Seminar at LNGS, July 23, 2015

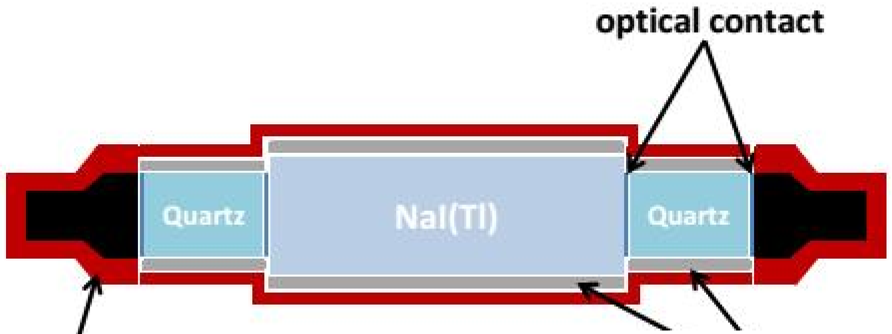
The NaI:Tl and CsI:Tl crystals for effective detection of X-rays and low energy charged particles

Alexander M. Kudin

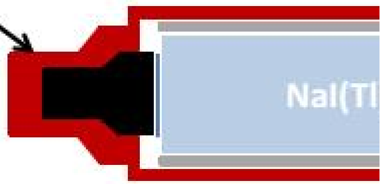
Institute for Scintillation Materials NAS of Ukraine
National University of Civil Protection of Ukraine

July 22, Assergi, Italy

DAMA single detector unit

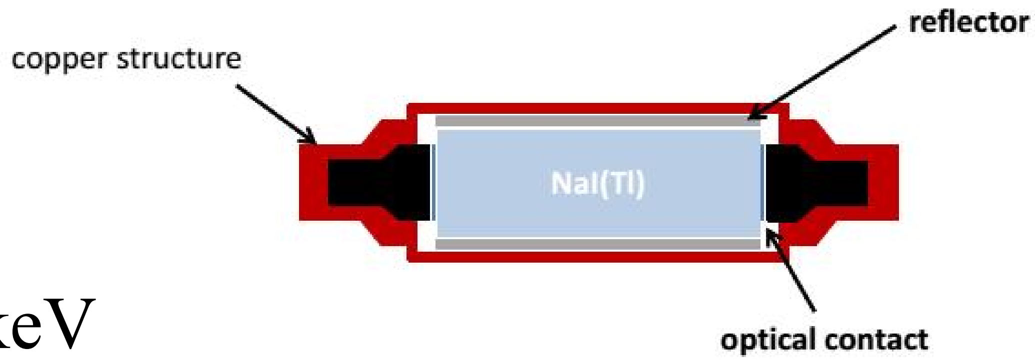


copper structure



Current **SABRE** single detector unit

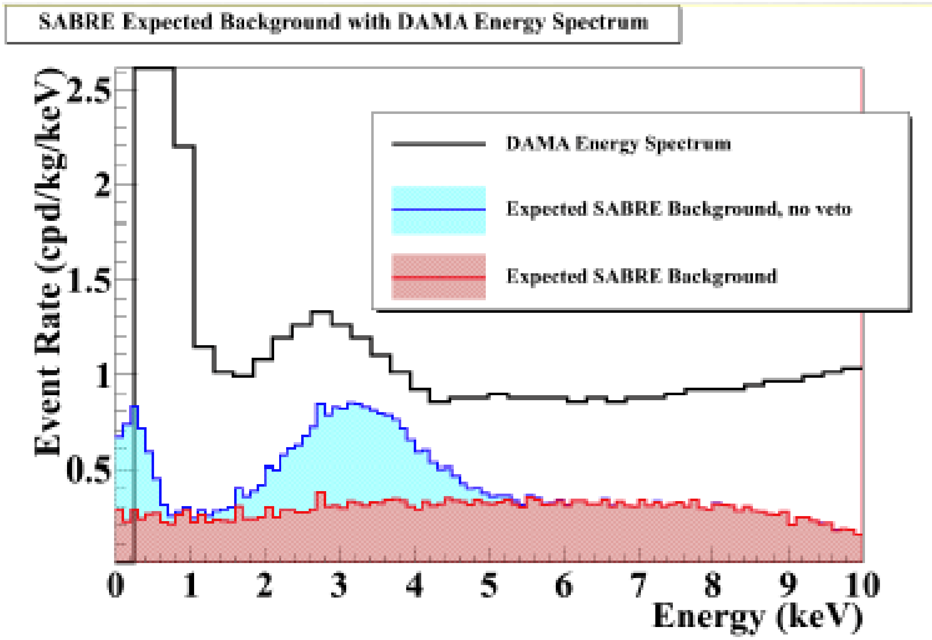
preliminary design



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

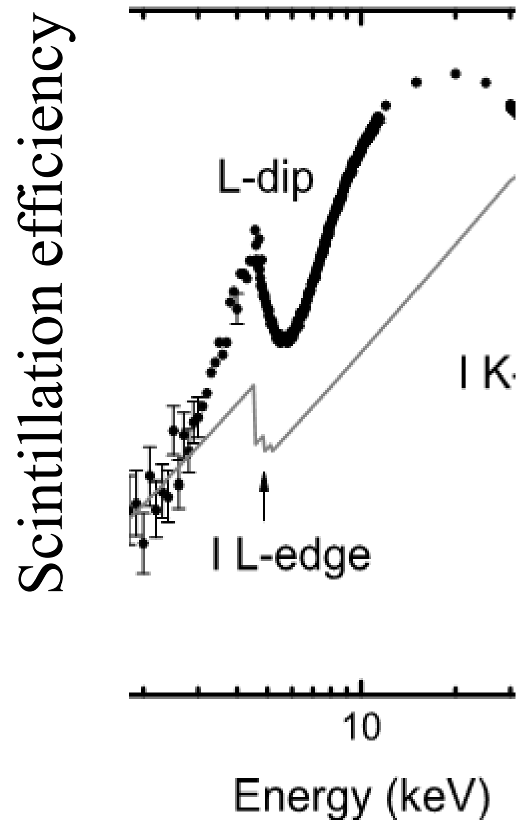
McCann M.F. and Smith K.M.

