On the absorber thickness of microcalorimetric detectors in experiments at nuclear storage rings

V. Andrianov[1,2], S. Kraft-Bermuth[2], P. Scholz[2]

[1] Lomonosov Moscow State University, Russia
[2] Justus-Liebig-University Gießen, Germany

1. Motivation

Precise measurements of energies for the Lyman-α transitions in hydrogen-like heavy ions provide a sensitive test of quantum electrodynamics (QED) in very strong Coulomb fields, not accessible otherwise. To increase the accuracy of such measurements, low temperature microcalorimeters for hard X-rays were successfully used since they combine excellent energy resolution with an acceptable detection efficiency.

These experiments were carried out at the Experimental Storage Ring (ESR) at GSI (Darmstadt) with $^{197}Au^{78+}$, $^{208}Pb^{81+}$ and $^{238}U^{91+}$ ions [1, 2]. X-ray Lyman lines were emitted while the ions moved with relativistic velocities. As a result, the energy of the Lyman-α lines was significantly shifted due to the Doppler effect. In addition, the finite size of the X-ray emitting region lead to variations in the angle of observation θ and caused an additional contribution to the Lyman line width, the so-called Doppler broadening.

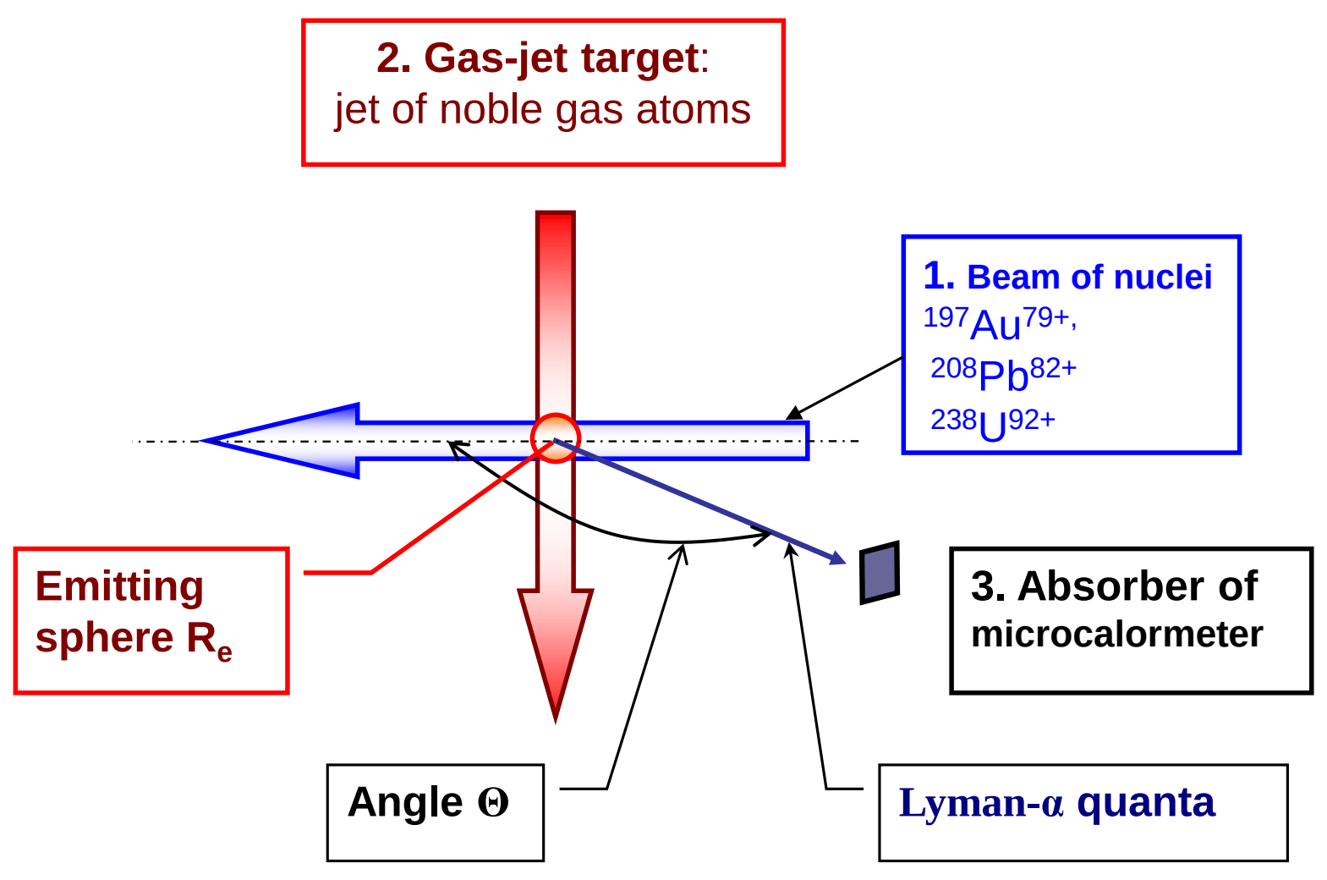
In this report, we introduce an optimization procedure for the selection of the absorber thickness of a calorimetric detector in the case of significant Doppler broadening. In particular, we discuss the mutual interference of the self line width w_s, the Doppler broadening w_D and the absorption efficiency, taking into account the possibility of the escape of secondary radiation.

