Школа-семинар
«Сцинтилляционные процессы и материалы»

Кристаллы NaI:Tl и CsI:Tl для регистрации низкоэнергетических заряженных частиц в экспериментах по поиску темной материи

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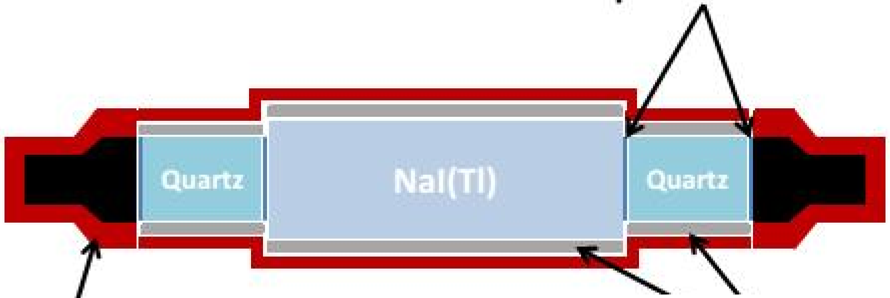
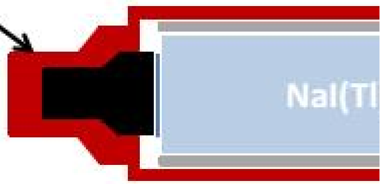
13 сентября 2016 г, Харьков

DAMA single detector unit





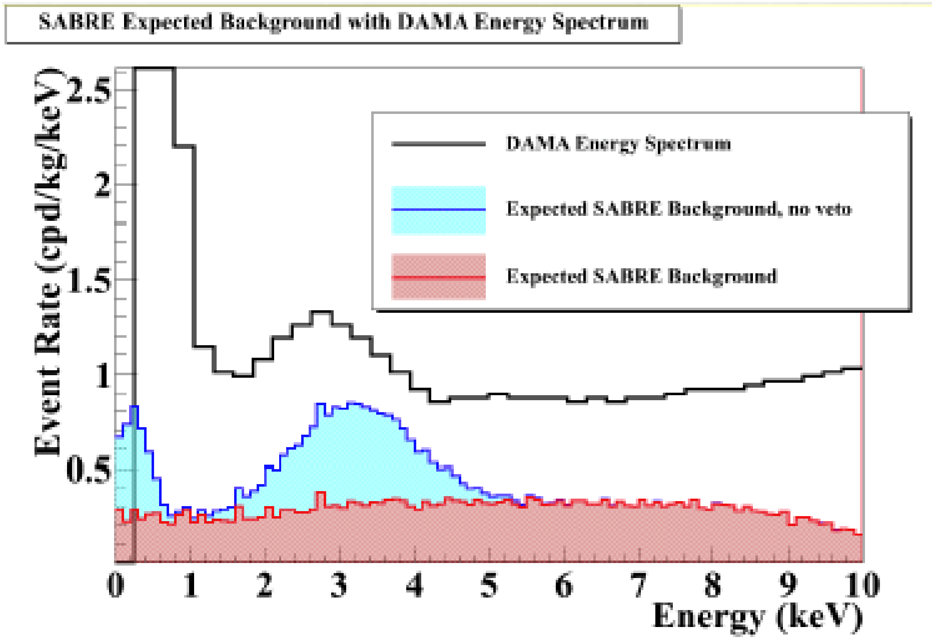
Current **SABRE** single detector unit

preliminary design

Expected events in the energy range of 3–10 keV

Design like DAMA II stage....
Why not think about how to improve it?

In DAMA/SABRE experiments expected energy range is 2-4 keV



See Talk by E. Shields at TAUP2013

Internal Source: 0.84 keV

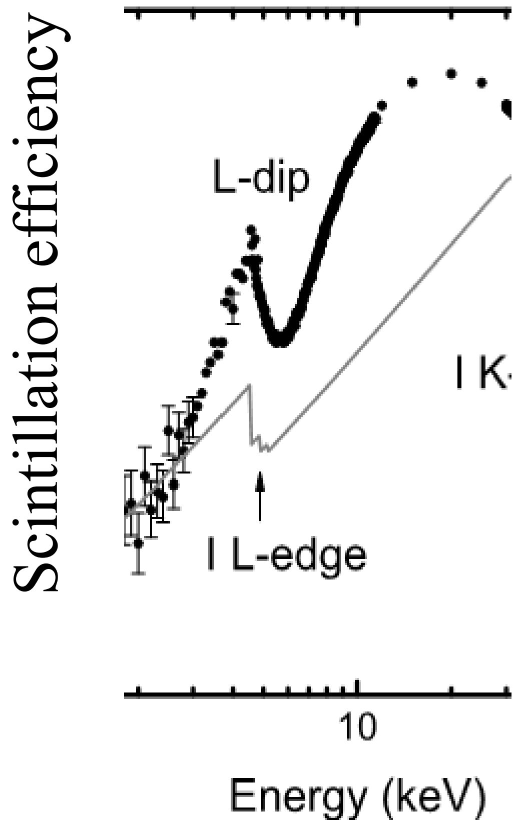
McCann M.F. and Smith K.M.

On the Detection of 1 keV Events in NaI:Tl

NIM, 65 (1968) 173.