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



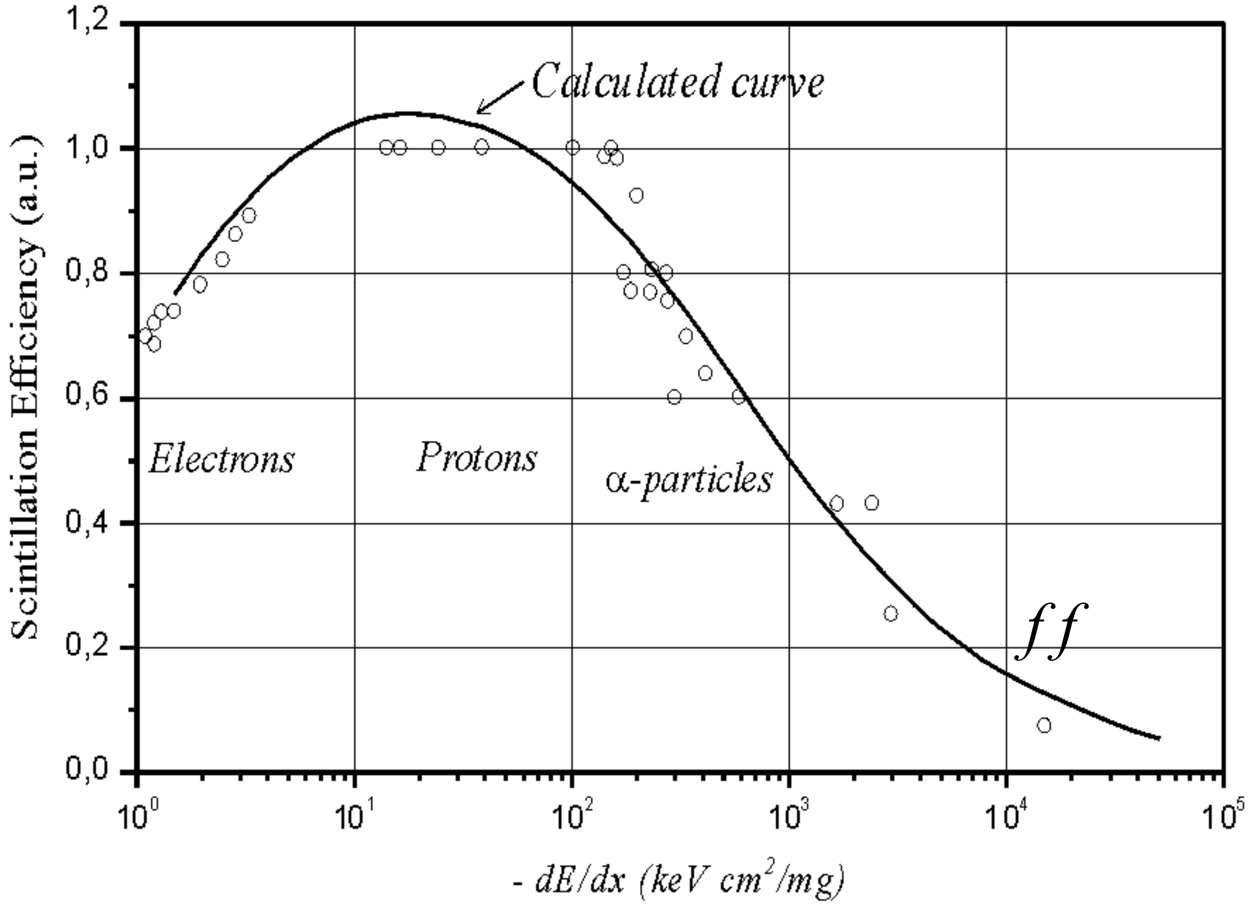
NaI:Tl crystal

External source of synchrotron radiation

Problems of low energy particle detection

Light yield depends on *dE/dx*

Energy resolution and
non-proportionality of response

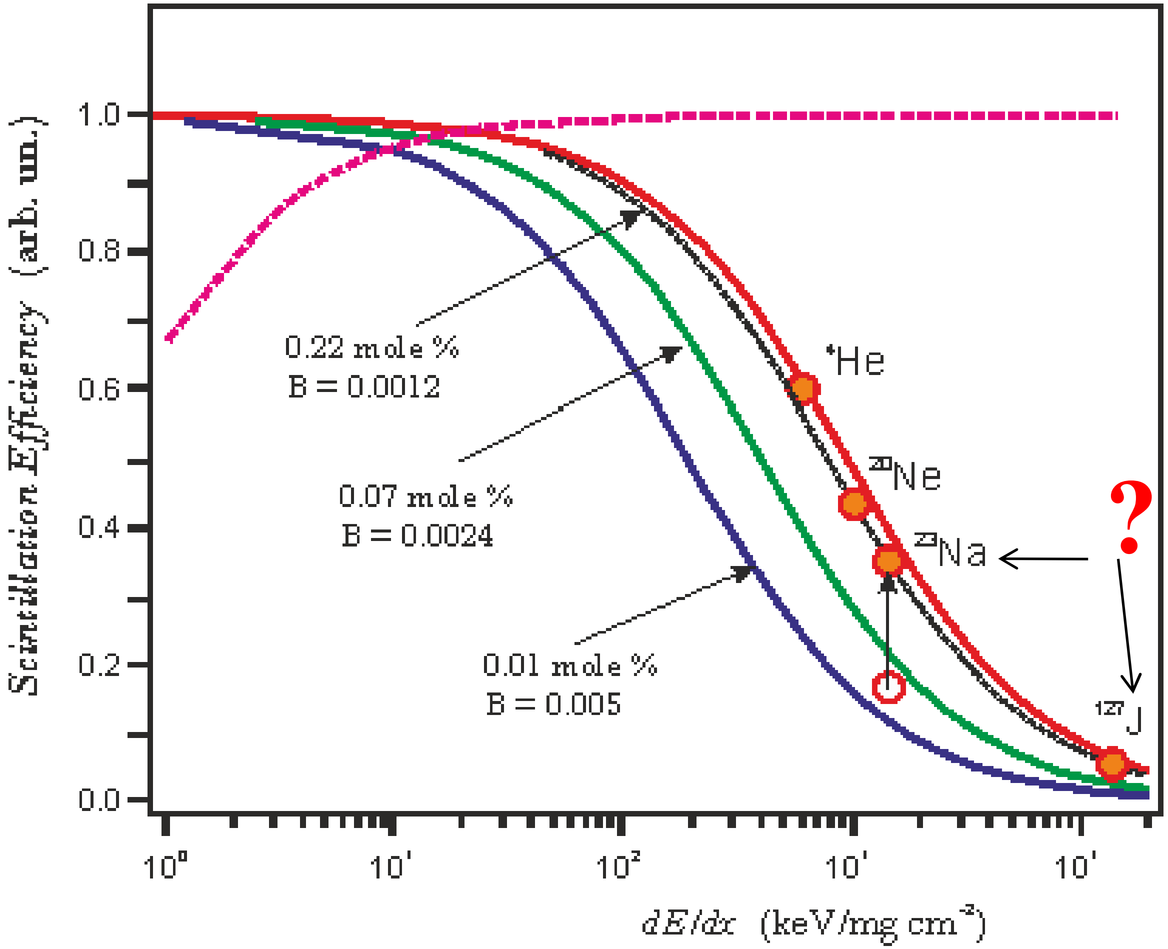


QF – quenching factor

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

Dark matter search with NaI and CsI

According to Birks model



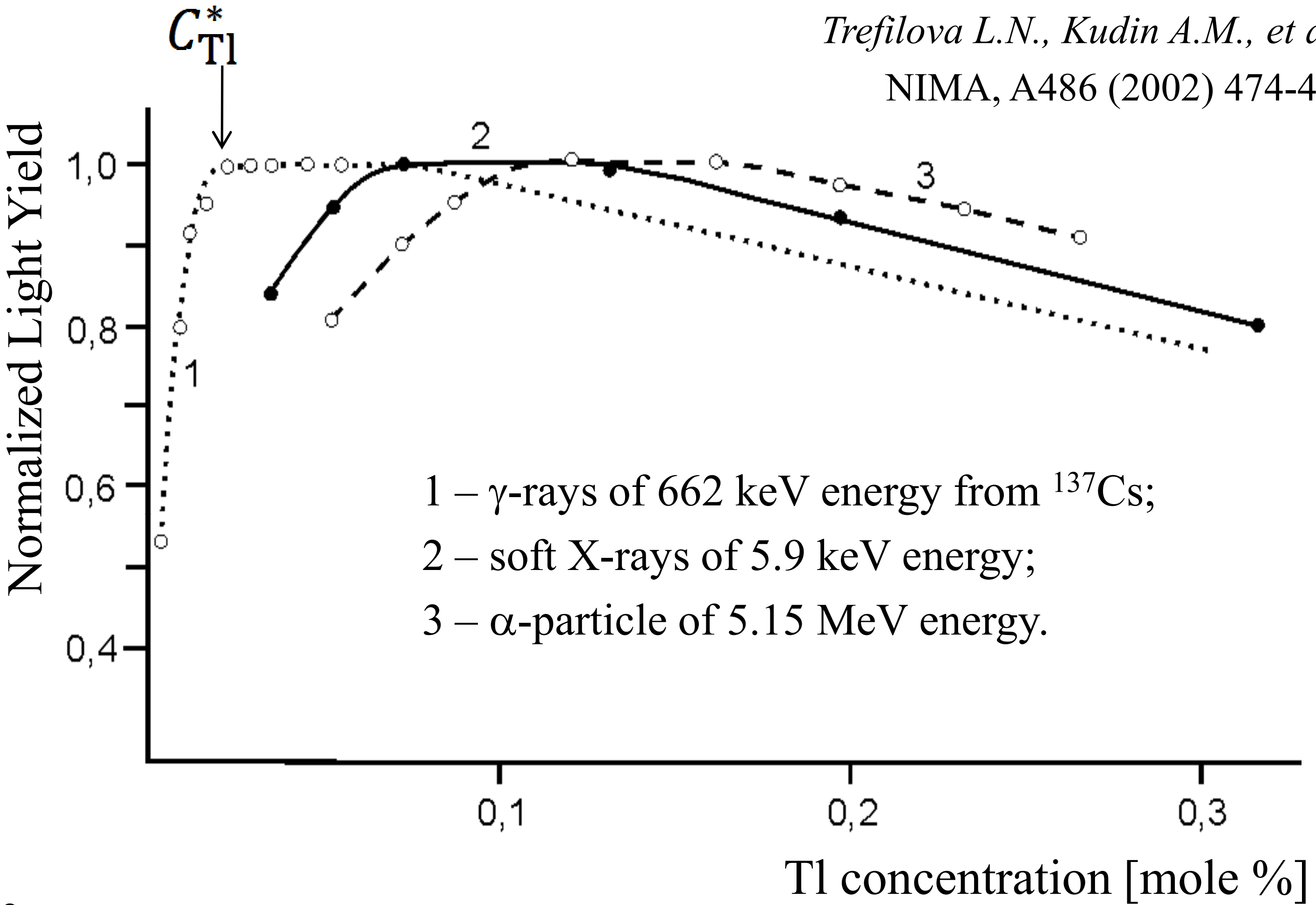
Quenching factor for ^{23}Na and ^{127}J

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

Trefilova L.N., Kudin A.M., et all.,
NIMA, A486 (2002) 474-481.