[1] V. A. Andrianov et al., AIP Conference Proceedings **605** (2009) 409
[2] S. Kraft-Bermuth et al., J. Low Temp. Phys. **176** (2014) 1002

2. Experiments at GSI

2.1. The scheme of the experiment

The scheme of the experiment is shown in Fig. 1. A beam of bare nuclei (U, Pb or Au) was injected into the ESR, stored, cooled and decelerated to a velocity $\beta = v/c \approx 0.5$, with very small momentum spread of $\Delta\beta = 3 \times 10^{-6}$. Then the beam of nuclei crossed the gas target (2), which was an ultrasonic jet of noble gas atoms. When the nuclei interacted with the noble gas atoms, part of them captured one electron and promptly emitted Lyman X-rays. The Lyman X-rays were detected by the microcalorimeters (3) mounted under an angle of $\theta \approx 145^\circ$ relative to the ion beam.


2. Gas-jet target: jet of noble gas atoms

1. Beam of nuclei $^{197}Au^{79+}$, $^{208}Pb^{82+}$, $^{238}U^{92+}$

Emitting sphere R_e

3. Absorber of microcalormeter

Angle Θ

Lyman-α quanta

Fig. 1

2.2. Doppler shift of Lyman-α1 energies

The Lyman-α lines were Doppler-shifted according to the formula

$$E_{Lab}(Ly) = E_{Emi}(Ly)\frac{\sqrt{(1-\beta^2)}}{(1-\beta\cos(\theta_i))}$$

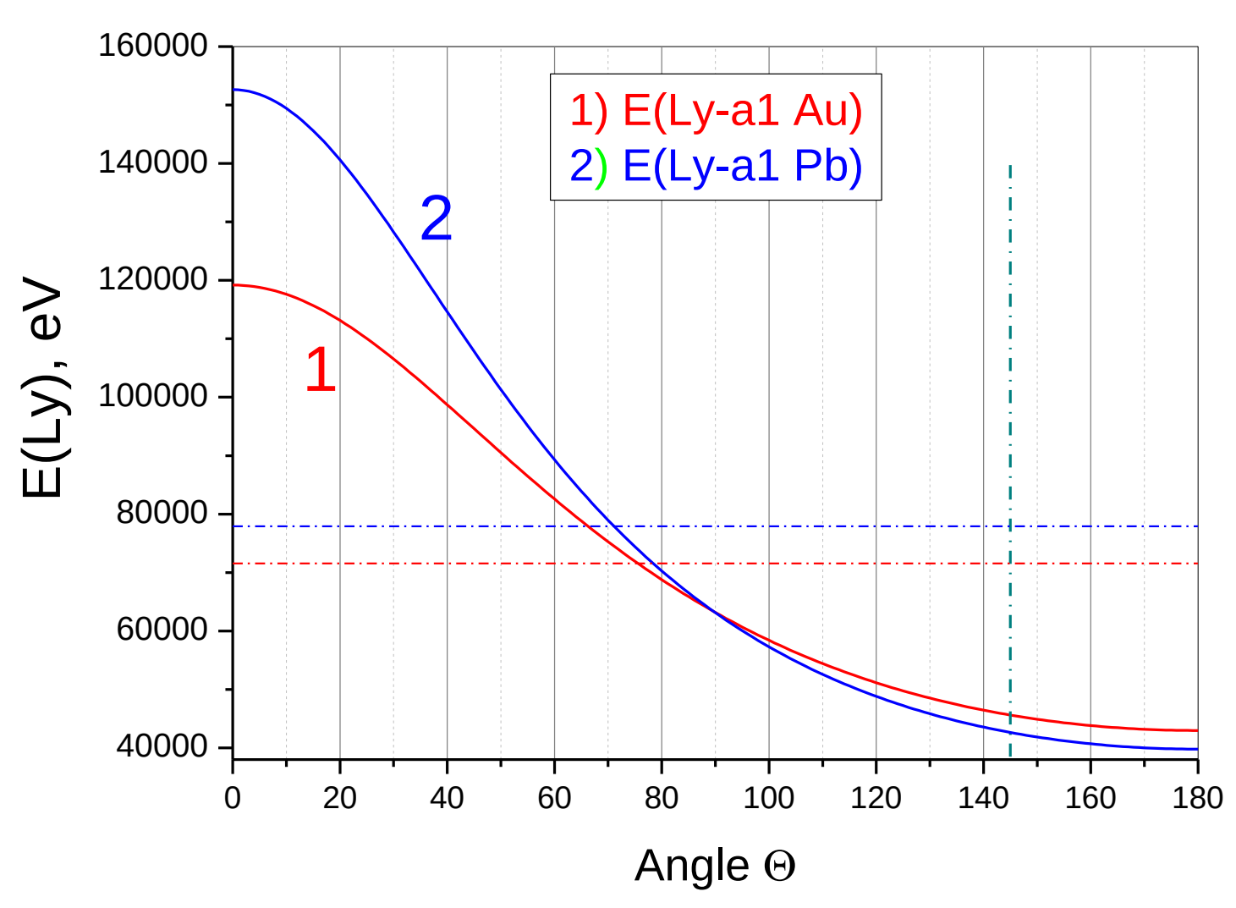


Fig. 2

2.3. Doppler broadening of the Lyman-α line

The Doppler broadening is calculated according to

$$w_D = 2.35\cdot\frac{dE_{Lab}}{d\Theta}\cdot\frac{d\Theta}{dx}\cdot R_s = 2.35\cdot D_e\cdot R_s \qquad (1)$$

