Measurement of Laser Fusion Targets Parameters by X-ray Spectral Methods.

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Introduction

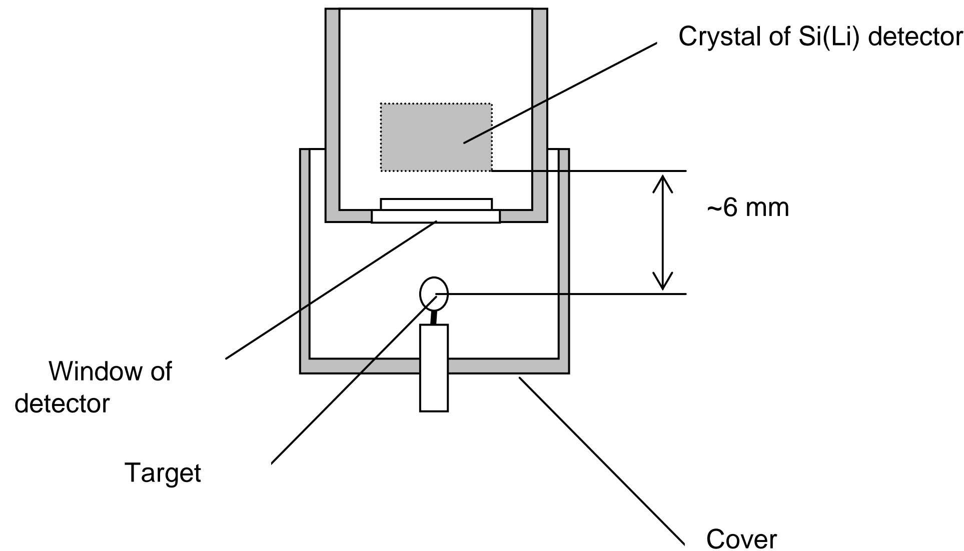
All X-ray spectral techniques of the analysis can be applied practically to a problem of characterization of spherical, cylindrical and flat targets.

For universal certification it is optimal to use the techniques of the analysis developed on the basis of fundamental parameters [1]. This way allows to define simultaneously element composition and thickness of a film [2,3], to develop the analysis of multilayered samples in view of inside- and interlayer matrix effects [4,5], to measure of composition and component quantity of a gas mix in spherical targets [6], and also composition of their shells. At its realization it is not required a plenty of standard samples.

The given report is evolution of works on use of x-ray techniques for characterization of targets which last results have been described earlier [7].

Measurement of parameters of the spherical targets filled with tritium

- For the targets containing with tritium the excitation of x-ray radiation is carried out by beta-electrons of tritium. Thus the spectrum of radiation consists of characteristic lines of elements and a continuous background.

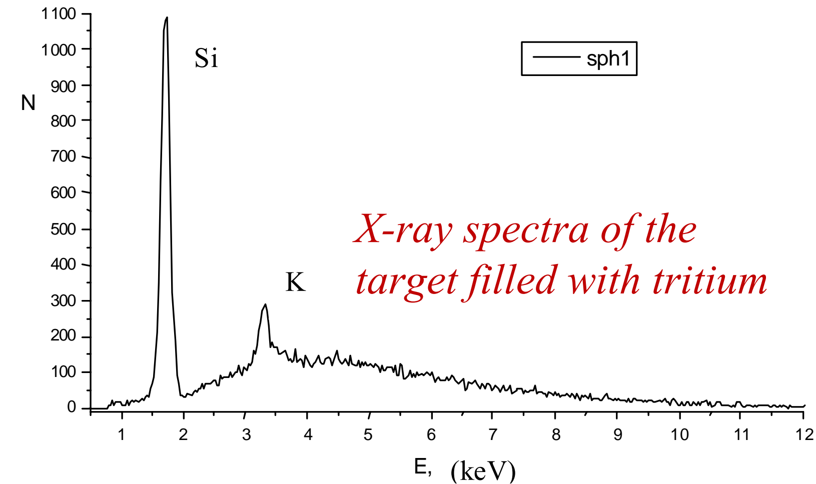


Geometry of parameters measurements by X-ray fluorescence method

Measurement of parameters of the spherical targets filled with tritium

Definition of tritium quantity.