$C^*_{Tl} = 2.2\cdot10^{-2}$ % for γ-rays;
$C^*_{Tl} = 7.3\cdot10^{-2}$ % for soft X-rays of 5.9 keV;
$C^*_{Tl} = 1.3\cdot10^{-1}$ % 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;

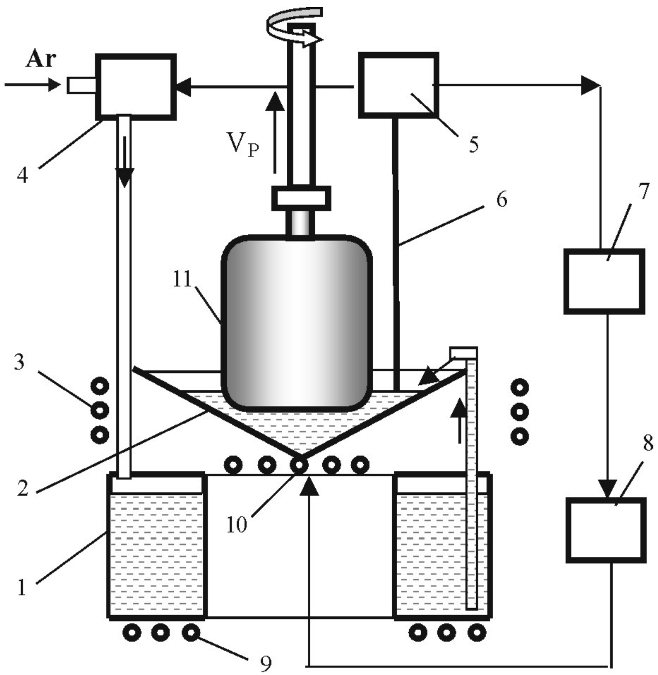
Additional:

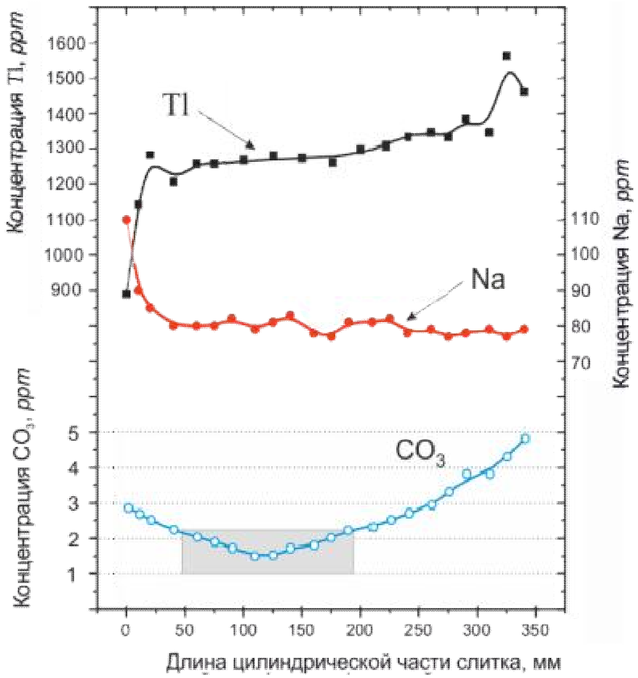
- increased Tl concentration to rich best scintillation efficiency for charged particles detection;
- stability of surface state;
- absence of dead layer.

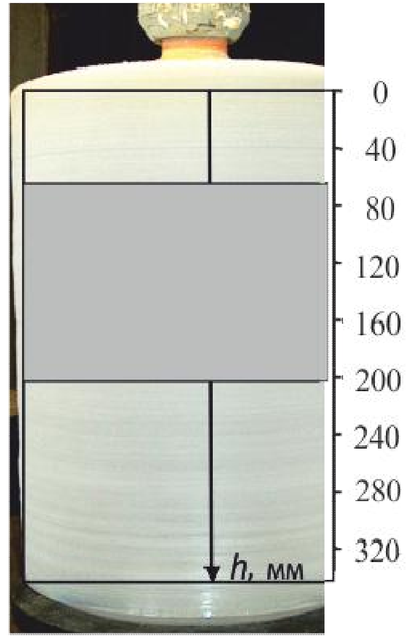
$C^{*}_{\mathrm{Tl}} > 0.15$ % for ion detection in NaI:Tl

NaI:Tl crystal for particle detection: homogeneity

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







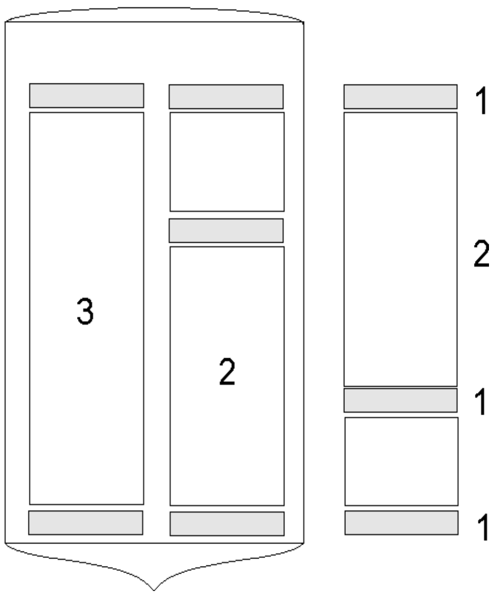
Distribution of Tl and other co-activators in scintillation material "CsI:Tl,Na,CO_3" along height.

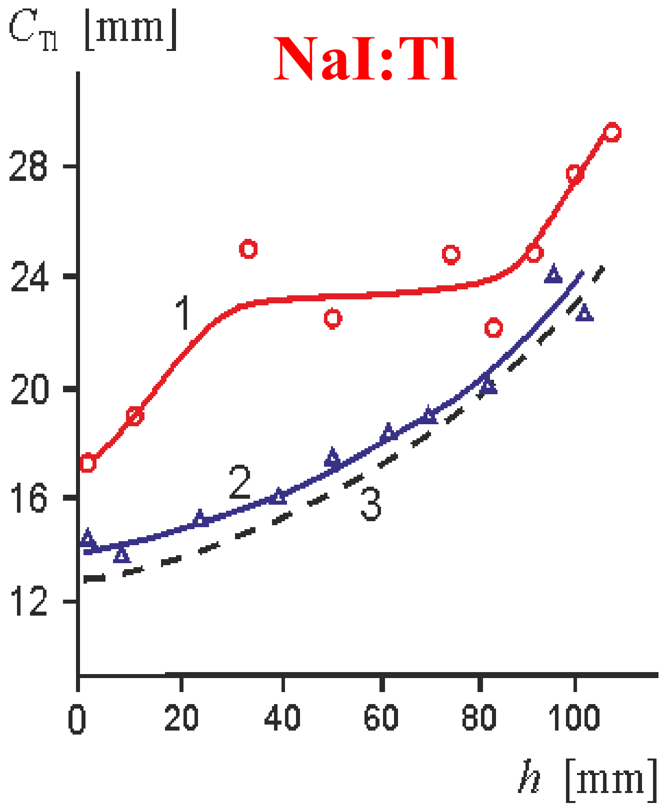
The same is thru for NaI:Tl

Impurity distribution in crystal grown by Bridgman-Stockbarger technique

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

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)

