transportation system and experimental setup



Setup «MAIS» created by NUUz and INP AS Uz scientists allows one to measure the “prompt” and/or “activation” γ-quanta and β-particles



Topic of this presentation: Activation method with annihilation γ – quanta detection based at «MAIS»



Advantage:

- Good registration geometry (close to 4π);
- simple counting mode of accumulated information;
- directly final nuclei are registered (σ_{tot}(E), Y(E));
- . suppression of background events.

Disadvantages:

- only β+ - decayed nuclei are detected
- absence of identification of the reaction channel;
- relatively small detection efficiency;
- loss of nuclear decay statistics during irradiation.

Examples of the reactions for which the method is useful

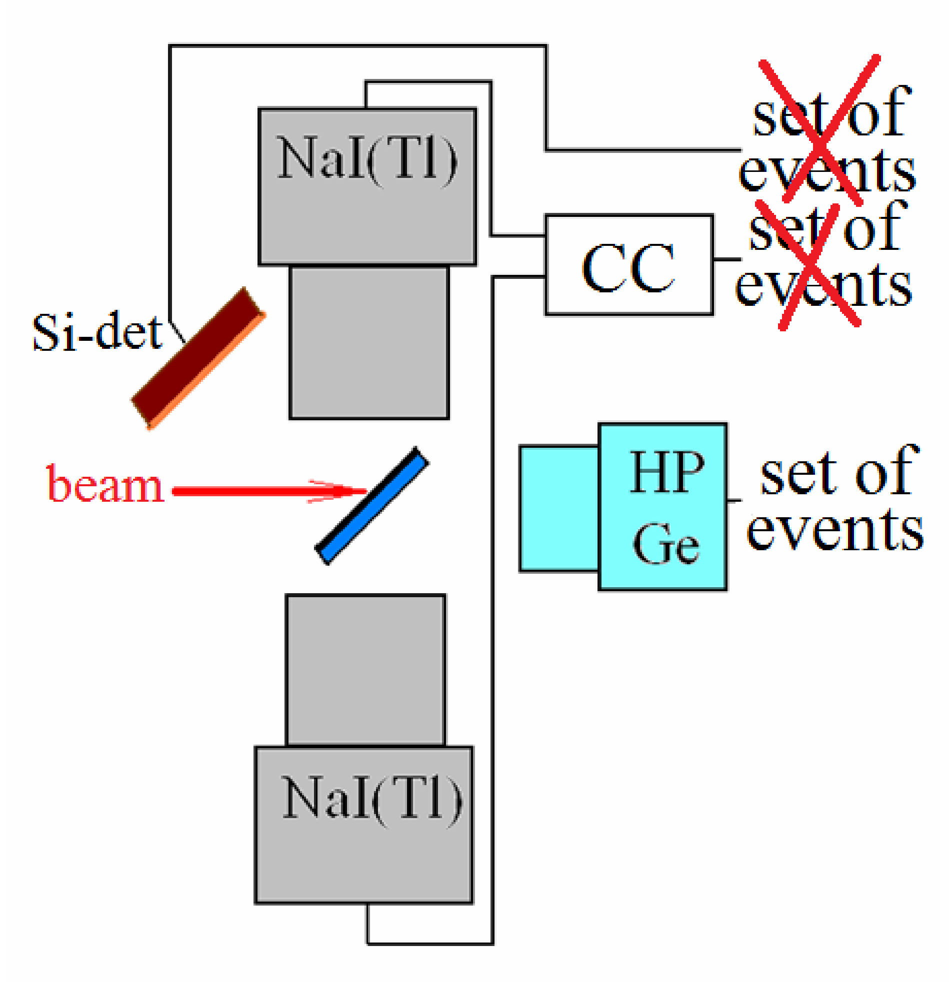
(p,γ) reactions with stable nuclei:

	T1/2	decay
$^{10}\mathrm{B}(p,\gamma)^{11}\mathrm{C}$	20.4 min,	$\beta+$
$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}$	10 min,	$\beta+$
$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$	2 min,	$\beta+$
$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$	1 min,	$\beta+$
$^{17}\mathrm{O}(p,\ )^{18}\mathrm{F}$	110 min,	$\beta+$
$^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}$	7.2 sec	$\beta+$
$^{29}\mathrm{Si}(p,\gamma)^{30}\mathrm{P}$	2.5 min,	$\beta+$
$^{42}\mathrm{Ca}(p,\gamma)^{43}\mathrm{Sc}$	233 min,	$\beta+$
$^{43}\mathrm{Ca}(p,\gamma)^{44}\mathrm{Sc}$	236 min,	$\beta+$

RI beams, inverse geometry:

$^{1}\mathrm{H}(^{13}\mathrm{N},\gamma)^{14}\mathrm{O}$	71 sec	$\beta+$
$^{2}\mathrm{H}(^{10}\mathrm{C},p)^{11}\mathrm{C}$	20.4 min,	$\beta+$
$^{2}\mathrm{H}(^{13}\mathrm{O},p)^{14}\mathrm{O}$	71 sec,	$\beta+$
$^{2}\mathrm{H}(^{14}\mathrm{O},p)^{15}\mathrm{O}$	2 min,	$\beta+$
$^{2}\mathrm{H}(^{17}\mathrm{F},p)^{18}\mathrm{F}$	110 min,	$\beta+$