Basic relation is the expression for amount of the analytical line quantum falling of microsphere wall on the detector in unit of time -



X-ray spectra of the target filled with tritium

$$\dot{N} = \frac{1}{4\pi}\int_0^{2\pi} d\Phi \int_0^X x \cdot dx \int_0^{2\pi} d\varphi \int_0^{\pi} \sin\vartheta \cdot d\vartheta \int_{r0}^{r0+d} w \cdot \frac{L - r\sin\vartheta\sin\varphi}{l^3} \cdot \exp(-\sum \mu_i l_i) \cdot r^2 dr$$

X is radius of the detector, *x,Φ* - polar coordinates of the detector plate, r_0 and *d* - internal radius and thickness of a microsphere wall, *r,θ,φ* - spherical coordinates for microsphere volume, *L* and *l* - distances from the microsphere center up to the center of the detector and between any points of microsphere and the detector, l_i, μ_i - length *of i-th* piece of a way and factor of absorption in gas, a microsphere wall, air and a material of the detector window.

$$w = \frac{A_T n_T}{4\pi} \cdot \gamma \cdot n \int_0^{2\pi} d\varphi \int_0^{\pi} \cos\vartheta \cdot d\vartheta \int_0^{r0} r^2 dr \int_{Ec}^{Em} f(E) \int_0^{\mathrm{Re}} \phi(E,x) \cdot \sigma(\varepsilon) \cdot dx$$

A_T and n_T are a constant of decay and density of tritium particles in microsphere, γ - efficiency of fluorescence, *n* - density of an element atoms, *f (E)* - function of distribution β-electrons on energy, φ(*E,x*) - the function considering elastic scattering of electron [8,9], σ(ε) - section of ionization from a corresponding electron shell (for example, K-shell) at collision of atom with β-electron having energy ε, E_C and E_m - boundary energy of ionization and the maximal energy of β -electrons, R_e - distance on which the electron energy decreases up to E_C.

Measurement of parameters of the spherical targets filled with tritium

Definition of tritium quantity

In table results of calculation of gaseous D-T (0.5:0.5) pressure for two microspheres on spectral data of K-lines of silicon and potassium with use of equations (1) and (2) are presented. Values of parameters – an energy distribution of β-electrons, path length and the factor of the account of elastic electron scattering, section of ionization and efficiency of fluorescence, and also spectral attenuation factors of x-ray radiation have been taken in [8-12]. Here the values of pressure obtained by method of an optical interferometry [13] are given.

Number of microsphere	P, (atm)		
	K- series Si	K- series K	Optical measurement
1	48	73	40
2	31	36	23

From the table it is visible, that there is a significant difference of the calculated value of pressure from the value obtained by an optical method. Therefore calculation on fundamental parameters can be used today only for an estimation of value. For more exact determination calibration of all measuring scheme as a whole is required.

Measurement of parameters of the spherical targets filled with tritium

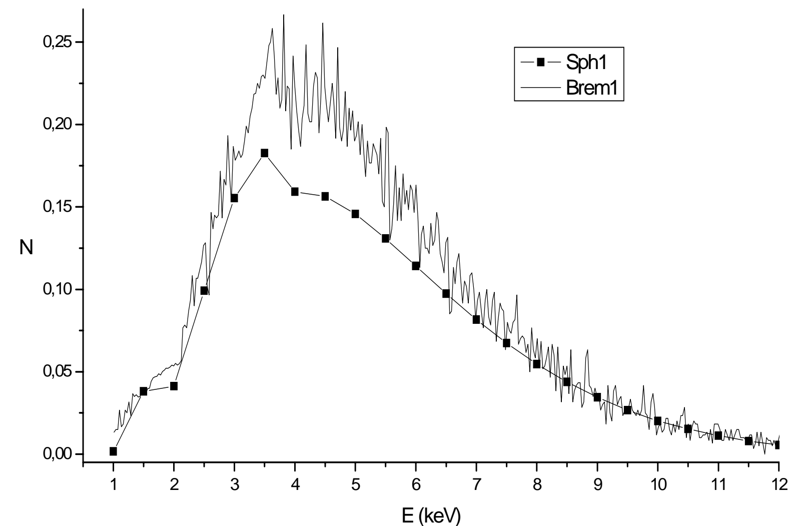
Definition of tritium quantity

For calculation of intensity of the continuous radiation generated in microsphere, the expression (1) was used. The value w was defined by expression