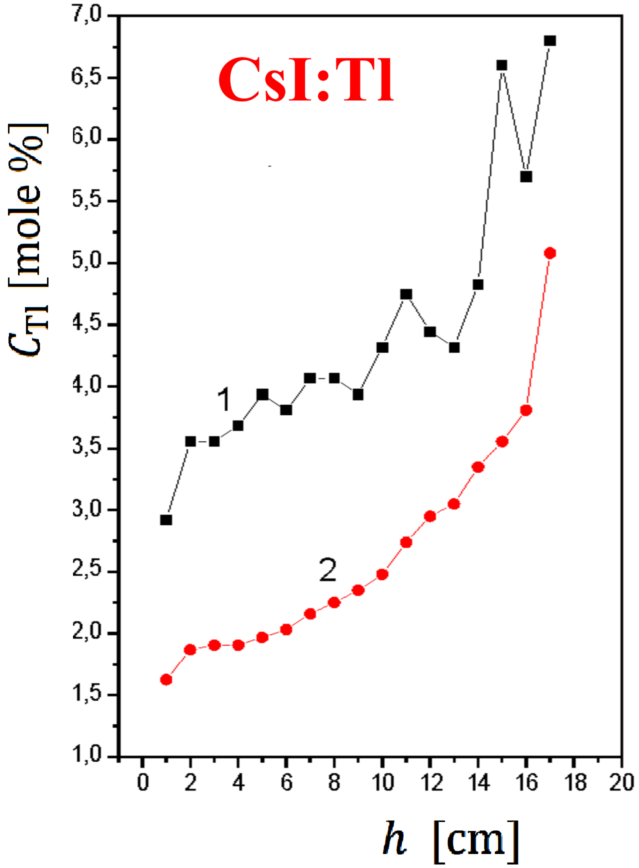


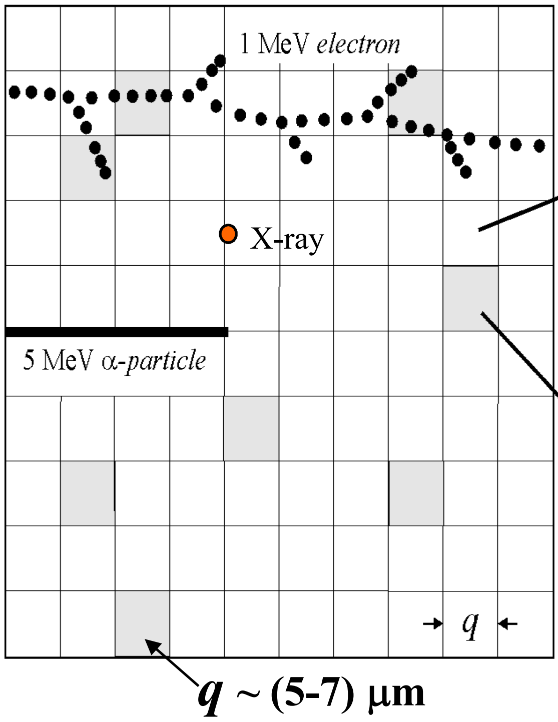
Table: PIXE analysis results

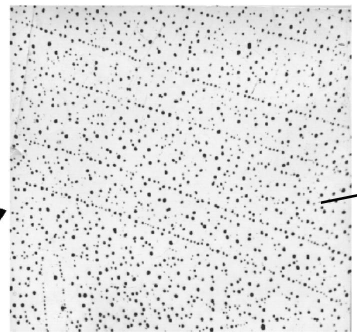
Brand	CsI n.	Nominal Tl conc.(ppm)	Measured Tl conc. (ppm)	Type of measure
GB	1	4000	6400±200	Face A, av
GB	1	4000	9300±300	Face A, point
GB	1	4000	5400±200	Face A, point
GB	1	4000	6100±200	Face B, av
GB	1	4000	4610±180	Side, av
GB	2	3000	2950±110	Face A, av
GB	2	3000	4900±200	Face B, point
GB	2	3000	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

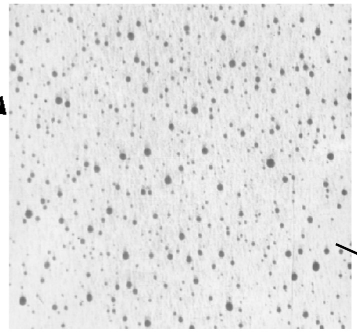
FAZIA collaboration results

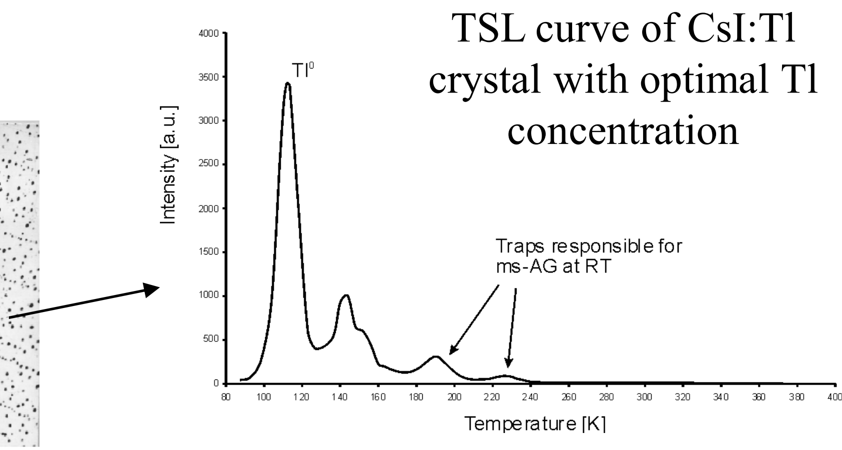
In $C_{Tl} > 0.2\%$ the activator is not homogeneous distributed both macroscopically and microscopically

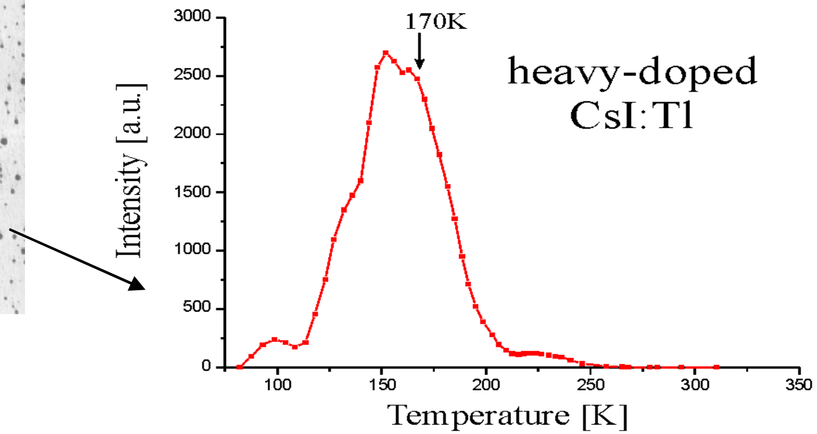
Nature of concentration quenching











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

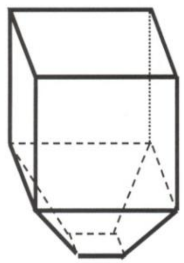
Photodiode scintillator of 200 cm^3 volume.

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.



a

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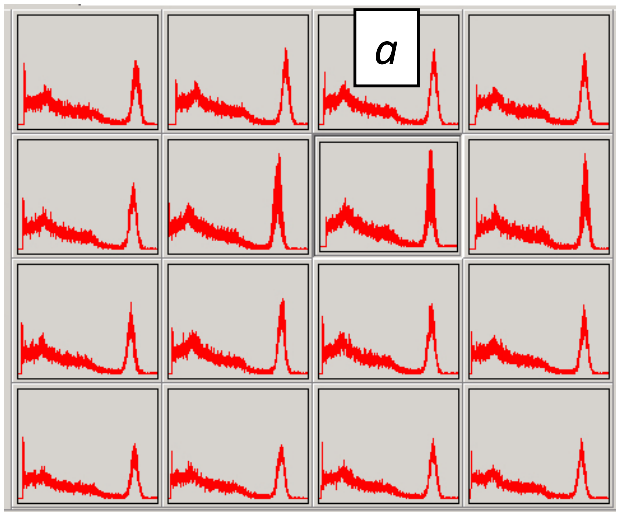
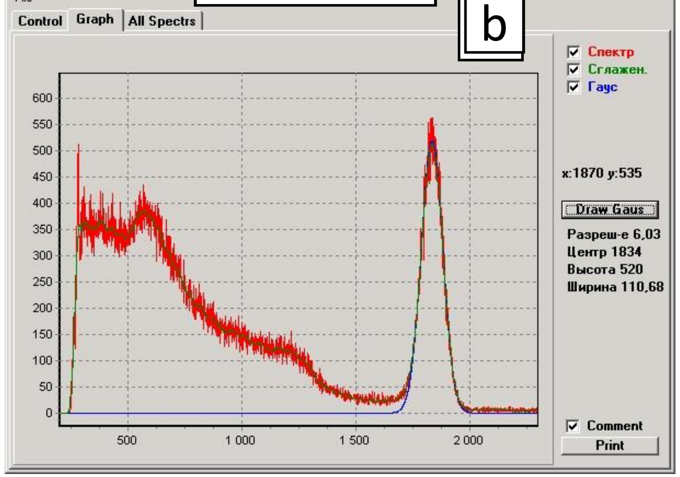
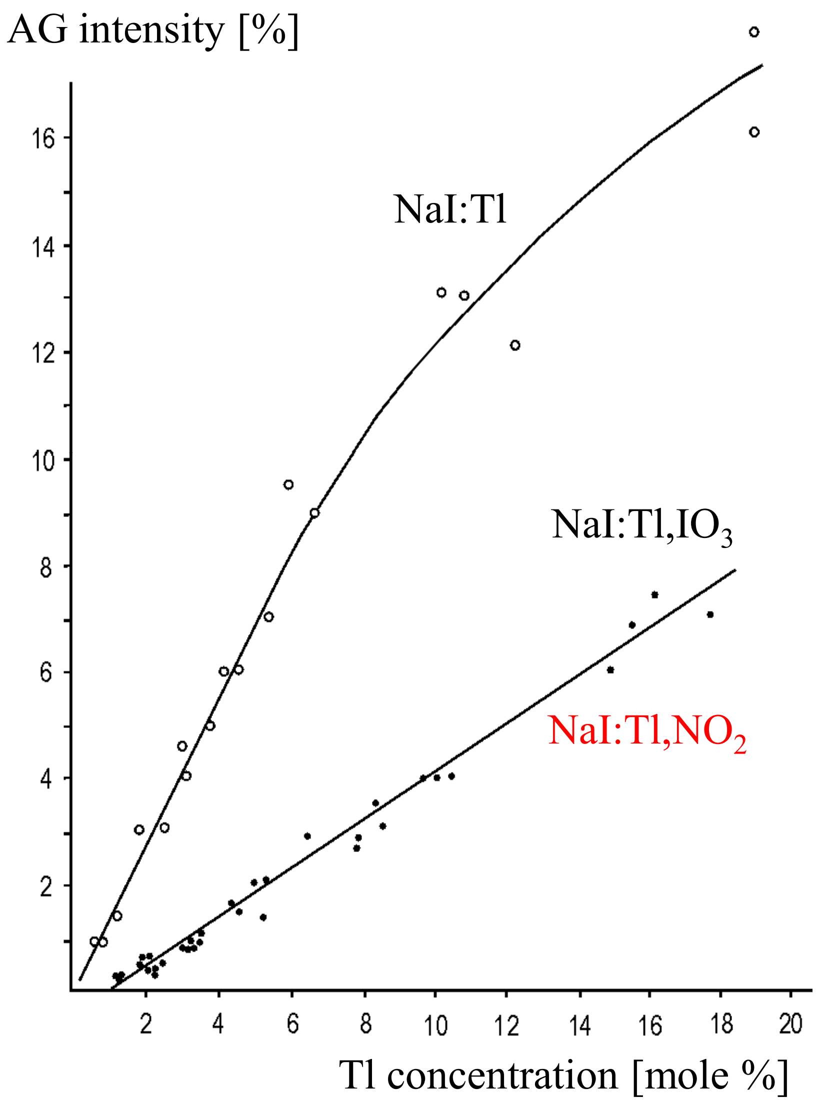