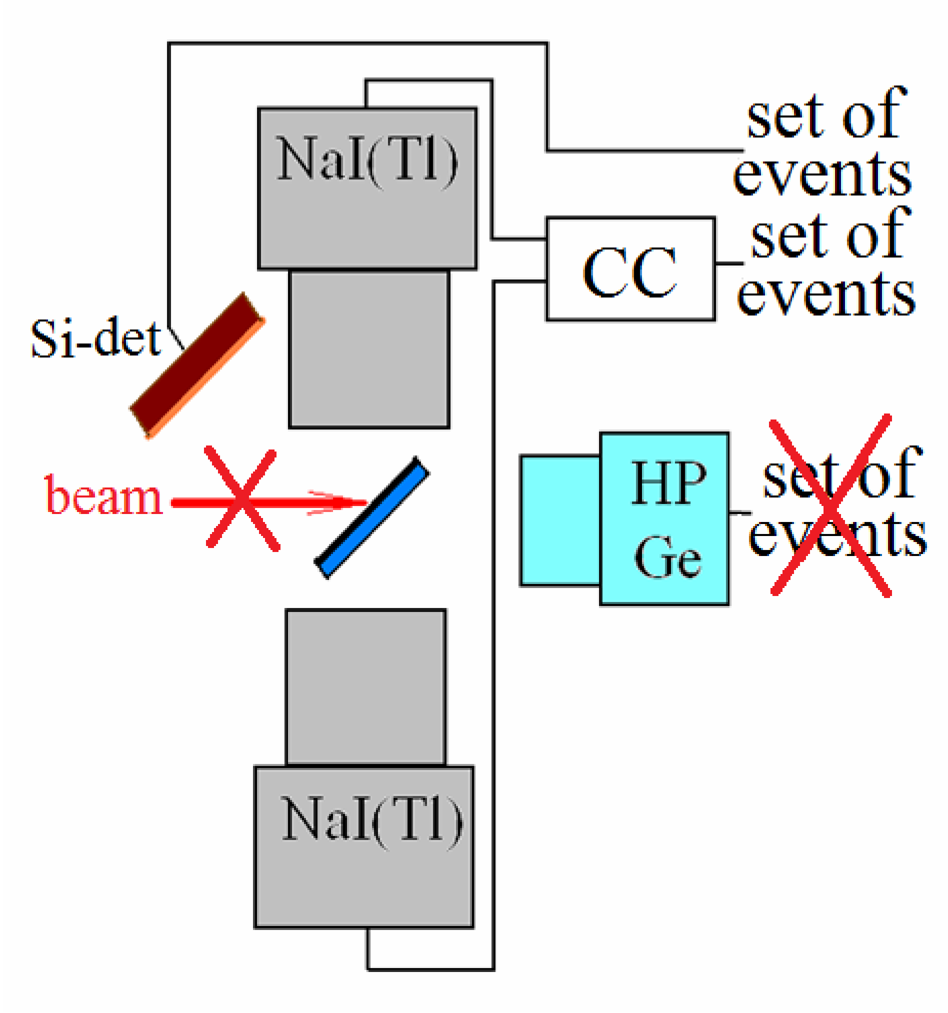
Procedure of data acquisition



The duration of the beam at the target in one cycle ~$T_{1/2}$

During this time, the spectrum of “instant” γ quanta continues

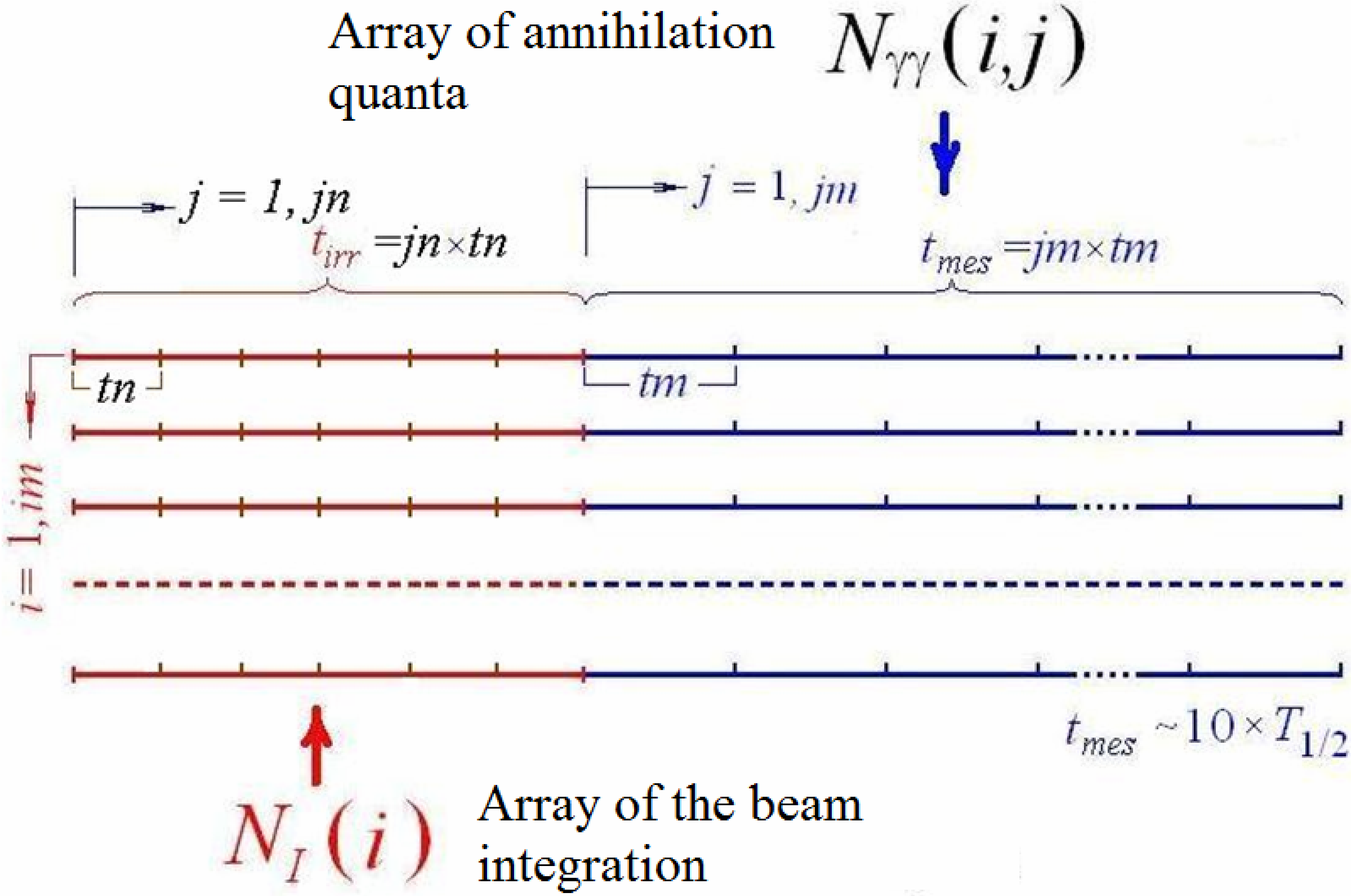
Procedure of data acquisition



The duration of the pauses between the feeds of the beam is usually ≤$T_{1/2}$

During this time there is a set of the number of γγ - coincidence

The file structure of the experimental data.