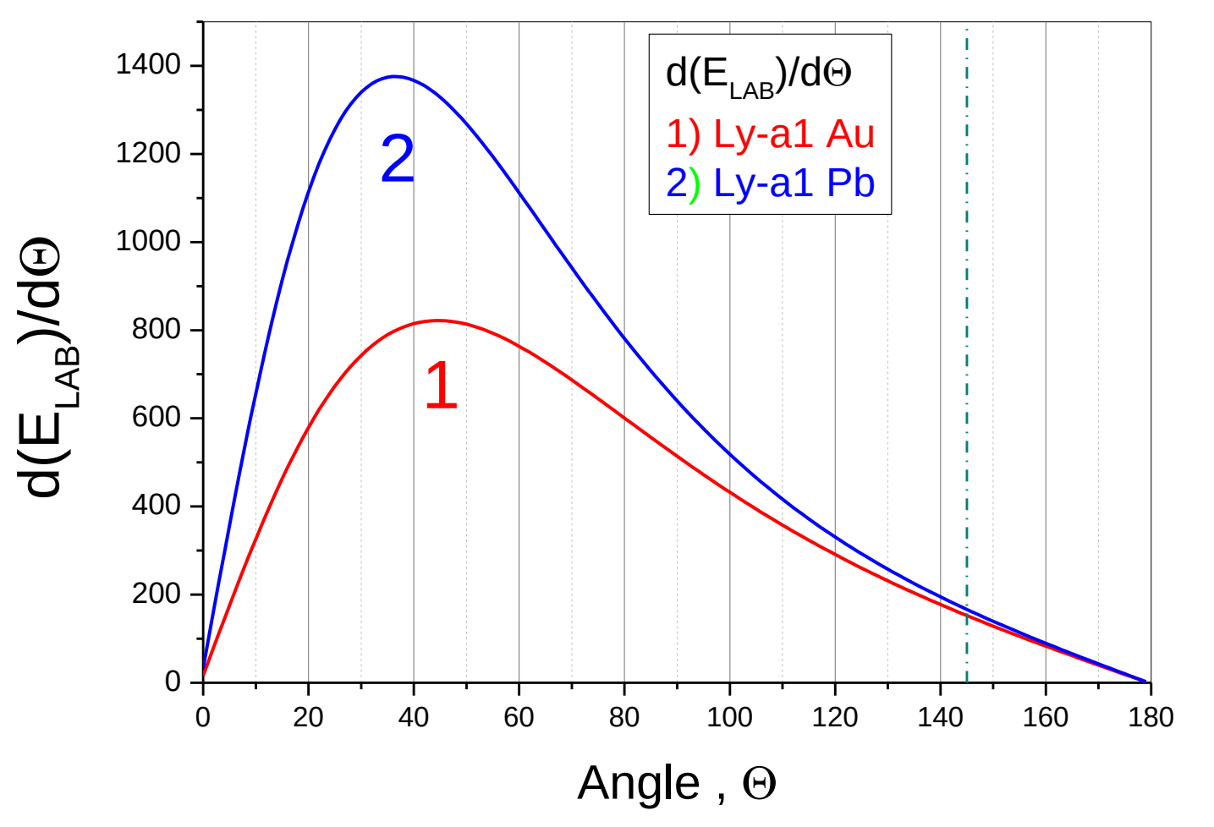


Fig. 3

2.5. Full width of the Lyman-α line

$$w_{Ly} = \sqrt{w_s^{\,2} + w_D^{\,2}} \qquad (2)$$

Here w_D is Doppler broadening of the detector line **(1),**
w_s is the self (or lab) width of the line.
Suppose that self line width w_s is determined
by the electronics noise σ_e:

$$\frac{w_s}{E} = \frac{2.35*\sigma_e}{A} \qquad w_s = w_{s0}\frac{d}{d_0} \qquad w_{Ly} = \sqrt{\left(w_{s0}\frac{d}{d_0}\right)^2 + \left(2.35\cdot D_e\cdot R_s\right)^2} \qquad (3)$$