$$w = \frac{A_T n_T}{4\pi} \int_0^{2\pi} d\varphi \int_0^{\pi} \cos\vartheta \cdot d\vartheta \int_0^{r0} \frac{r^2 dr}{R^2} \int_{Ec}^{Em} f(E) \int_0^{\mathrm{Re}} \phi(E,x) \cdot \sum_i n_i \left(k \frac{d\sigma_i(k,\varepsilon)}{dk} \right) \cdot dx$$

*where **k** is energy of X-ray quantum, n_i and $d\sigma_i(k,\varepsilon)/dk$ - density of atoms and section of radiation of X-ray quantum with energy **k** at electron braking with energy **ε** [14] for an element of **i**-th kind of substance.*

Here the agreement of a calculated spectrum with registered spectrum is good enough.



Experimental and calculated spectra of continuous radiation of β-electrons in microsphere.

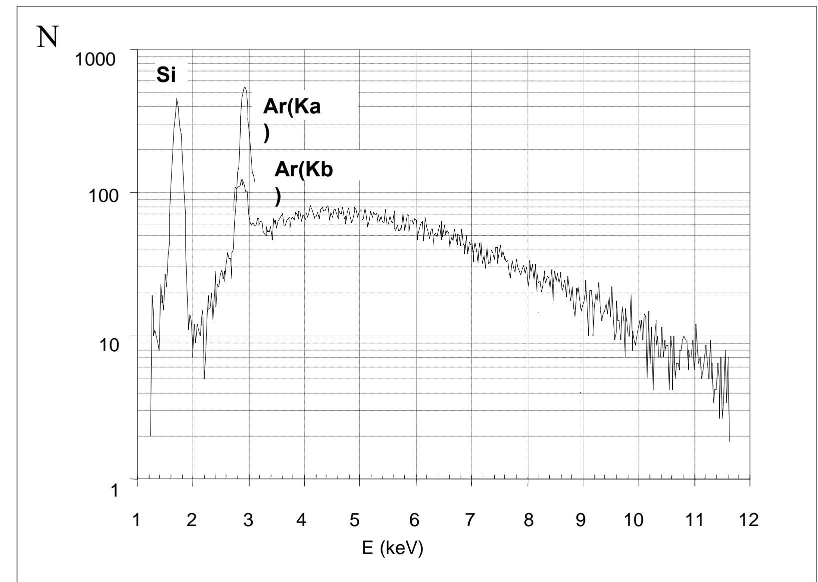
Measurement of parameters of the spherical targets filled with tritium

Definition of tracer gas amount (argon).

Definition of argon amount in the microspheres containing tritium is based on comparison of intensity of characteristic peaks of argon and intensity of continuous radiation in a power range of argon peak. The tritium amount does not influence almost result, but it is necessary to know composition of glass. For definition of argon pressure in microsphere the simple formula [6] is used