Characteristic X-rays

Figure from: *I. Khodyuk and P. Dorenbos*, IEEE TNS, 2012

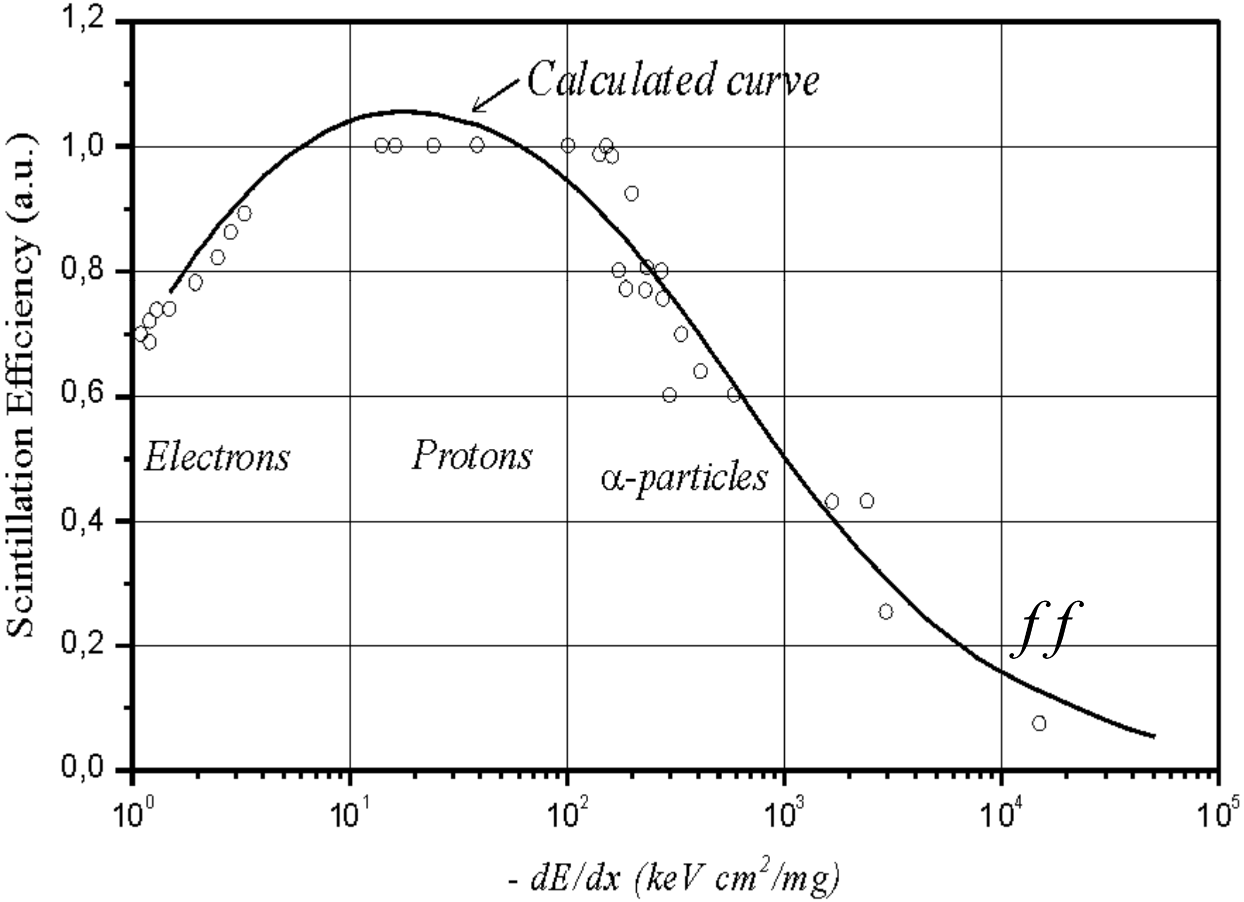


NaI:Tl crystal

External source of synchrotron radiation

Problems of low energy particle detection

Light yield depends on *dE/dx*



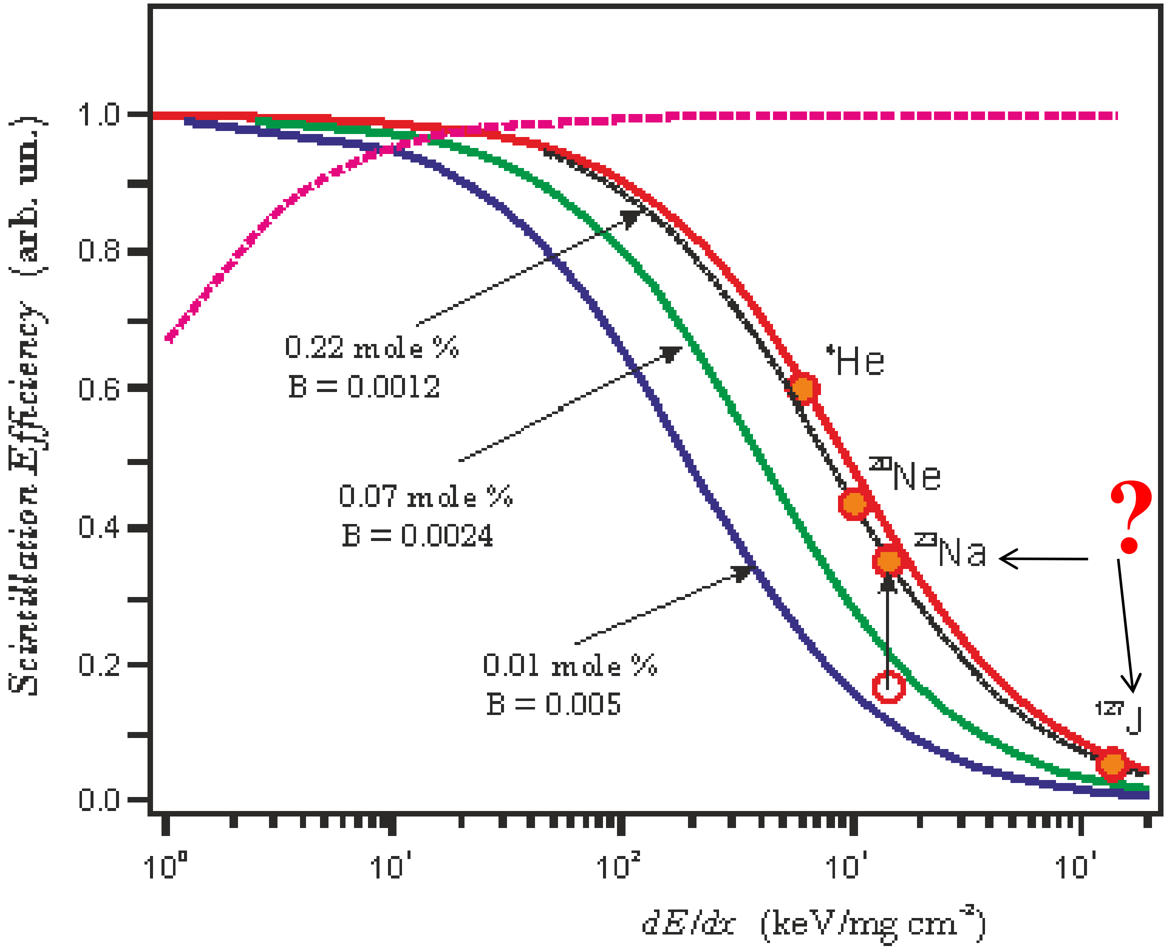
Energy resolution and non-proportionality of response