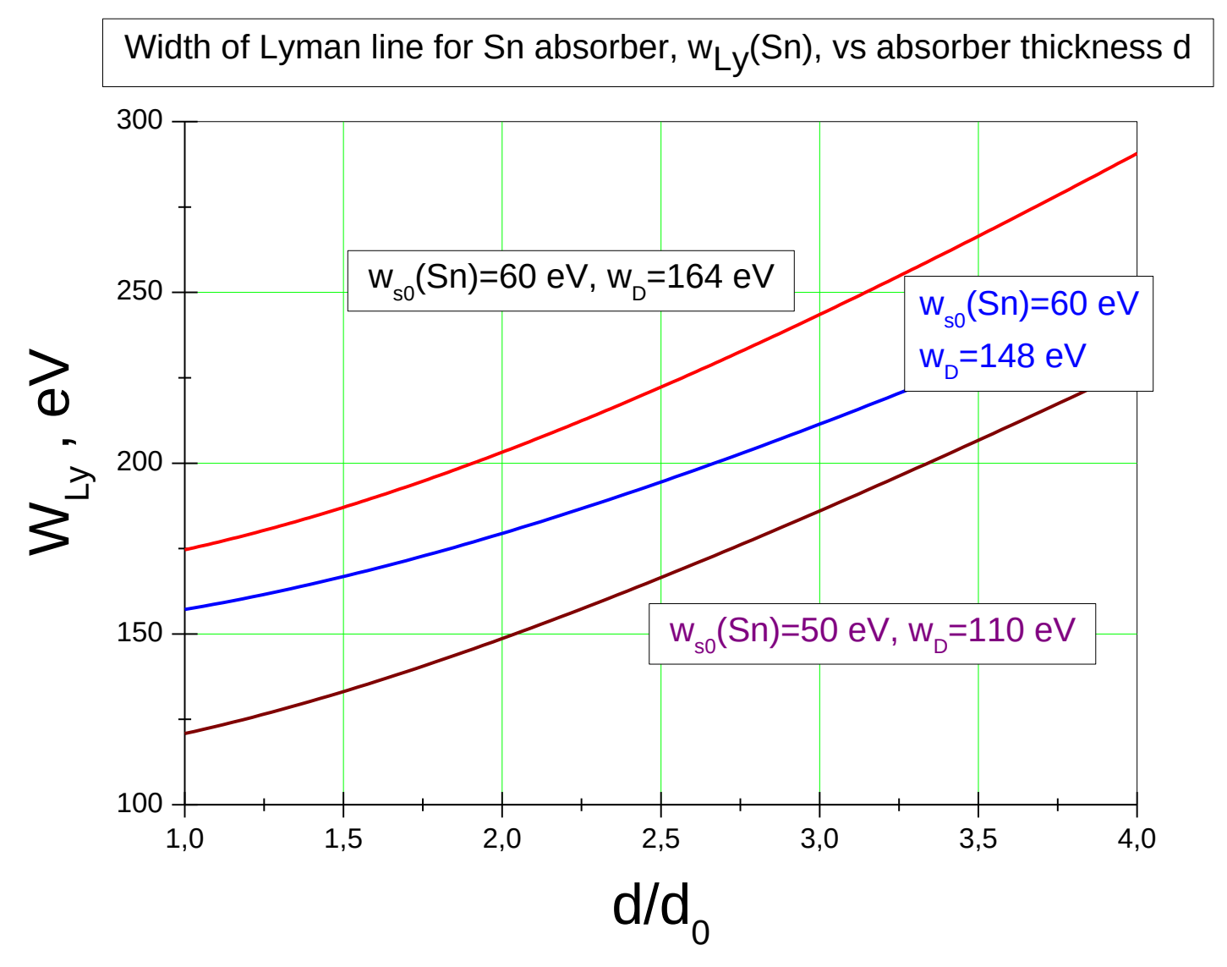