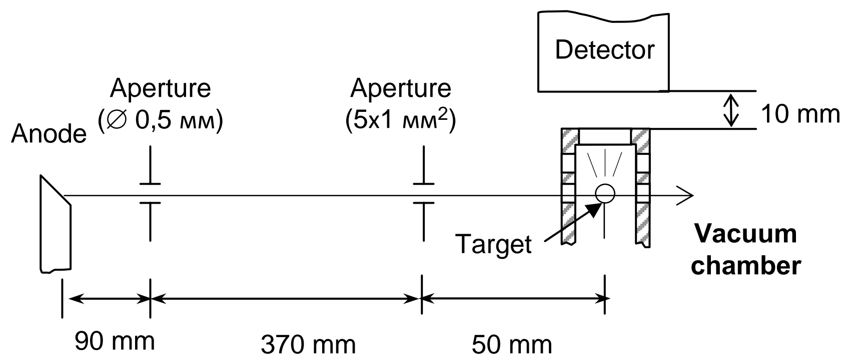
$$p = C \cdot \frac{Q}{r_0}$$

where ***Q*** *- the ratio of intensity of a argon line to intensity of continuous radiation in a spectral range of this line.*
Factor C is a constant in small limits of change $\boldsymbol{r_0}$ *and* ***d*** *and at small amount of argon. Its value can be defined in calibration experiment. For use of this expression in wider range* $\boldsymbol{r_0}$*,* ***d*** *and* ***p*** *it is necessary to remember, that C is function of these parameters and the formula turns to the nonlinear equation.*

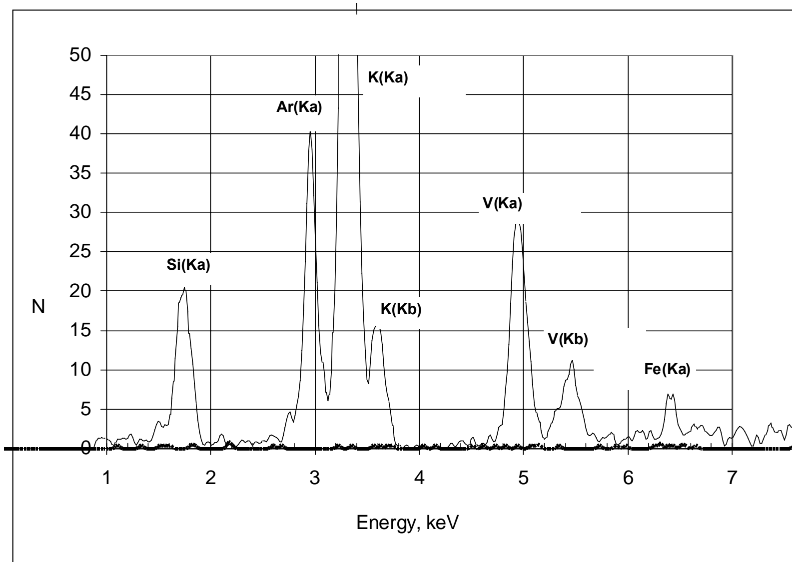


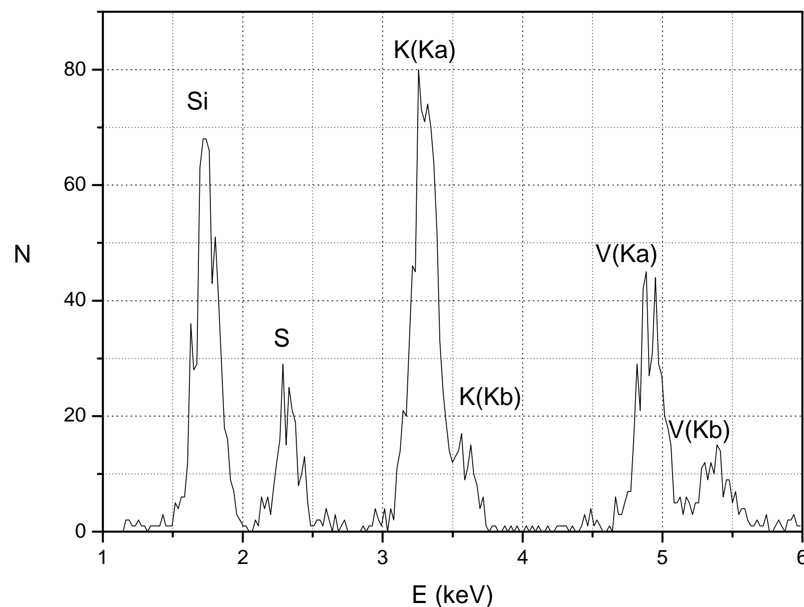
Spectrum of X-ray radiation of the target filled with tritium and argon

Measurement of parameters of spherical targets without tritium with excitation of a X-ray spectrum by an external source



The scheme of measurements of gas amount in microspheres with external excitation of fluorescence.