QF – quenching factor

Fission fragments (*ff*) have only 10% of maximum light yield, *QF* ~ 0.1

Dark matter search with NaI and CsI

According to Birks model

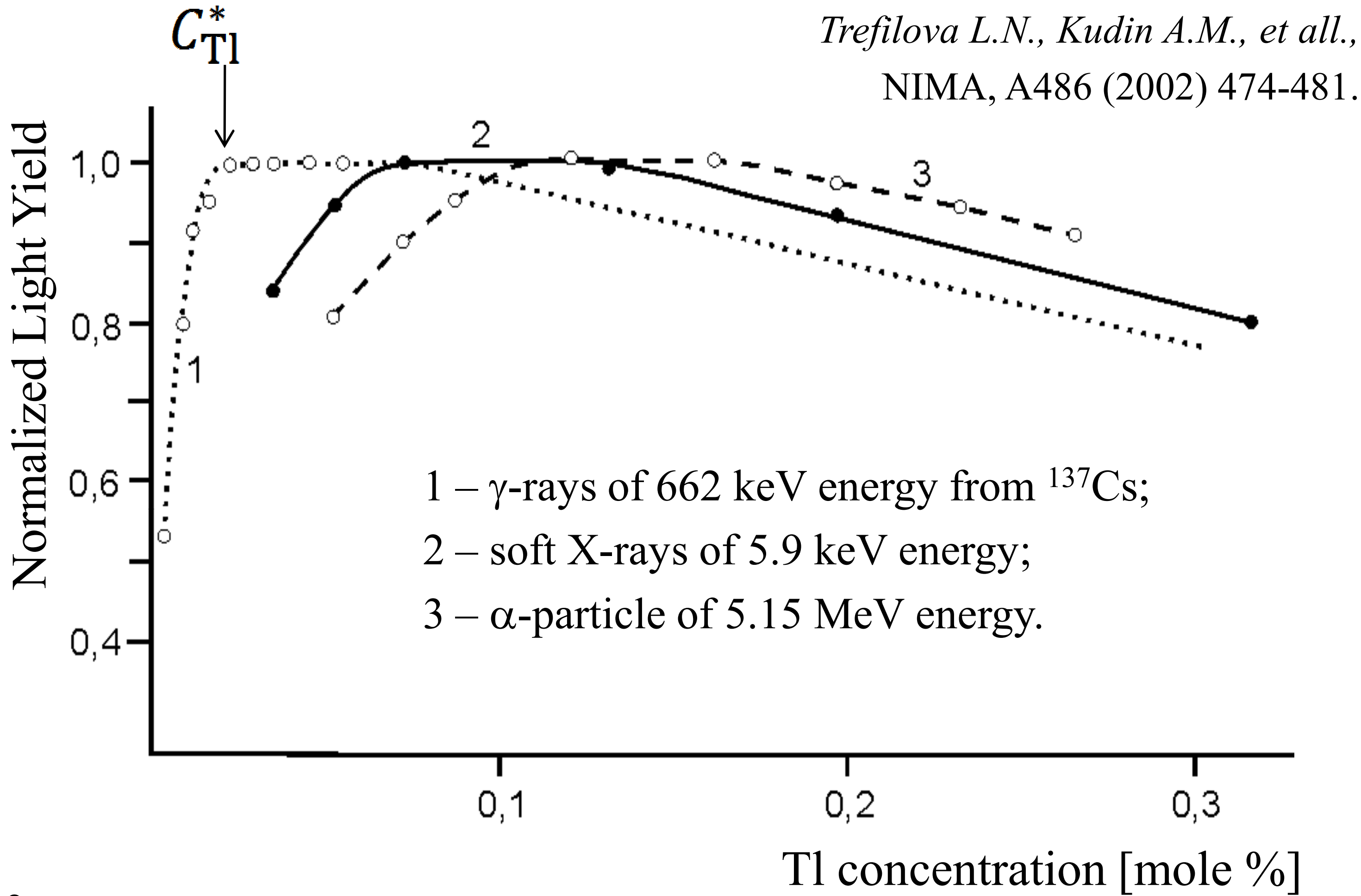


Quenching factor for ^{23}Na and ^{127}J

Protons	100 %
Alphas	60 %
^{20}Ne	42 %
it can be estimated	
^{23}Na	~ 35%
^{127}I	~ 8 %

Quenching factor depends on Tl concentration

Optimum Tl concentration (C^*_{Tl}) in NaI:Tl



$C^*_{Tl} = 2.2 \cdot 10^{-2}$ % for γ-rays;
$C^*_{Tl} = 7.3 \cdot 10^{-2}$ % for soft X-rays of 5.9 keV;
$C^*_{Tl} = 1.3 \cdot 10^{-1}$ % for α-particles.

Requirements to scintillation material for charged particles and light ions detection:

- maximum scintillation efficiency to photons detection;
- high transparency to rich maximum light collection coefficient;
- homogeneity of thallium distribution and other dopands to rich best value of energy resolution;

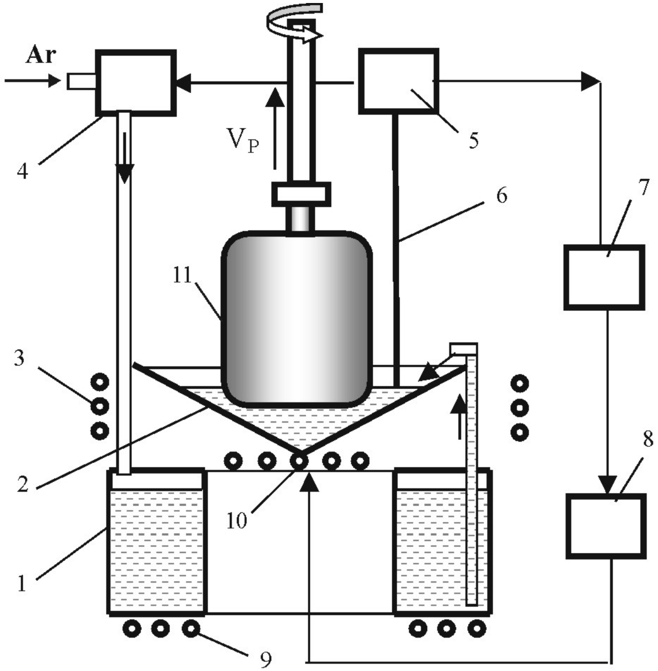
Additional:

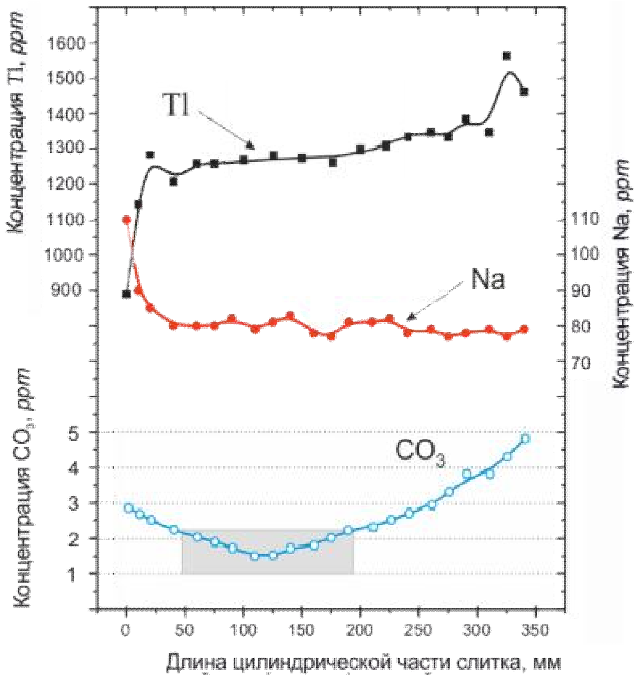
- increased Tl concentration to rich best scintillation efficiency for charged particles detection;
- stability of surface state;
- absence of dead layer.

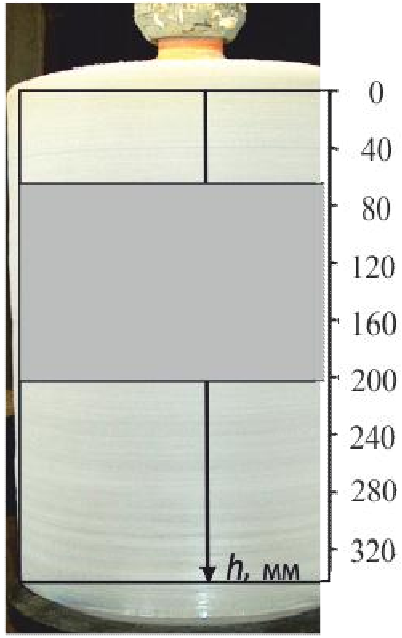
$C^{*}_{\mathrm{Tl}} > 0.15$ % for ion detection in NaI:Tl

NaI:Tl crystal for particle detection: homogeneity

Furnace for crystal growth with conical crucible "Crystal-400"







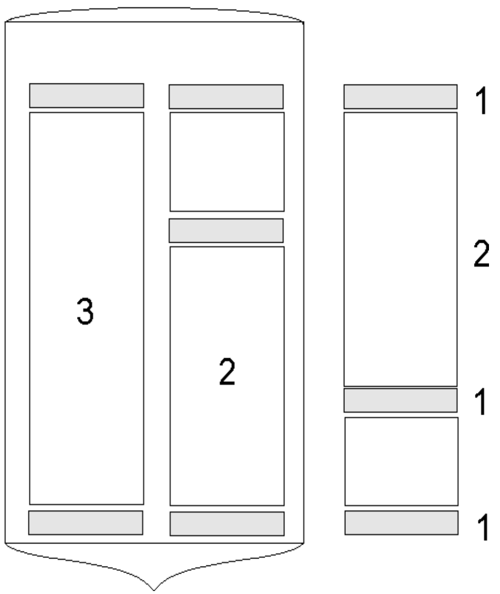
Distribution of Tl and other co-activators in scintillation material "CsI:Tl,Na,CO_3" along height.