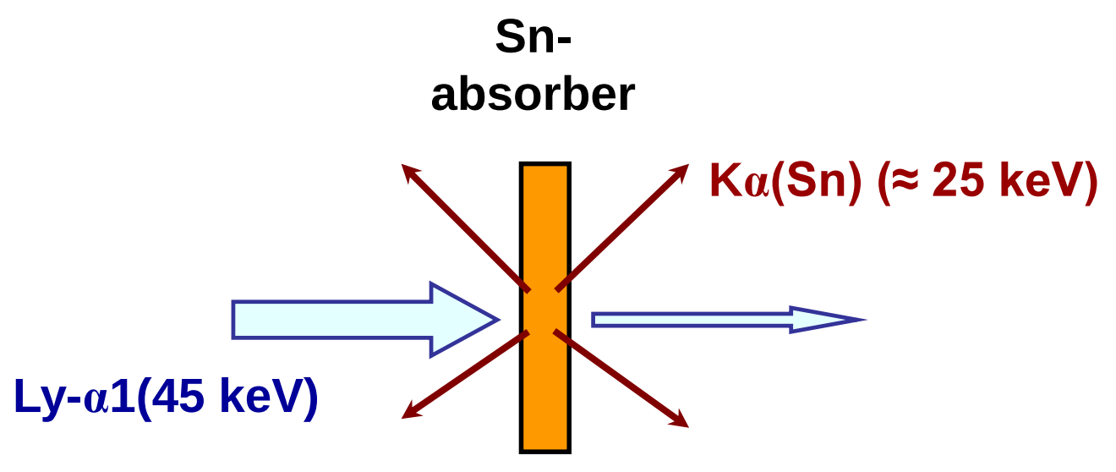