Spectra of X-ray radiation of the shells filled with argon up to 1 atm (on the left) and sulfur hexafluoride (on the right) (SF6) (a thin line) and a background (a thick line).

Measurement of parameters of spherical targets without tritium with excitation of a X-ray spectrum by an external source

Determination of gas amount in microsphere is made by comparison of intensity of characteristic radiation of the element which is a part of gas and a reference element of shell. The quantity of sulfur hexafluoride was defined by intensity of a K-line of sulfur. As a reference element silicon of glass shell is taken. Partial pressure of gas P in a target can be defined by expressions

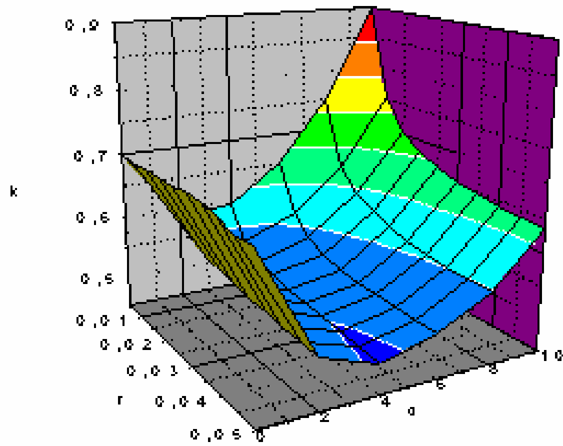
$$P = k(r_0, d, p) \cdot \frac{d}{r_0} \cdot \frac{S_g}{S_{Si}} \qquad k = [1 + \frac{d}{r_0} + \frac{1}{3}\left(\frac{d}{r_0}\right)^2] \cdot \frac{3RT\rho_{gl} C_{Si}}{M_{Si}} \cdot \frac{\gamma_{gl} A_{gl} T_{gl}}{\gamma_g A_g T_g} \cdot Q,$$

$$Q = \frac{V_g \cdot \int_0^{\pi} d\varphi \int_0^{\pi} \sin\vartheta \cdot d\vartheta \int_{r_0}^{r_0+d} r^2 dr \cdot (L - r\sin\vartheta \cdot \sin\varphi) \cdot A(r,\vartheta) \int_0^{2\pi} d\Phi \int_0^{X} \frac{xdx}{l^3} \cdot i \cdot B(r,\vartheta,\varphi; r',\varphi')}{V_{gl} \cdot \int_0^{\pi} d\varphi \int_0^{\pi} \sin\vartheta \cdot d\vartheta \int_0^{r_0} r^2 dr \cdot (L - r\sin\vartheta \cdot \sin\varphi) \cdot A(r,\vartheta) \int_0^{2\pi} d\Phi \int_0^{X} \frac{xdx}{l^3} \cdot j \cdot \exp\{-b_g l_g - b_{gl} l_{gl}\}}$$

where S_g and S_{Si} are the areas under corresponding to experimental peaks of an gas element and silicon, and d and r_0 - a wall thickness and radius of shell, accordingly. The factor k is or in calibrating experiment, or by calculation determined, R is a universal gas constant, T - temperature, ρ_{gl} - glass density, C_{Si} - mass concentration of silicon in glass, M_{Si} - nuclear weight of silicon. Factors A and B consider decreasing the exciting and fluorescent radiations, ***i*** *and* ***j*** *are intensities of fluorescent radiation in gas and glass.*