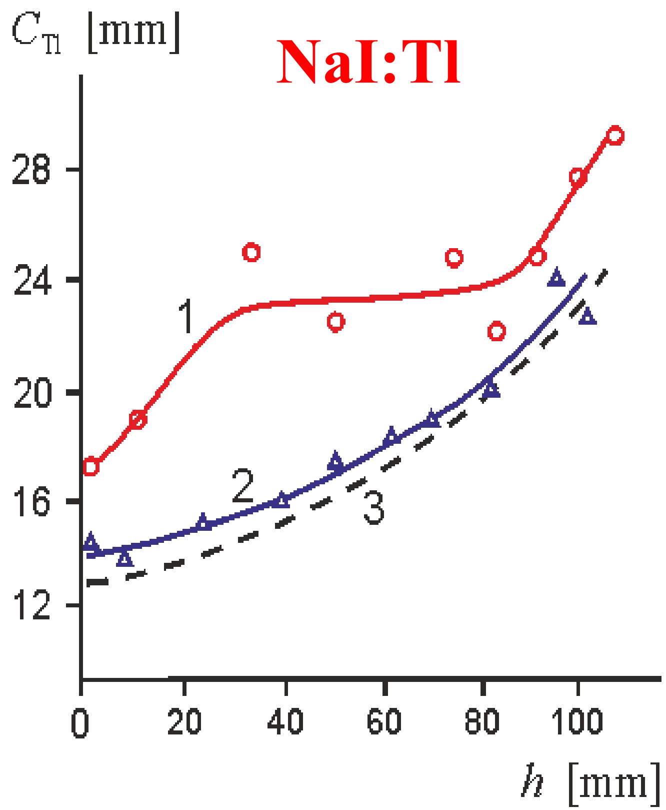
The same is thru for NaI:Tl

Impurity distribution in crystal grown by Bridgman-Stockbarger technique

$$C_{\mathrm{Tl}} = C_0 k_0 \left(1 - \frac{V}{V_0}\right)^{k_0 - 1}$$

k_o – equilibrium segregation coefficient





1 – crystal growth in vacuum;

2 - crystal growth in oxygen;

3 – calculated curve for $k_o = 0.25$, $C_o = 0.36$ %

In heavy doped crystal activator is distributed non-uniformly

Non-homogeneous distribution of activator in CsI:Tl (microscopic)