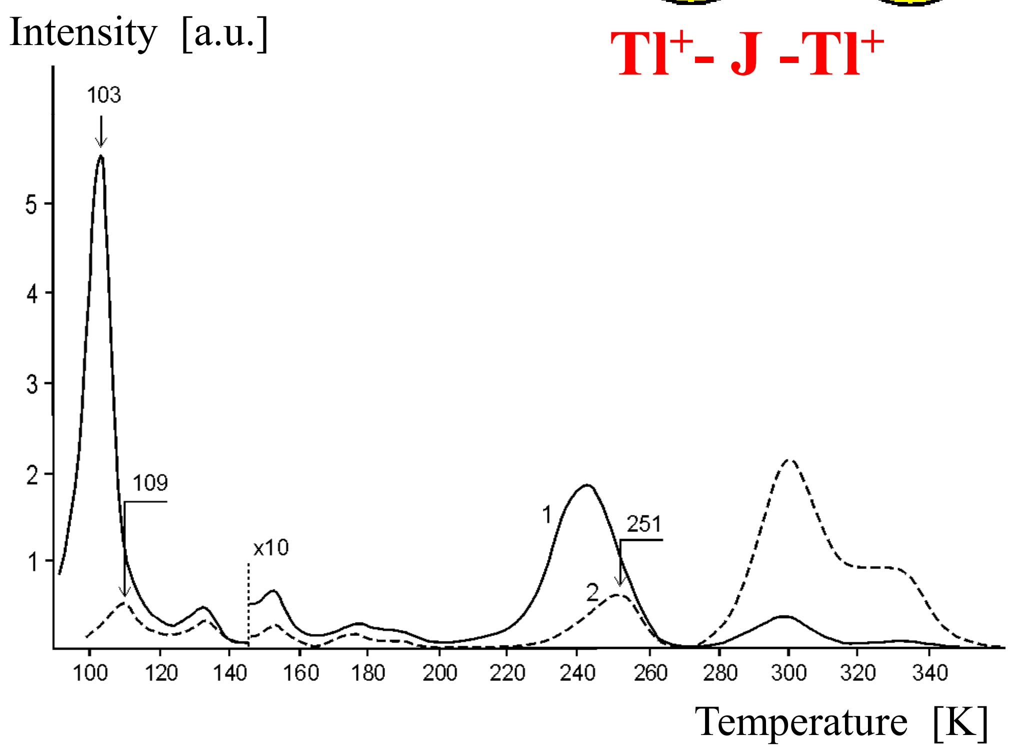
R = 5.8 %

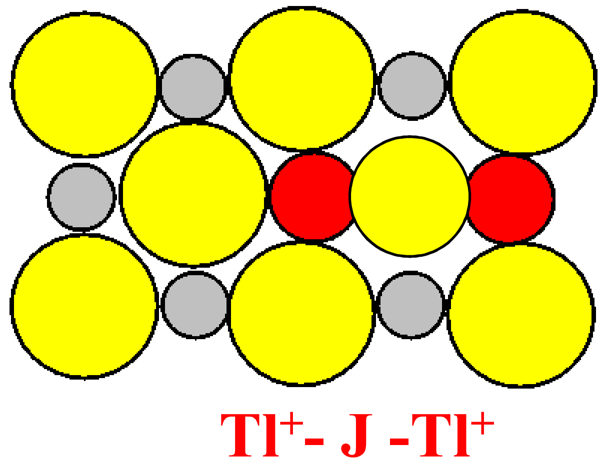
b



Nature of millisecond afterglow

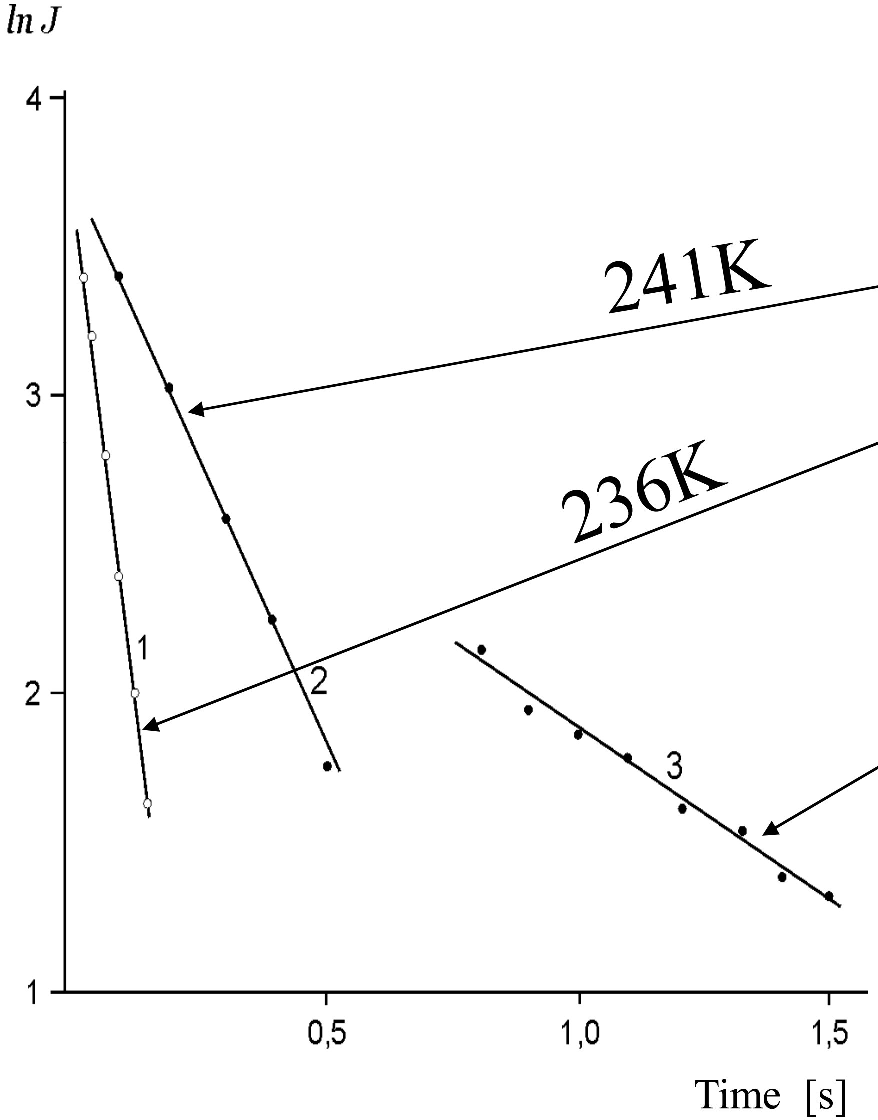


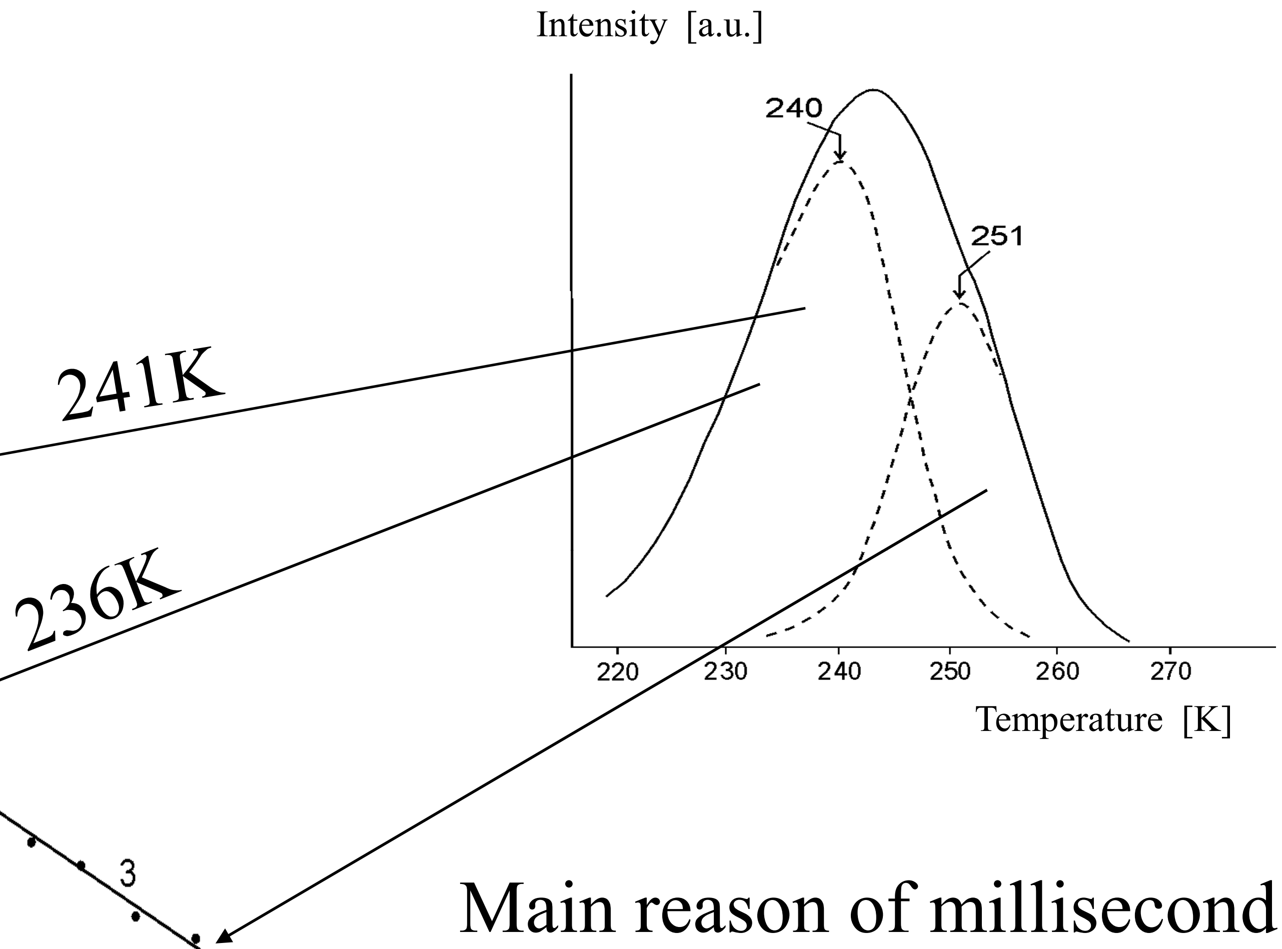




Two components of ms-AG