Fig. 4

3.3. Probability of the escape of the secondary X-rays



$$f(d) = 1 - P_{escape}$$

$$P_{escape} = \int_0^d dx \int_0^{\pi/2} d\theta \int_0^{2\pi} \left(\frac{\mu_x \sin\theta}{4\pi}\exp\left(-\frac{\mu_x * d}{d_0}\right)\right)\cdot \cdot\left(\exp\left(\frac{\mu_2\cdot x}{\cos\theta}\right) + \exp\left(\frac{\mu_2\cdot(d_0 - x)}{\cos\theta}\right)\right)d\varphi \qquad (7)$$

Here, μ_2 is the absorption coefficient for secondary X-rays.

Figure 5 shows the probability of absorption of photons with E = 45 keV, and the probability of the yield of secondary radiation (E≈25 keV), depending on the thickness of the Sn absorber.

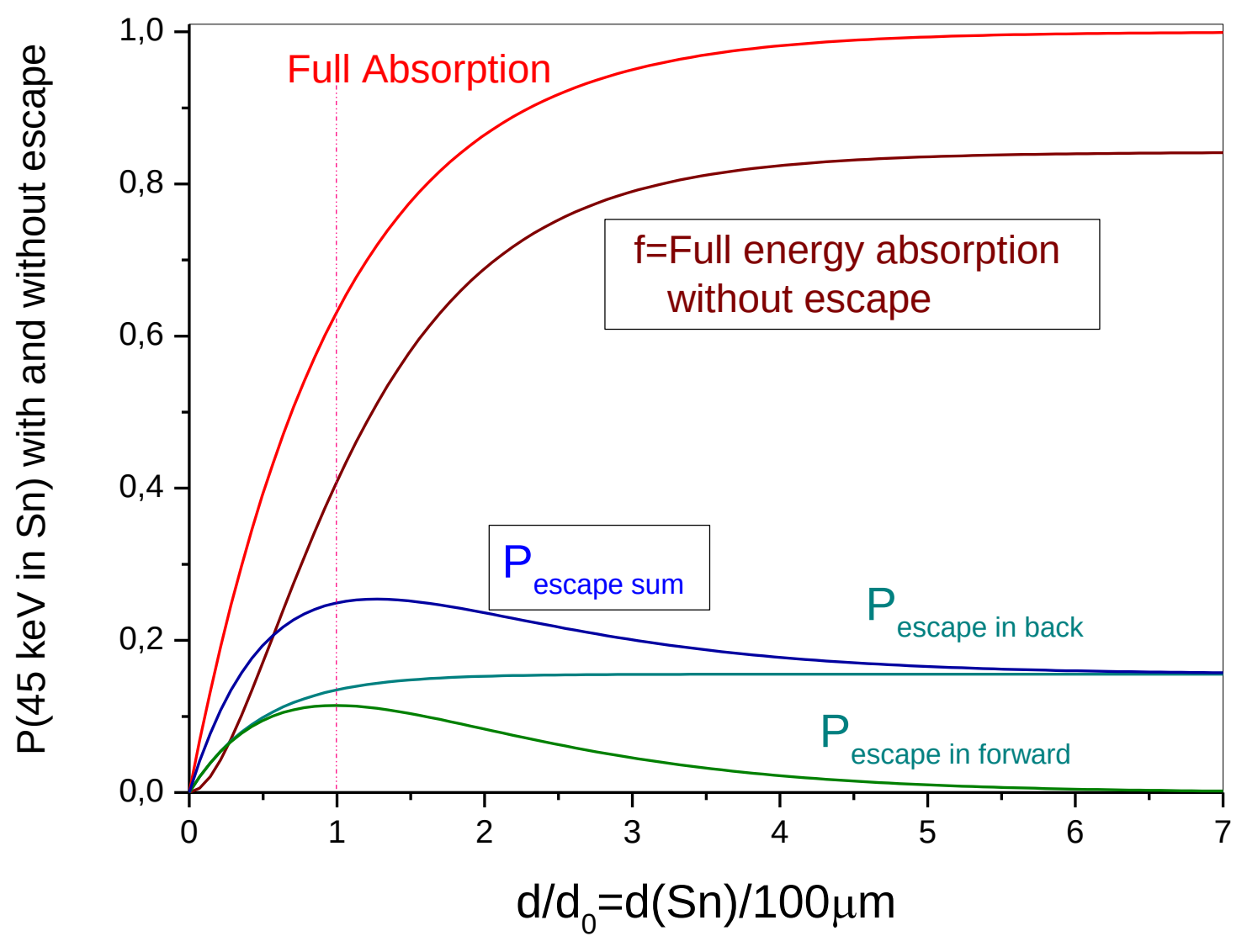


Fig. 5

3. Optimal thickness of absorber in calorimetric detectors

3.1. General

The accuracy of the peak position ΔE_{Lab} is eventually determined by the line width w_{Ly} and the number of the recorded photons N.

$$\Delta E_{Lab} = \frac{w_{Ly}}{2.35\sqrt{N}} \qquad (4)$$

$$N(d) = N_0\cdot f\cdot(1-\exp(-\mu_X d)) \qquad (5)$$