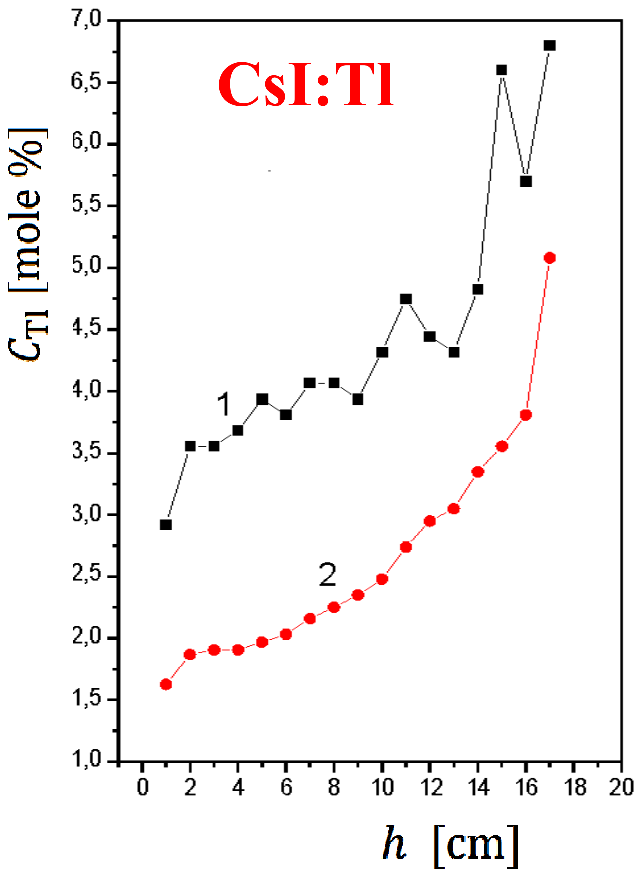


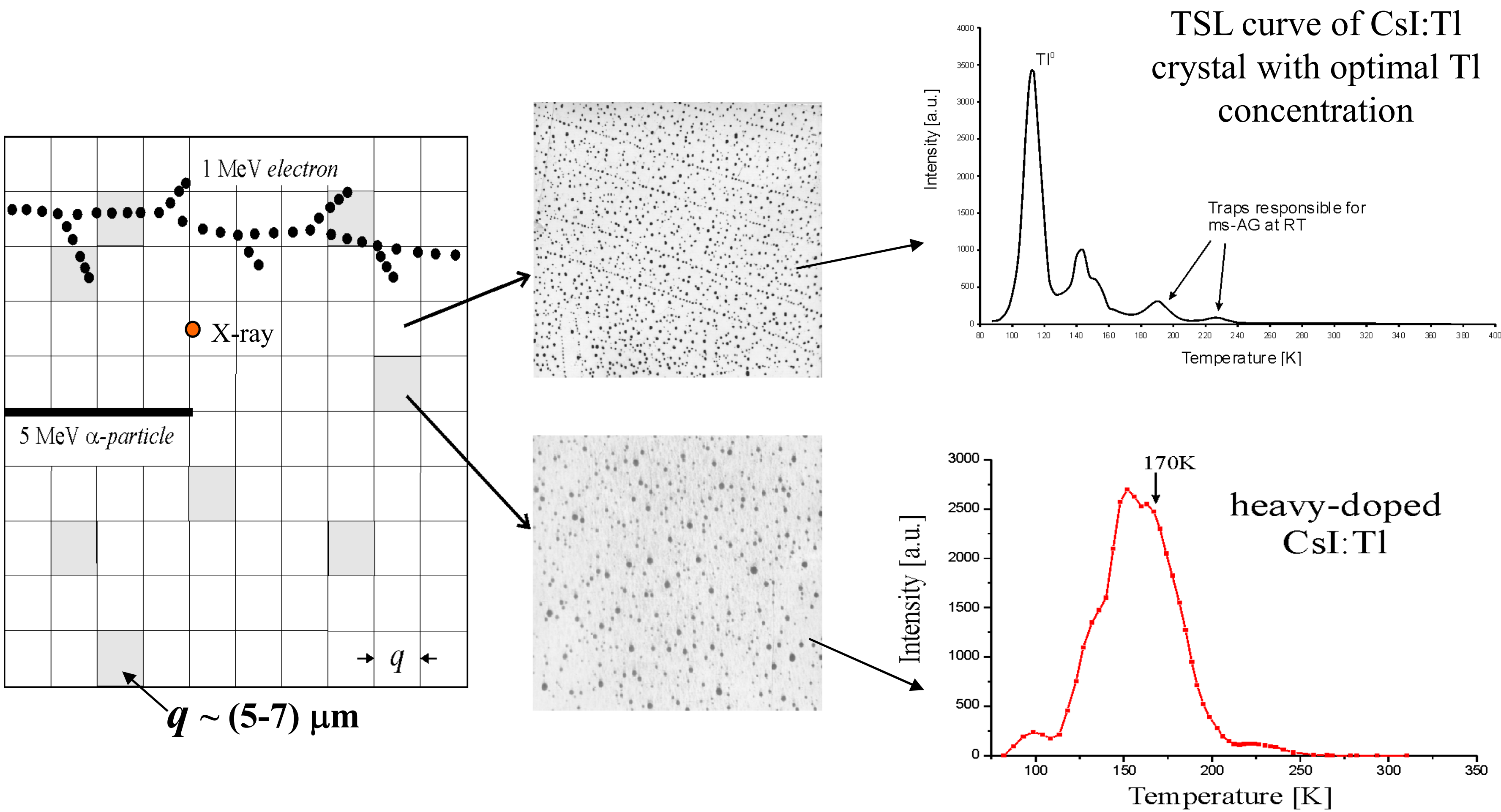
Table: PIXE analysis results

Brand	CsI n.	Nominal Tl conc.(ppm)	Measured Tl conc. (ppm)	Type of measure
GB	1	4000	6400±200	Face A, av
GB	1	4000	9300±300	Face A, point
GB	1	4000	5400±200	Face A, point
GB	1	4000	6100±200	Face B, av
GB	1	4000	4610±180	Side, av
GB	2	3000	2950±110	Face A, av
GB	2	3000	4900±200	Face B, point
GB	2	3000	3030±120	Face B, av
St. Gobain	3	500	440±50	Face A, av
St. Gobain	4	200	280±30	Face A, av
Marketech	5	700	520±30	Face A, av
Scionix	6	2500	5220±160	Face A, av

FAZIA collaboration results

In $C_{Tl} > 0.2\%$ the activator is not homogeneous distributed both macroscopically and microscopically

Nature of concentration quenching