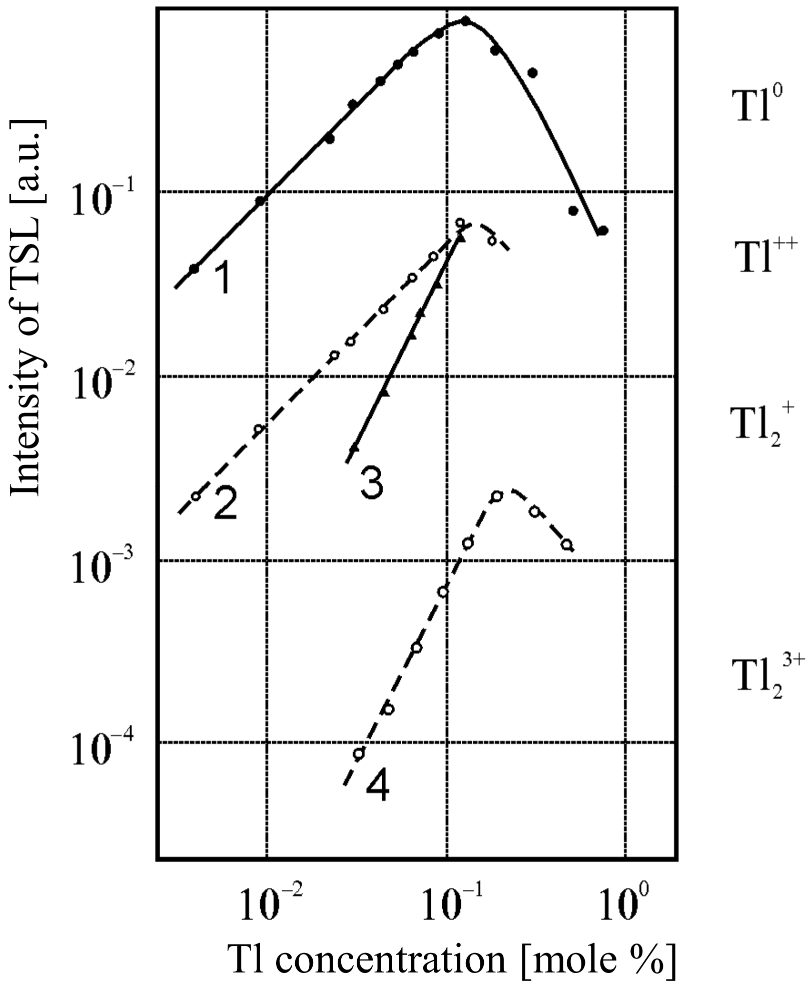
Two peaks of TSL

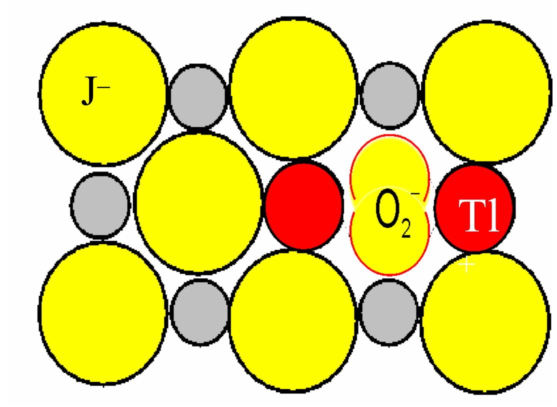


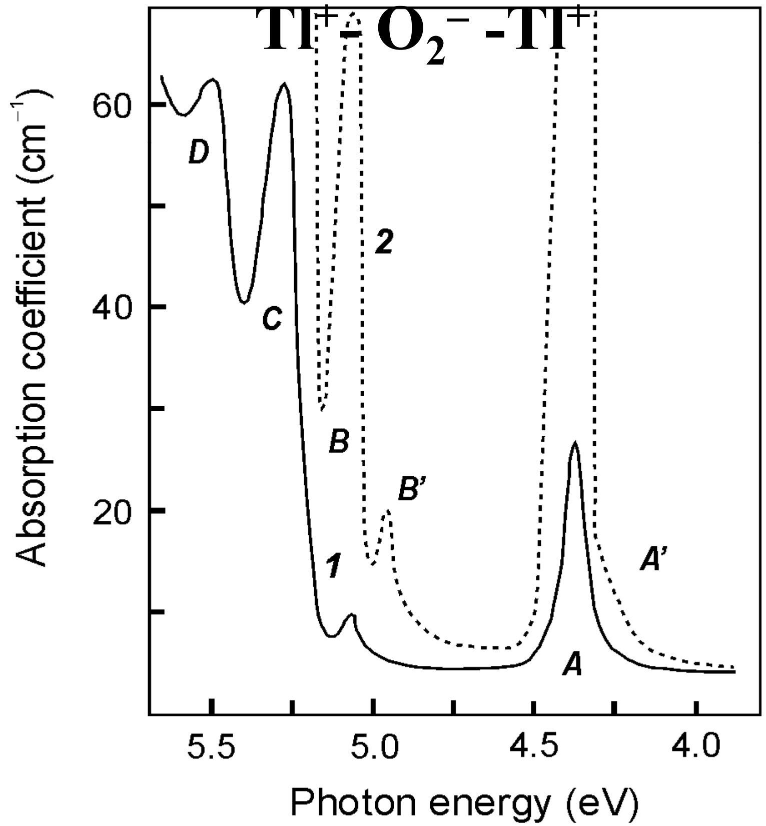


Main reason of millisecond AG in NaI:Tl is an existence of stable $(Tl^{+})_2$ centers (activator dimers)