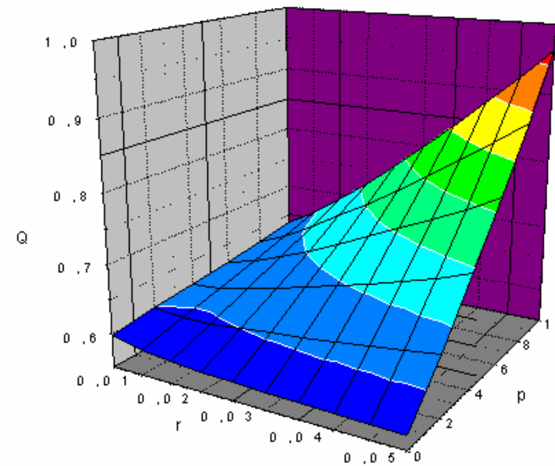
Measurement of parameters of spherical targets without tritium with excitation of a X-ray spectrum by an external source

Dependence of factor Q(r,d,p) upon radius and wall thickness of shell and gas pressure



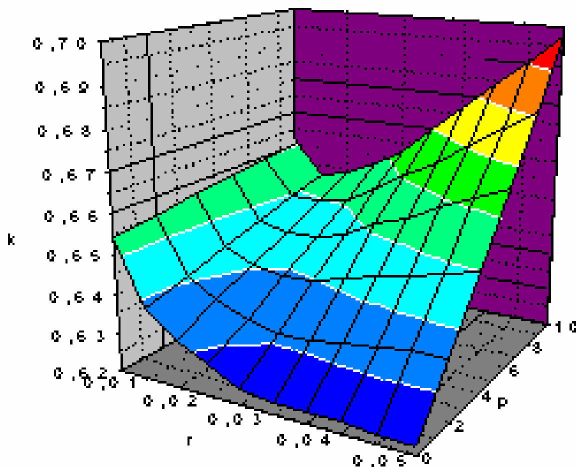
Argon

Q (*r*, *d*)
p = 0.5
atm

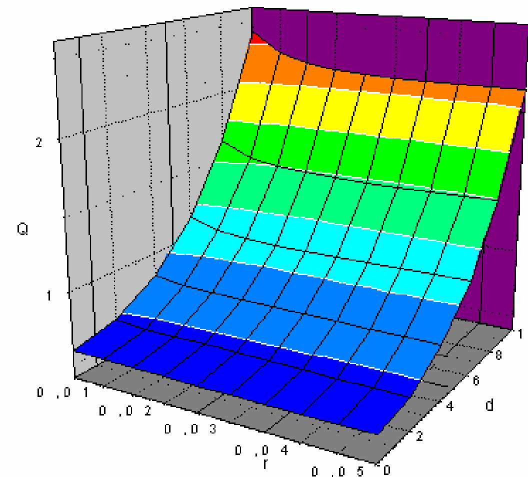


SF_6

Q (r, p)
d = 0.5
micron



Q (*r*, *p*)
d = 0.5
micron



Q (r, d)
p = 0.5 atm

Measurement of parameters of spherical targets without tritium with excitation of a X-ray spectrum by an external source

Comparison of calculated and experimental value of factor k (r,d,p)

Gas	Parameters of shell			Experiment				Calculation				δ (%)
	r_0 (micron)	d	p (atm)	S_g (pulse number)	S_{Si}	Q	k (atm)	S_g (pulse number)	S_{Si}	Q	k (atm)	
SF_6	192.5	1.5	1	409	1505	0.27	470	0.57	0.35	0.61	460	2.6
Ar	189	1.2	0.9	273	379	0.72	220	0.98	0.38	0.39	197	10

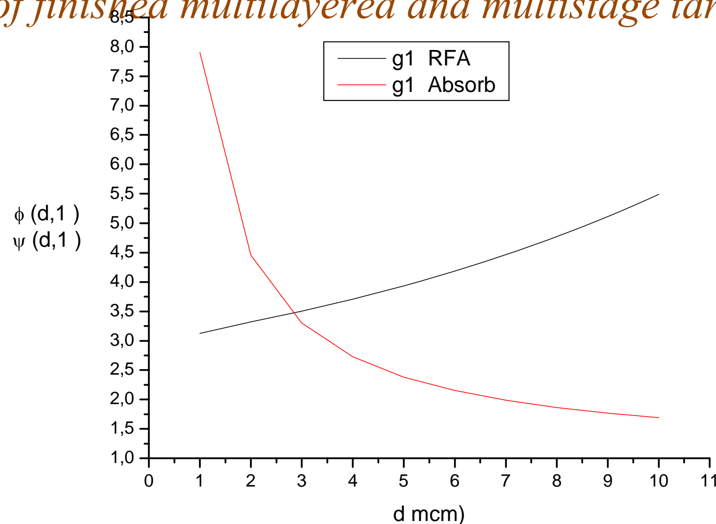
The difference between calculated and experimental value of factor k (r, d, p) does not exceed 10 %.