Schematic image of microscopic distribution of Tl^{+} center in CsI crystal at high Tl concentration. Photo represents the character of decoration of the cleavage plane in two different places. (Electron microscope; ×16 000; decoration by gold). Black squares correspond to places of increased Tl content (so-called spinodal decay of solid solution)

Uniformity of spectrometric parameters

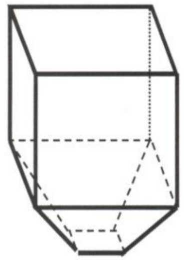
Photodiode scintillator of 200 cm^3 volume.

16 sample from selected region of ingot.

CsI:Tl ingot of 240 mm dia. and 360 mm heigh

Pulse height spectra for each element (left) and summarized spectrum of whole block (right).

V = 216 $см^3$.



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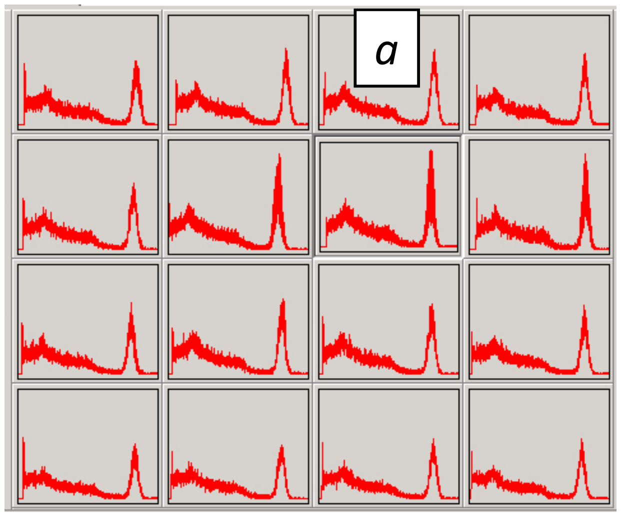
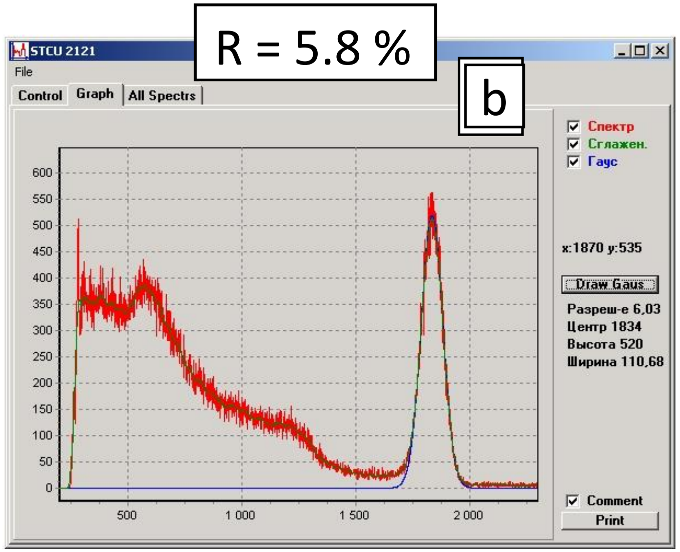
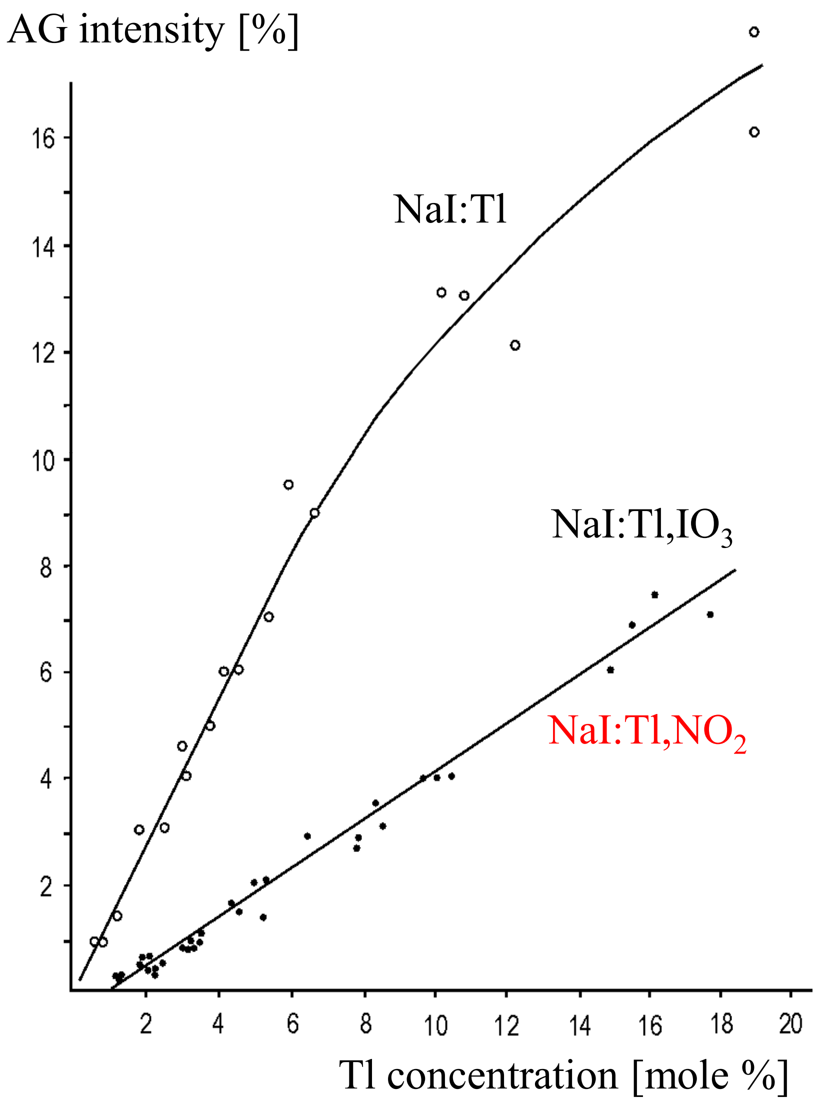
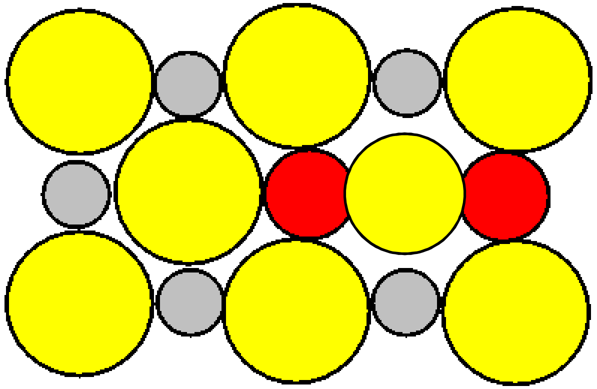