Array of annihilation quanta $N_{\gamma\gamma}(i,j)$

$N_I(i)$ Array of the beam integration

Determination of the reaction yield through the number of counts

$$Y(E) = n_A \int_0^E dE' / S(E') \times \sigma(E') \qquad (1)$$

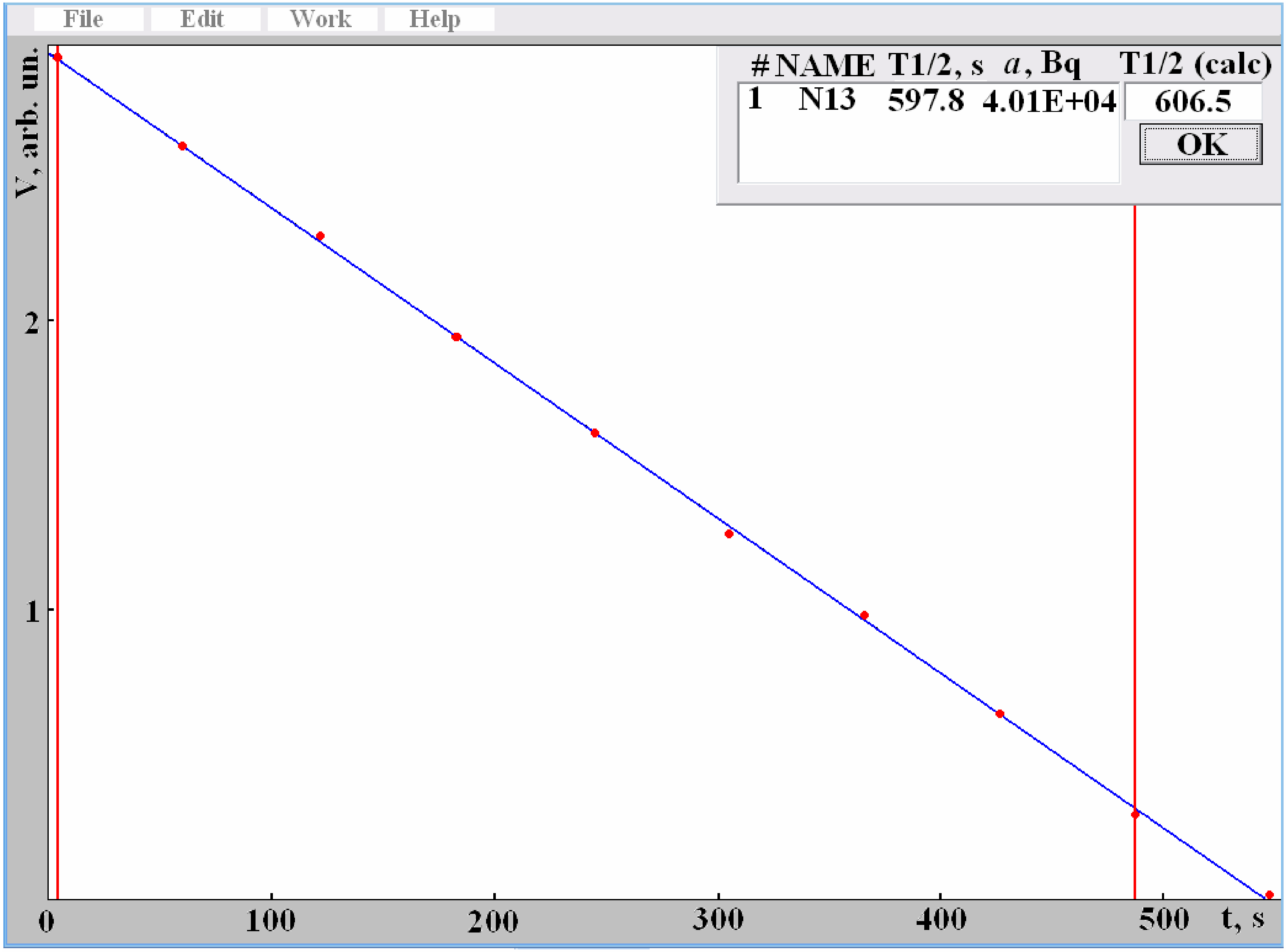
$S(E)$ - stopping power of protons

$$N_B(t_{irr}) = N_B = Y(E) \cdot (I_a / \lambda) \cdot [1 - e^{-\lambda \cdot t_{irr}}] \qquad (2)$$

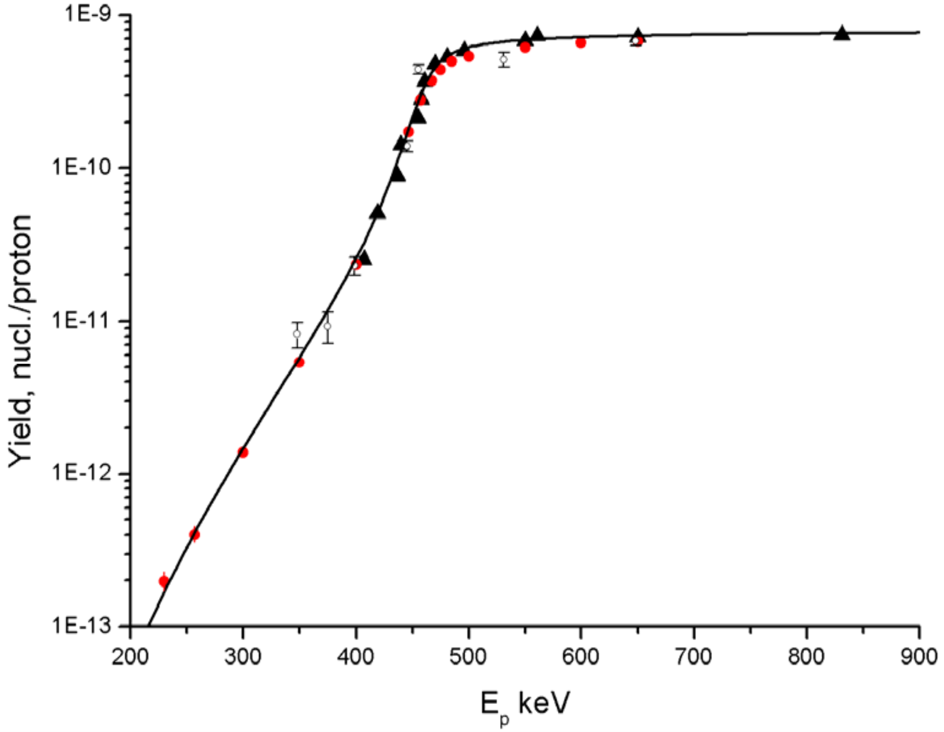
$$N_j = \xi \cdot \varepsilon \cdot a_B \cdot \int_{(j-1)\cdot t_m}^{j \cdot t_m} e^{-\lambda t} dt \qquad (3)$$