Here μ_x is X-ray absorption coefficient. The coefficient *f* gives the fraction of those absorbed photons which will release all their energy in the absorber. The factor *f* can be significantly less than unity in the case of the formation of the so-called escape peak.

$$\Delta E^*_{Lab} = \frac{\sqrt{\left(w_{s0}\frac{d}{d_0}\right)^2 + \left(2.35\cdot D_e\cdot R_s\right)^2}}{\sqrt{f(d)\cdot\left(1-\exp(-\mu_X d)\right)}} \qquad (6)$$

The optimum thickness of the absorber is determined by the minimum of the expression (6)

3.2. Absorbers for Microcalorimeters

We consider two types of the absorbers: absorbers from **Lead** and absorbers from **Tin**. Both materials were superconducting metals, which have low heat capacity at low temperatures.

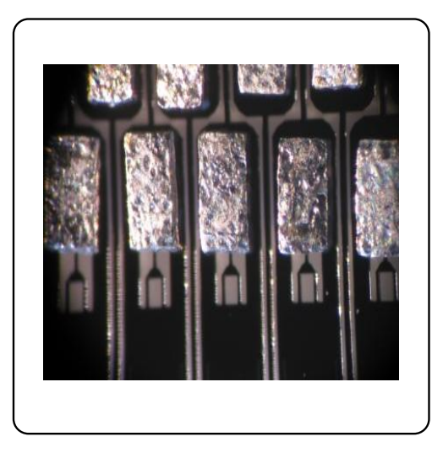


Table 1. Absorbers for microcalorimeters

Absorber	a*b, mm²	d_0,mm	K_{edge}, keV	$\mu_x d_0$(45 keV)	W_{s0}, eV	*f*
Sn	0.7*0.4	0.1	28.2	1	60	*f*(d)<1
Pb	0.7*0.4	0.05	88	0.61	90	*f*=1

Sn-absorber shows emission of secondary X-rays from the absorber and the formation of an **escape peak** in the spectrum. This means that

$f(Sn) = f(d) < 1.$

Pb atoms have K-edge = 88 keV> E_{Lab}(Ly). This means that no escape of secondary X-rays takes place.