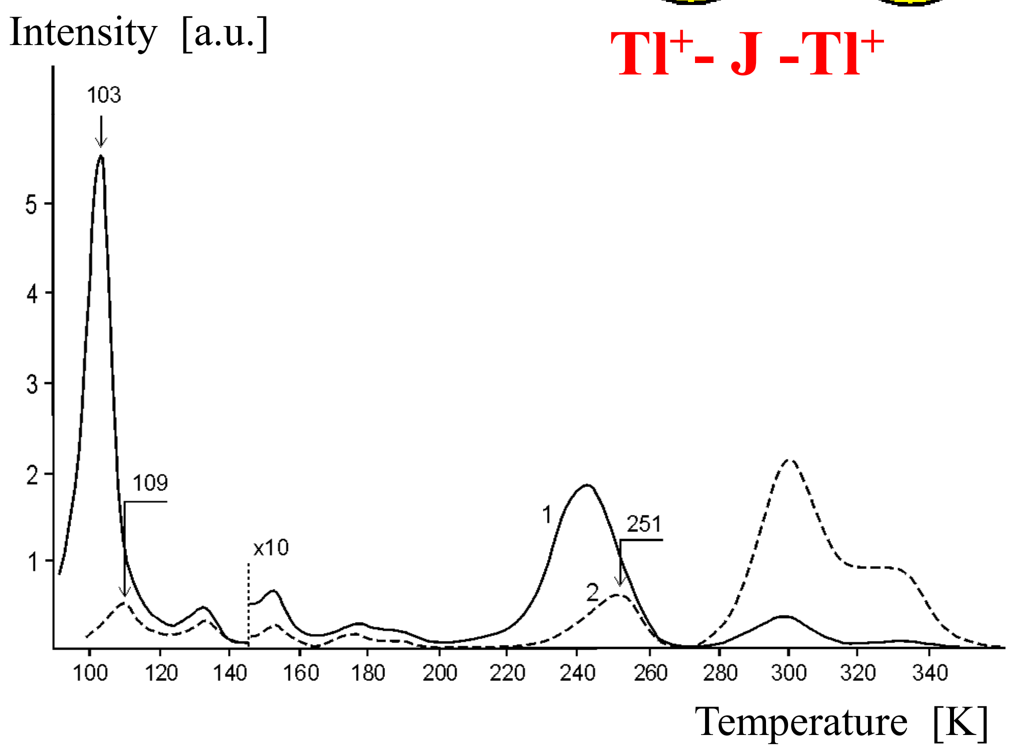


Nature of millisecond afterglow in NaI:Tl

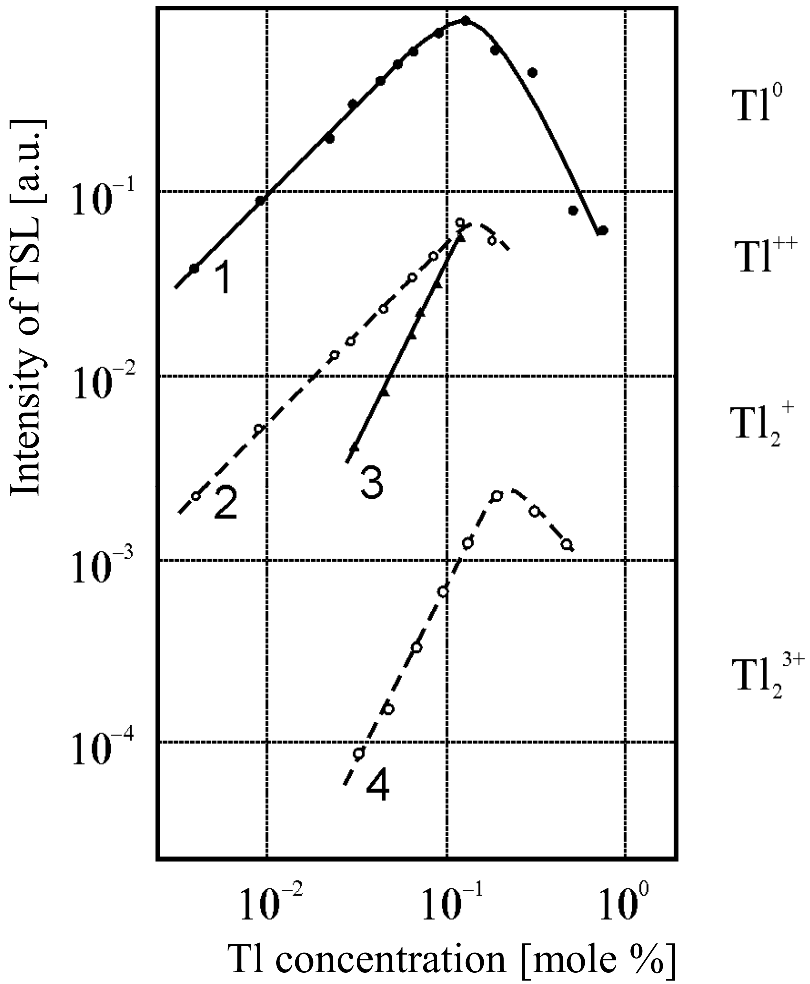


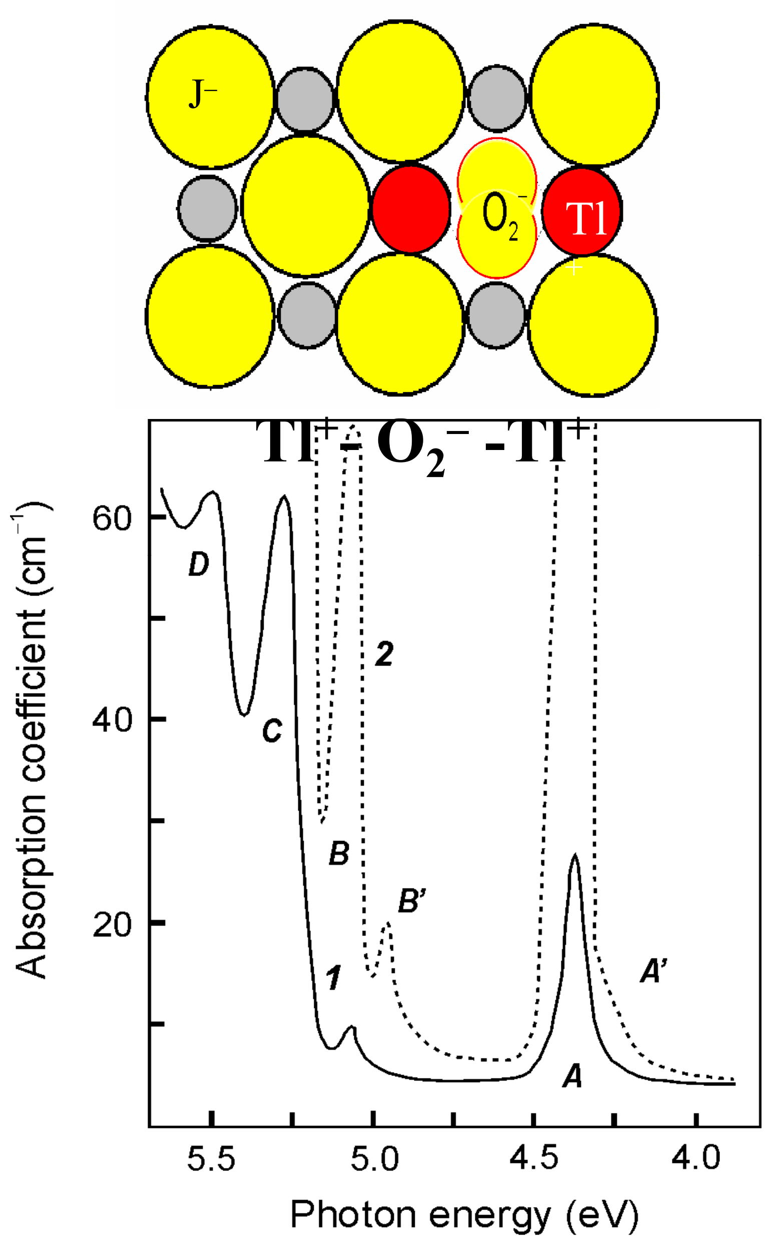


Tl^+- J -Tl^+



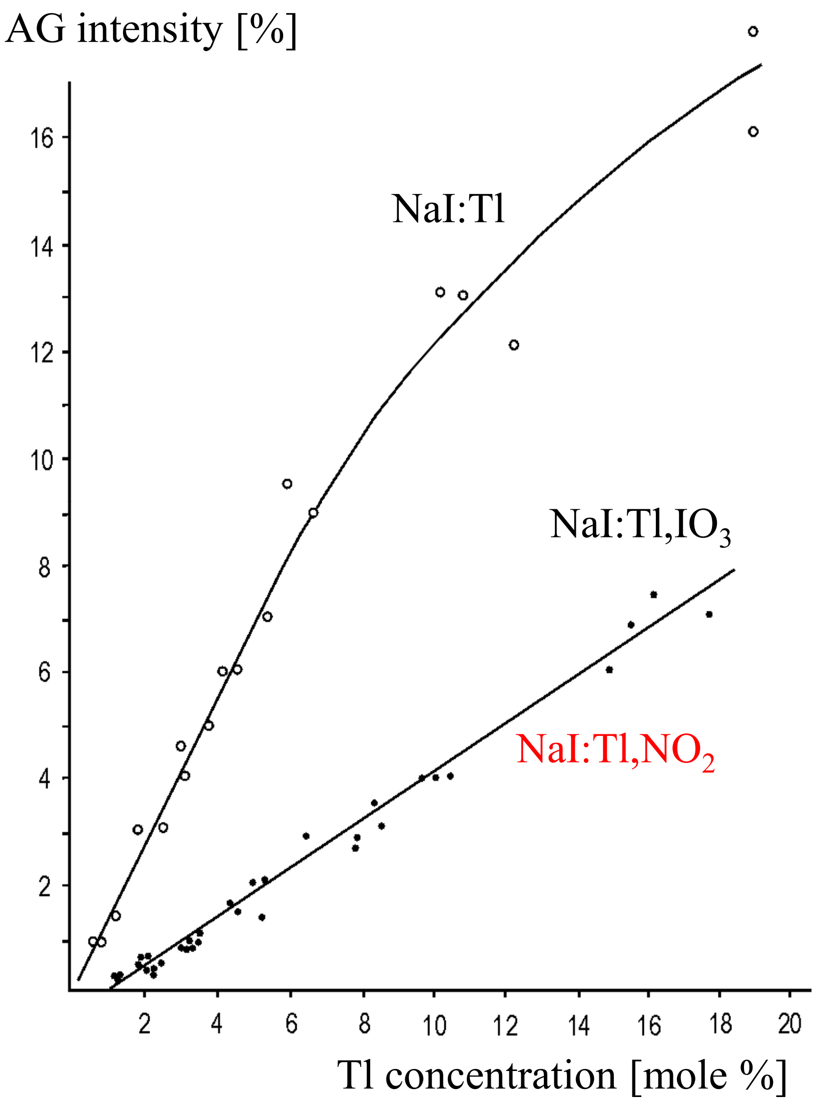
Nature of millisecond afterglow



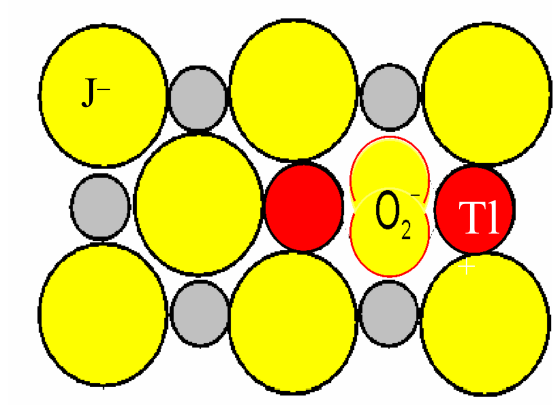


Oxygen suppress AG and LY

Nature of millisecond afterglow and its suppressing

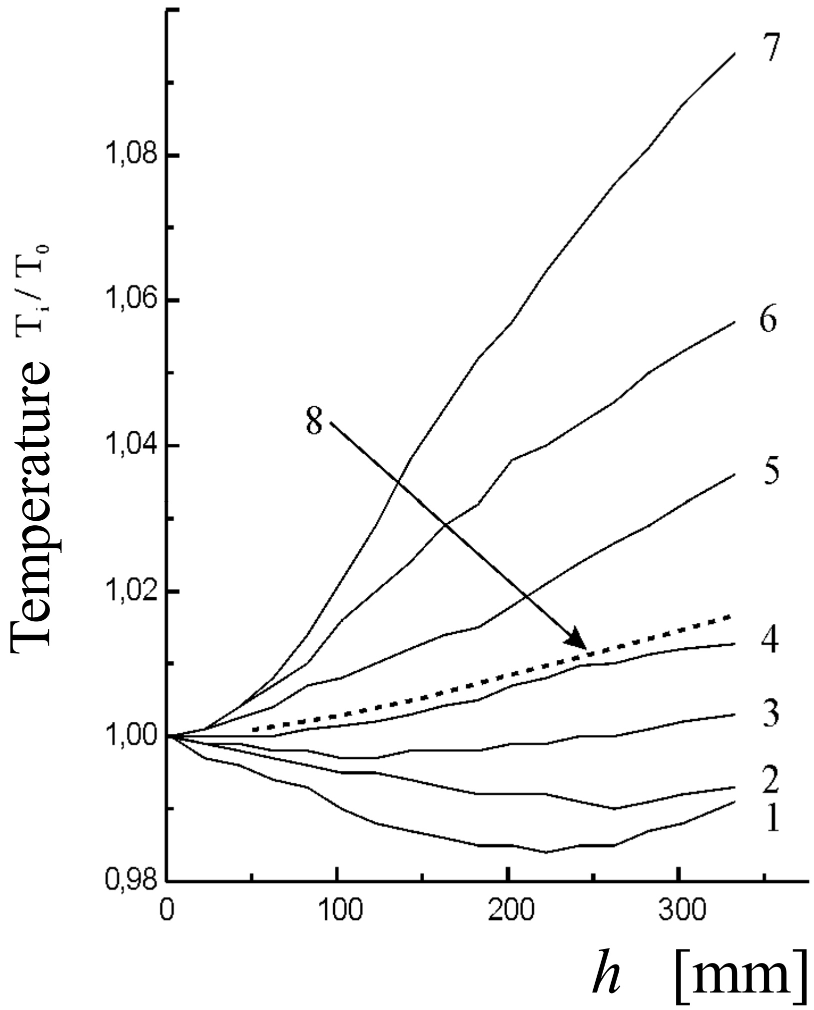


Tl^{+}- O_2^{-} -Tl^{+}



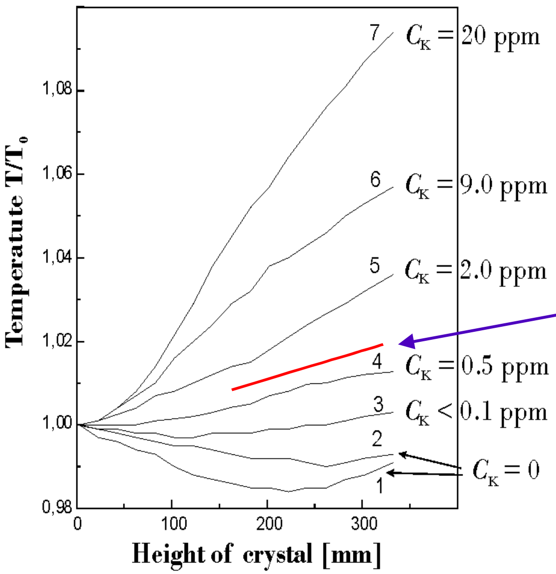
Model of electron trap which forms a quenching center for recombination luminescence

Crystal growth of uniform and heavy-activated ingot



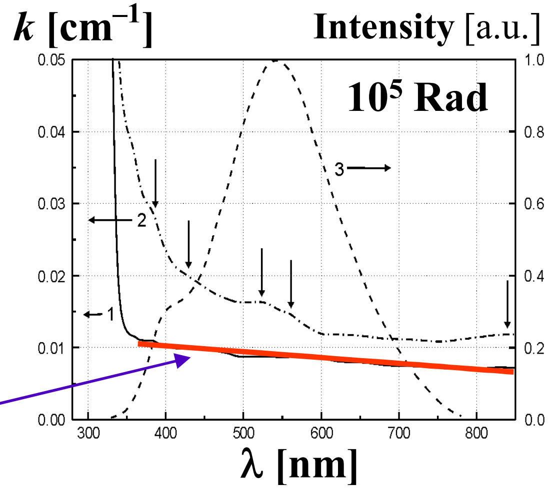
Scintillation materials: $CsI:Tl,CO_3$ or $NaI:Tl,CO_3$

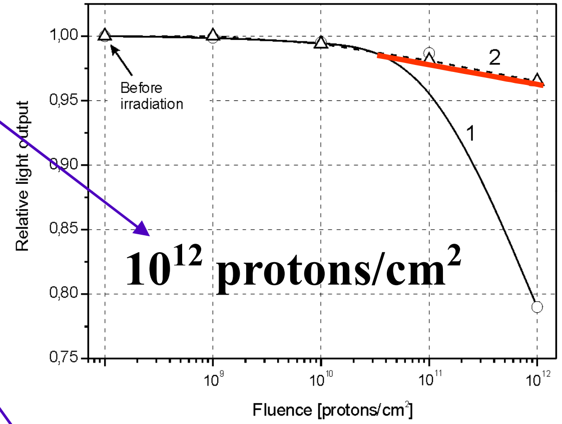
CsI:Tl, NO_2

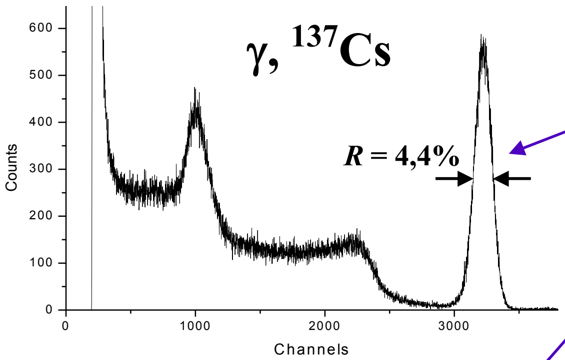


Growth conditions

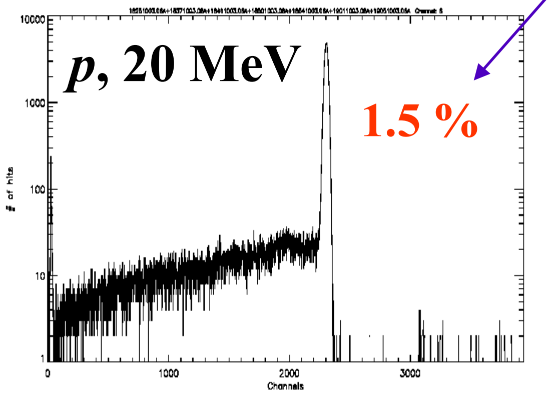
Rad. Hardness







Resolution



Afterglow

Material	AG (100 ms)
CsI:Tl	0,87…1,11%
CsI:Tl,NO_2	**0.42…0.57%**

Prospect

Limit of Tl concentration
0,5 %

Conclusion

- for Dark Matter search the heavy doped NaI:Tl crystals are needed;
- characterization of crystal quality should be done using alpha-particles and fissing fragments;
- it has been shown that NaI:Tl crystals with $C_{\mathrm{Tl}} \sim 0.3$ % are available (so called NaI:Tl,IO_3 crystals). CsI:Tl,IO_3 crystals with $C_{\mathrm{Tl}} \sim 0.5$ % can be grown by Stockbarger technique;
- uniformity of NaI:Tl,IO_3 and CsI:Tl,IO_3 ingots is bad due to used crystallization technique;
- to obtain large uniform NaI:Tl crystal the modified Kyropoulos technique should be used;
- to obtain large heavy doped NaI:Tl crystal we recommend NaI:Tl,NO_2 scintillation material for crystal growth.

Список публикаций, упомянутых в докладе

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