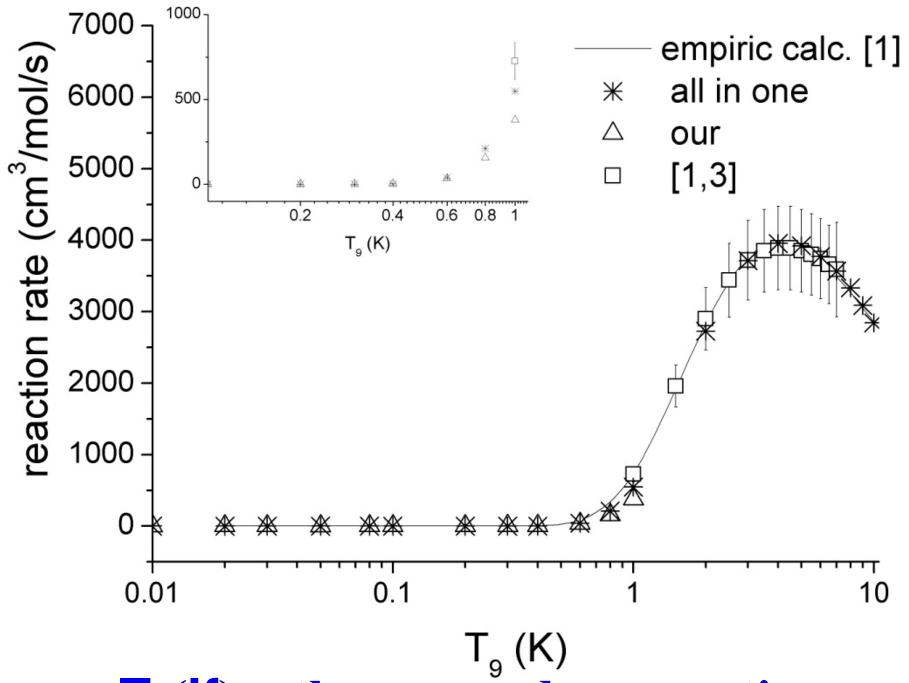
$$a_B = C \cdot Y_B \cdot (1 / \delta t_{irr}) \cdot (1 - e^{-\lambda \cdot \delta t_{irr}}) \cdot e^{-\lambda \cdot t_{irr}}) \times \\ \times \sum_{i=1}^{i_{\max}} \sum_{m=1}^{i} [e^{-\lambda \cdot \Delta t \cdot (i-m)} \cdot \sum_{k=1}^{k_{\max}} \{N_{m,k}^{I} \cdot e^{k \cdot \lambda \cdot \delta t_{irr}}\}] \qquad (4)$$

The screenshot of the program MAIS



#	NAME	T1/2, s	*a*, Bq	T1/2 (calc)
1	N13	597.8	4.01E+04	606.5





$$N_A\langle\sigma\upsilon\rangle_T = \int_0^\infty Y(E)\times\frac{d}{dE}\left[-\frac{W_2(E)}{W_1(E)}\right]dE$$