Nature of millisecond afterglow

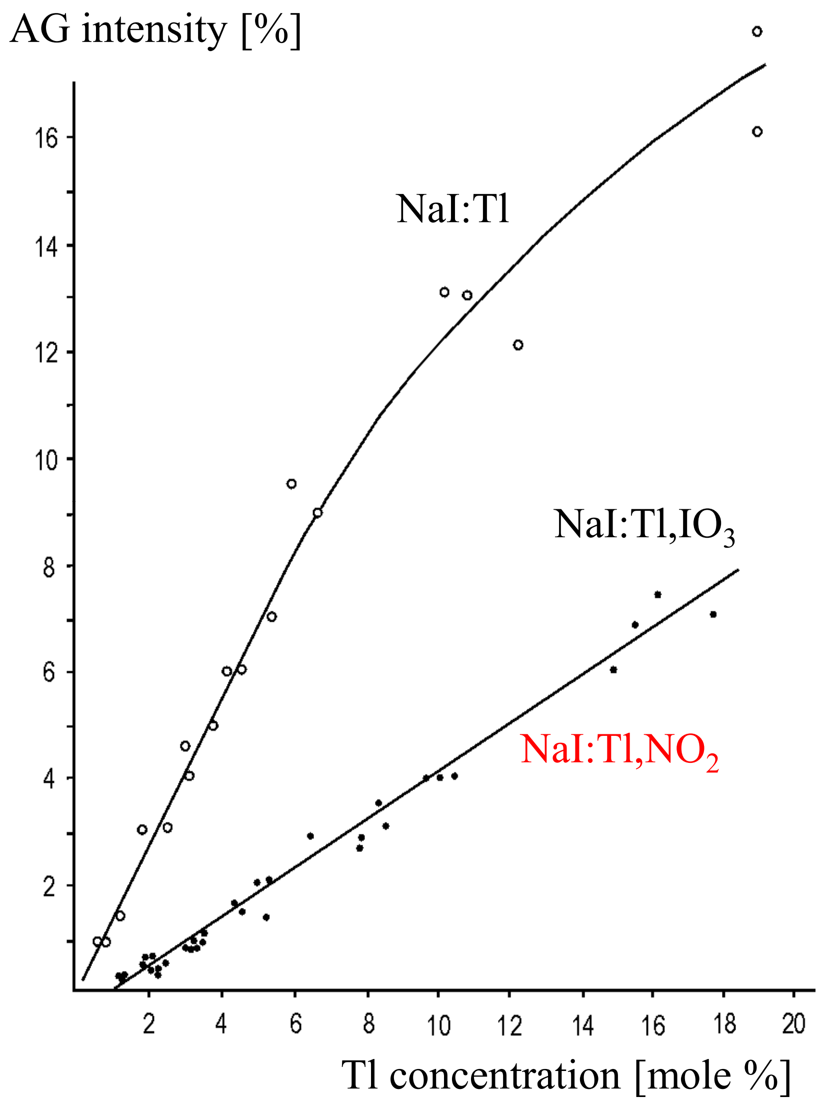




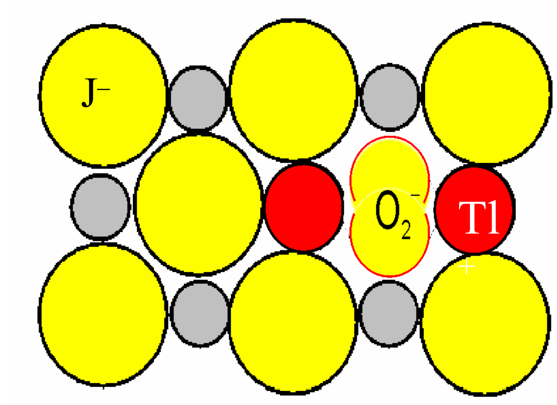


Oxygen suppress AG and LY

Nature of millisecond afterglow and its suppressing

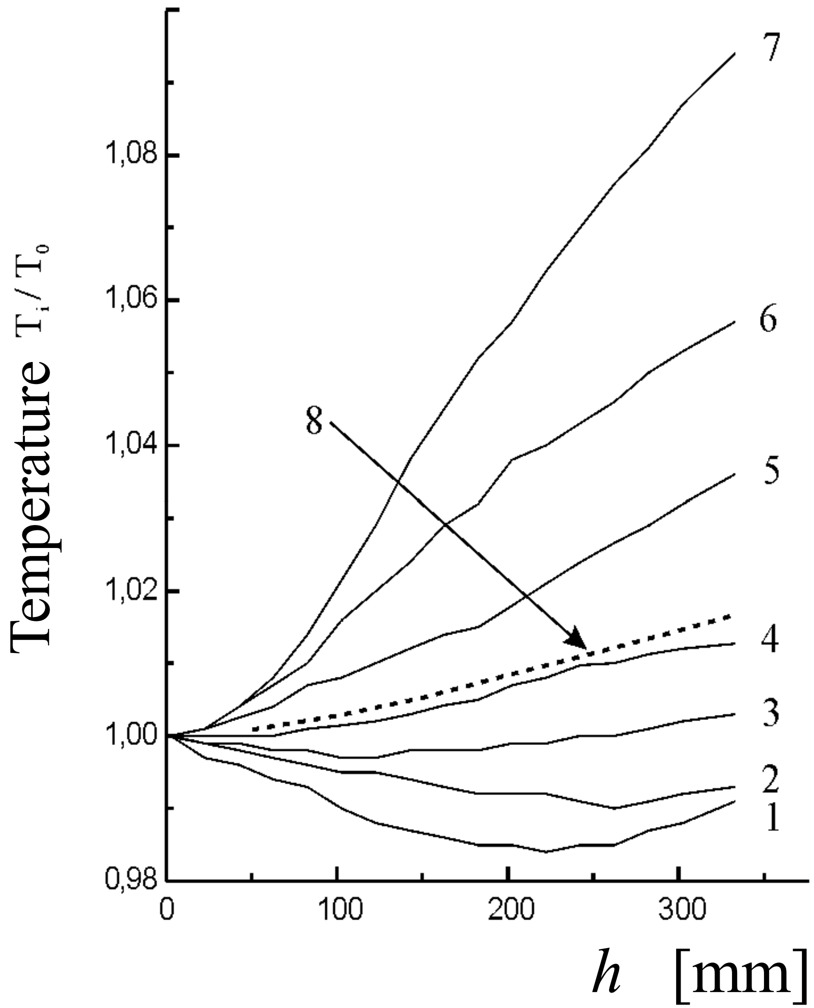


Tl^{+}- O_2^{-} -Tl^{+}



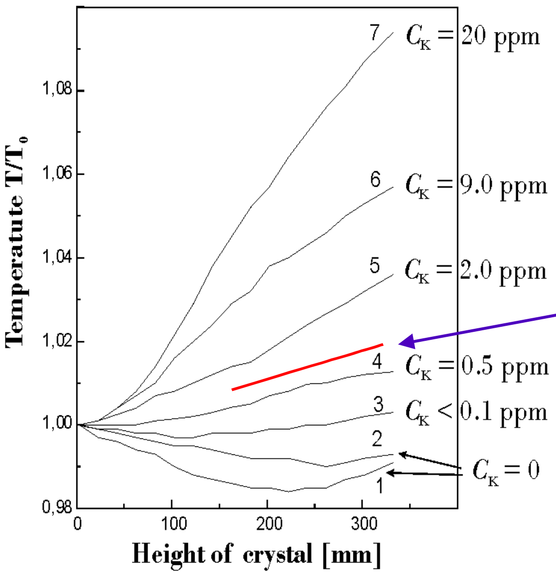
Model of electron trap which forms a quenching center for recombination luminescence

Crystal growth of uniform and heavy-activated ingot



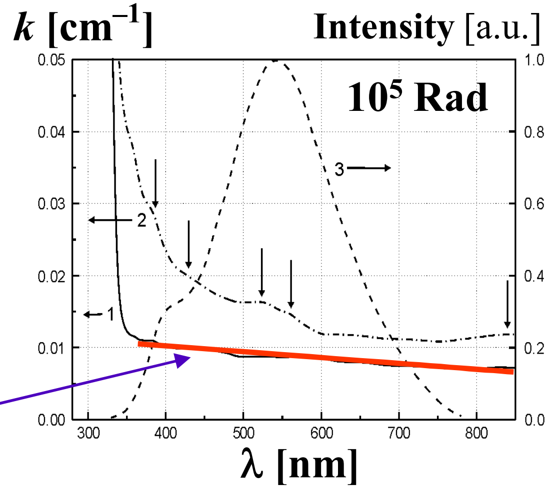
Scintillation materials: $CsI:Tl,CO_3$ or $NaI:Tl,CO_3$