$f(Pb) = 1.$

3.4. Calculation of the accuracy of the E_{Lab}(Ly) measurements

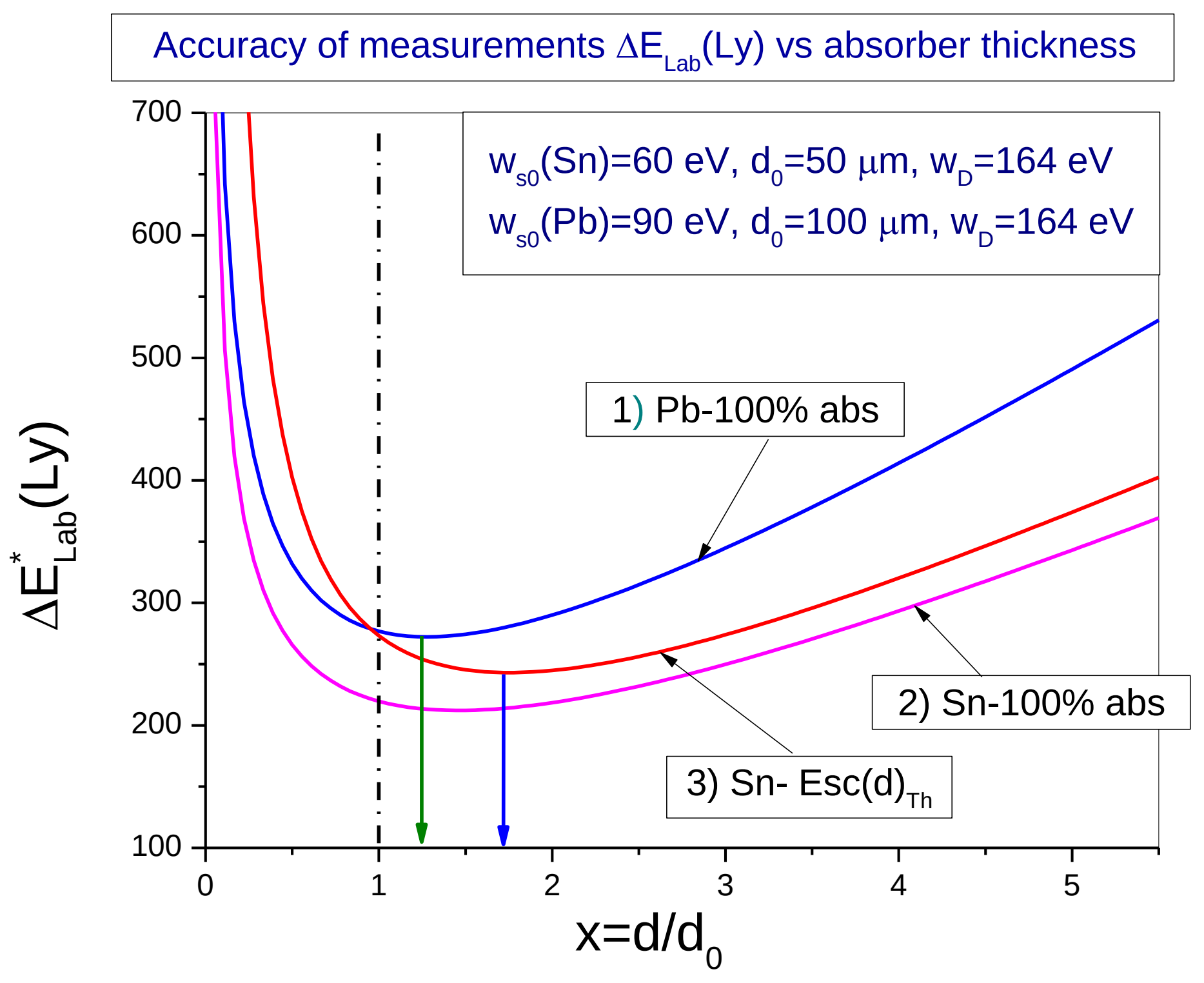


Fig. 6

4. Conclusion

1. We propose the optimization procedure for absorber thickness in the case of significant contribution of Doppler broadening of the line.
2. The material and thickness of the absorber must be determined taking into account the specific conditions of the experiment, in particular, taking into account self width of the detector line, the energy range, Doppler broadening and possibility of escape of secondary radiation.
3. At experimental conditions considered in the report, Sn-absorber is better than Pb-absorber. The optimal thickness for Sn is about 0.17 mm.
4. The thickness of Sn-absorber can be increased to 0.2 mm. This absorber has almost the same accuracy of the measurement and increases the count rates by 70%.