T_9(K) – thermonuclear reaction temperature

S.B. Igamov, O.R. Tojiboyev, et al., Int. Sci. Forum 12-15 Sep. 2017. Almaty

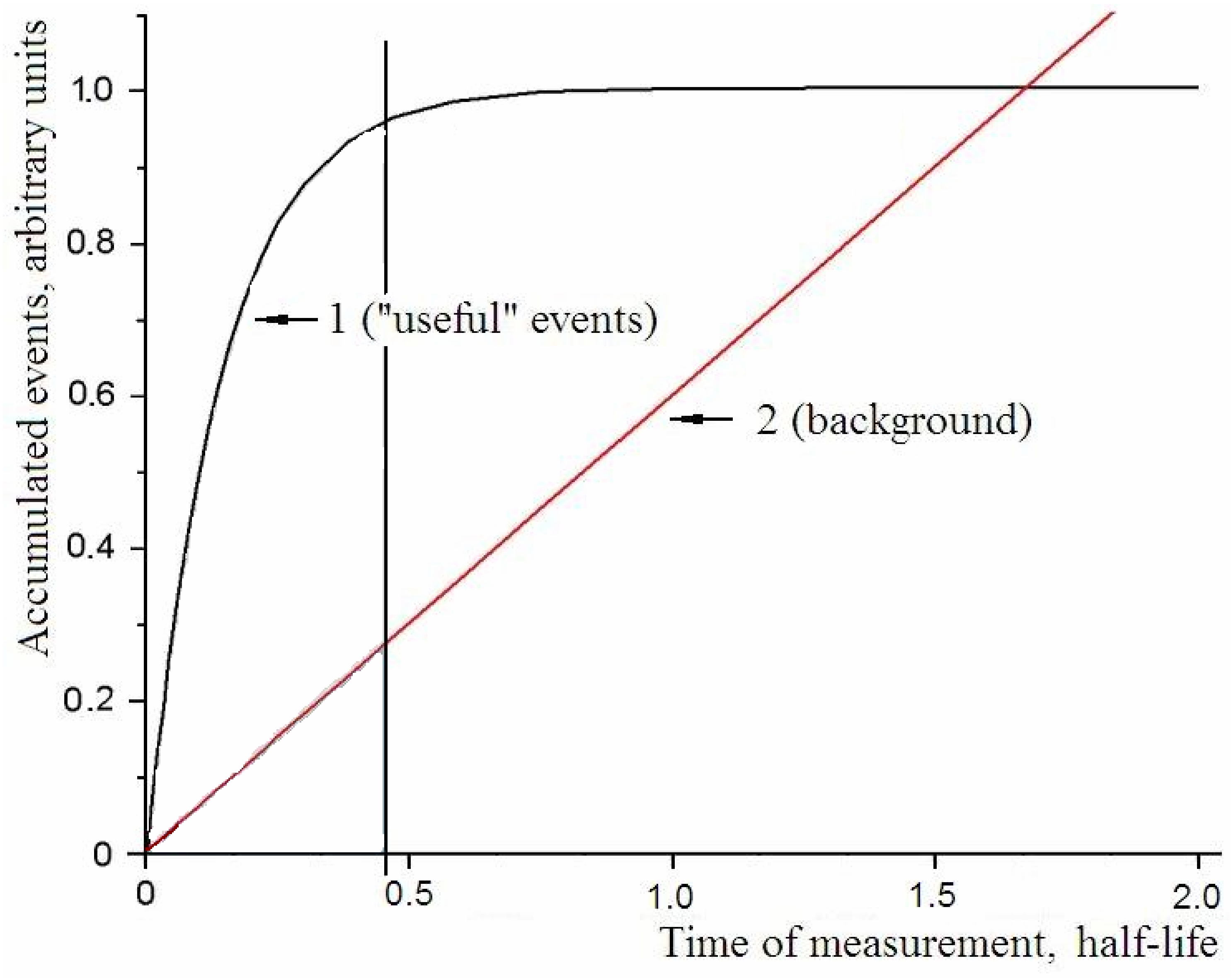
Yield and rate of the reaction $^{12}C(p,\gamma)^{13}N$

1) open circles- N.A.Roughton, et al., Astrophysical Journal, 205 (1976) 302.

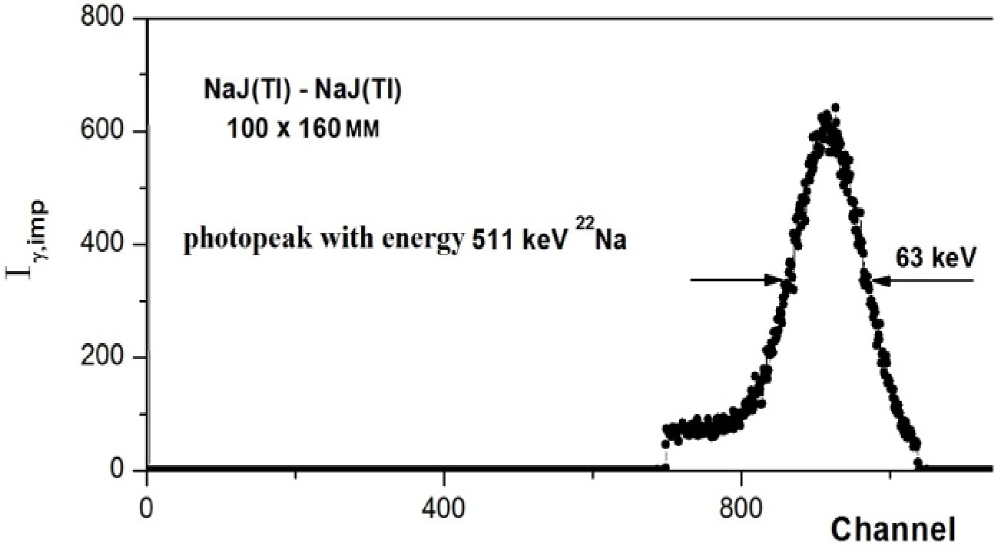
red circles- our measurements (S.V. Artemov, et al., Nucl. Insr. Meth. A825 (2016) 17)