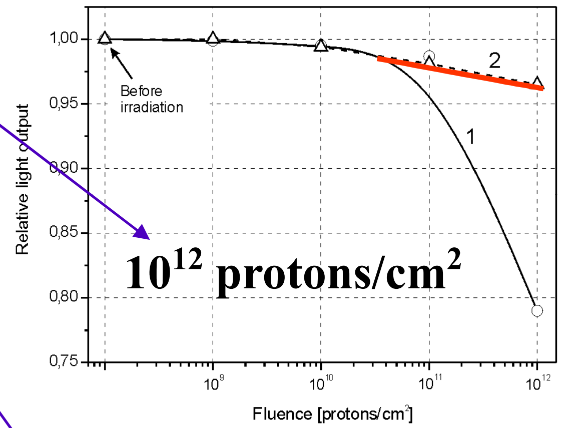
CsI:Tl, NO$_2$



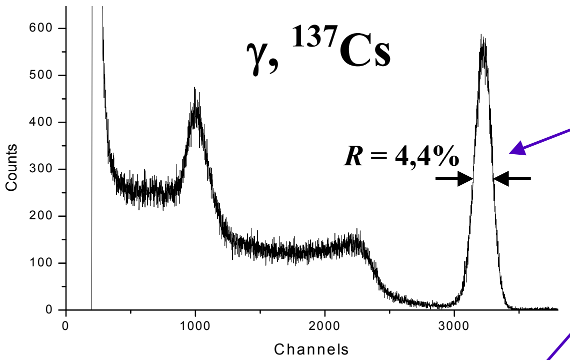
Growth conditions

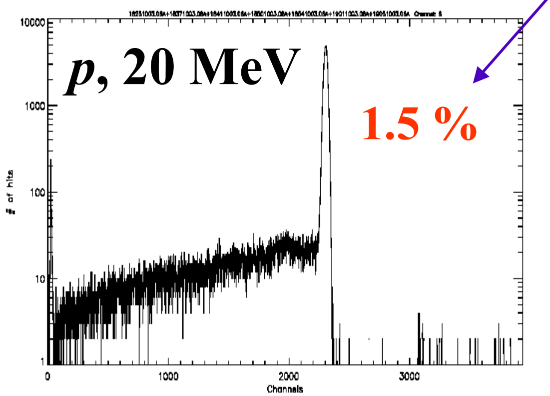
Rad. Hardness





Resolution





Afterglow

Material	AG (100 ms)
CsI:Tl	0,87…1,11%
CsI:Tl,NO$_2$	**0.42…0.57%**

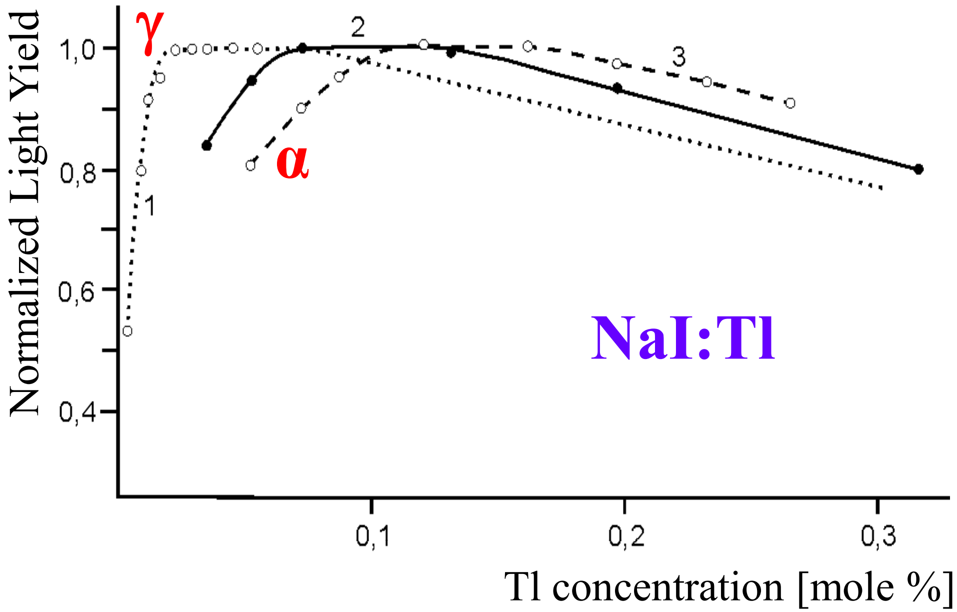
Prospect

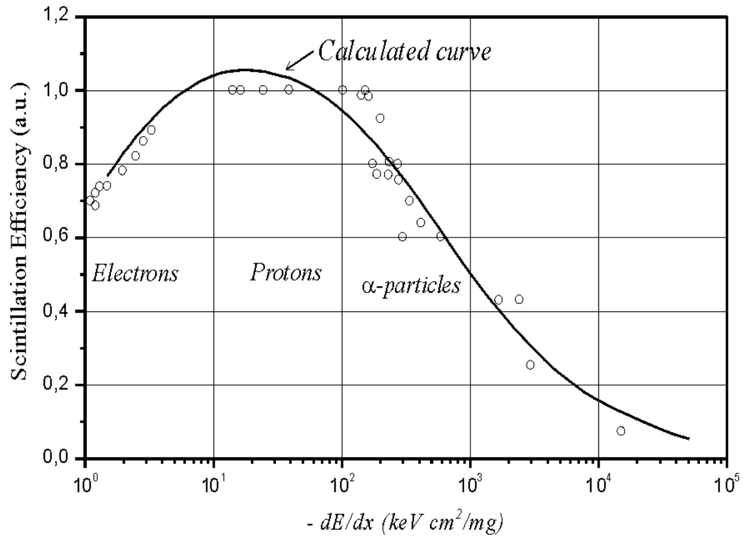
Limit of Tl concentration
0,5 %

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_{Tl} ~ 0.3 % are available (so called NaI:Tl,IO_3 crystals). CsI:Tl,IO_3 crystals with C_{Tl} ~ 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.

Concentration dependences of light yield





Density of *e-h* pair in electron track:

7.3/2.2 ≈ 3 {

$2.2\cdot10^{18}$ cм$^{-3}$ for 662 keV (1, γ)

$7.3\cdot10^{18}$ cm^{-3} for 5.9 keV (2)

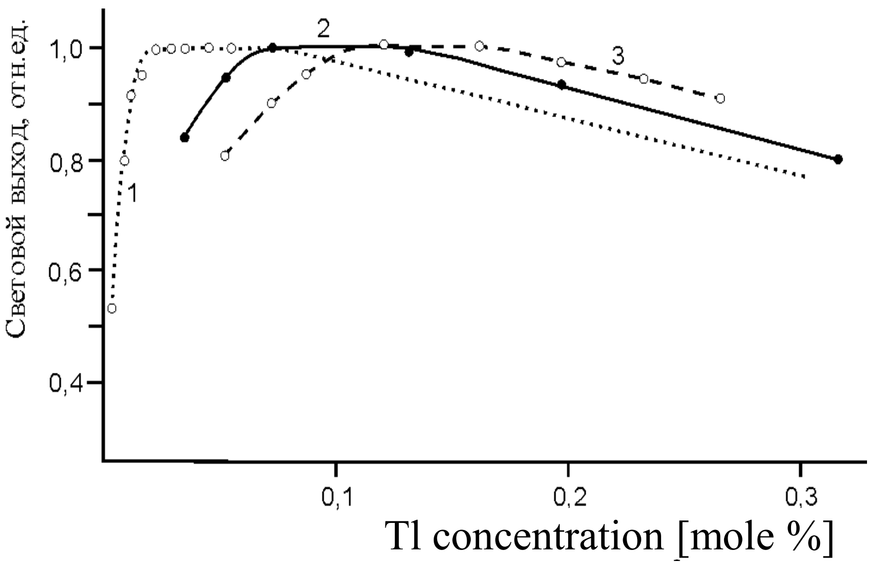
$1{,}3\cdot10^{19}$ cm^{-3} for **α** (5,15 MeV)

Volume density *dE/dx*^{3} is increased 3 times in L-deep

Nucl. Instr. Meth., vol. A486 (2002) 474

Conclusions

- Dep. L *vs* C_{Tl}
- Decay time
- Resolution



Cascade only (Auger electrons and X-ray) do not increase *dE/dx*

Cascade + Photoelectron of ~ 1 keV energy increase *dE/dx*