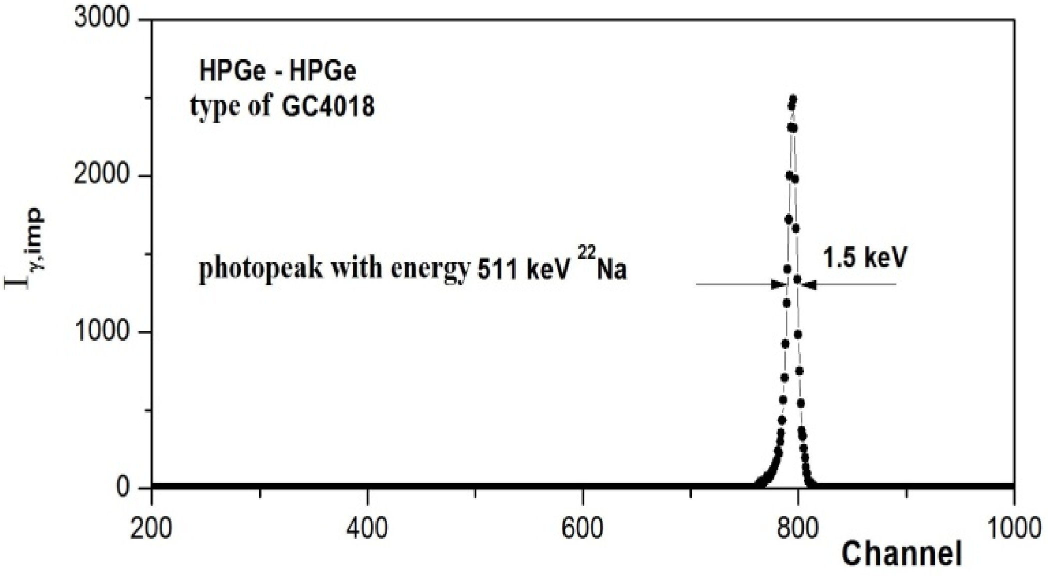
2) triangle - J. D. Seagrave. Phys. Rev. 84 (1951) 1219.

Choice of measurement time

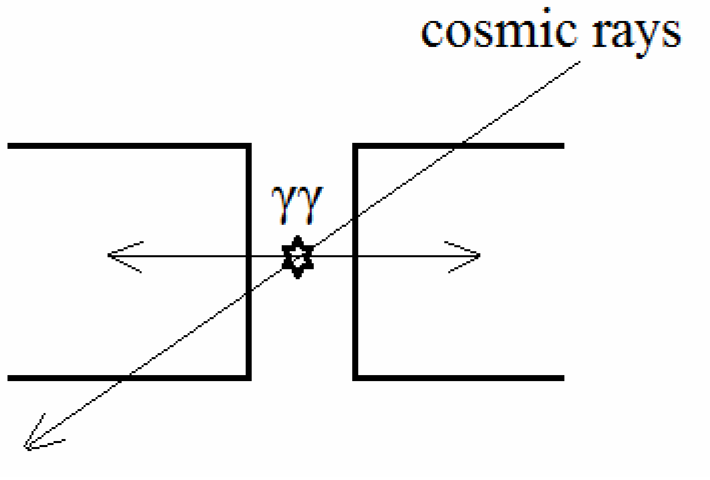


increase installation efficiency





background cosmic rays



Comparison of the characteristics of scintillation and semiconductor (HPGe) double-arm spectrometers

<table>
<tr><th colspan="2">The count rate of γγ - coincidence background</th><th>The count rate of γγ – coincidence β + source</th></tr>
<tr><td colspan="2">~0.1 pulse / sec</td><td>~130 pulse / sec</td></tr>
<tr><td colspan="2">~0.002 pulse / sec</td><td>18 pulse / sec</td></tr>
<tr><td>The ratio</td><td>50</td><td>7.2</td></tr>
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THANK YOU FOR ATTANTION!!!