Change of a voltage on the vanadic anode of X-ray tube from 20 кV up to 30 кV at an average voltage 25 кV leads to a mistake of measurements only on ±1 %. Thus for SF_6 it is approximately less on order of magnitude. Change of length of an air interval between a X-ray tube and a measured shell from 45 cm up to 55 cm at average length of 50 cm leads to a mistake ± (2-2.5) % for argon and ±0.5 % for SF_6. This mistake is connected mainly only with change of a spectrum of exciting radiation.

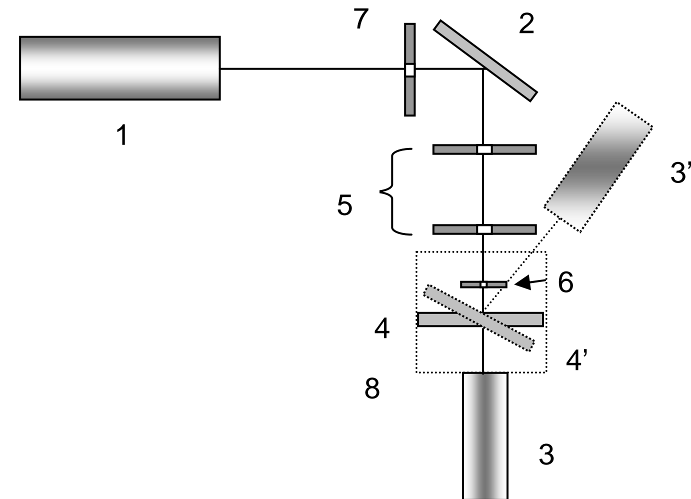
Measurement of composition and optical thickness of flat and profile film samples

The fullest and adequate description of properties of multilayered film samples the combination of X-ray absorptive and fluorescent (RFA) techniques of the analysis can give.

They allow defining composition and optical thickness of layers of a film. The X-ray absorptive method has the minimal mistake of measurement at greater thickness of film samples while the X-ray fluorescent method gives the minimal mistake at small thickness. Besides the fluorescent method allows to do the element analysis in multilayered film samples. Use of a probing beam of small diameter allows to carry out scanning on the area of the sample and to develop not destroying control of finished multilayered and multistage targets.



Dependence of a relative mistake of measurement of film thickness by fluorescent and absorptive methods



Scheme of measurement of film parameter

1 - X-ray tube, 2 - secondary target, 3 – detectors, 4 – sample, 5 – collimator, 6,7 – hole, 8 – evacuated chamber

Measurement of composition and optical thickness of flat and profile film samples

Fluorescent analysis

*At definition of film thickness by a fluorescent method it is used comparison of intensity of an analytical line of measured film and the massive sample. The equation for determination of film thickness **m**:*

$$\frac{I_m^i}{I_\infty^i} = \frac{\sum_r \frac{I(E_r)\tau_i(E_r)\{1-\exp[-K_i(E_r)m]\}}{K_i(E_r)}}{\sum_r \frac{I(E_r)\tau_i(E_r)}{K_i(E_r)}}$$

I_m^i *and* I_∞^i *is intensity of fluorescence of i-th element of the measured film and massive sample; I* (E_r) *- intensity of quantum with energy* E_r *of characteristic radiation of a secondary target; r - index of summation on all lines of fluorescence of a target material;* $\tau_i(E_r)$ *- section of a photo effect for quantum with energy* E_r *on atoms i-th element; m - surface density of the sample; m = r·d; r - density of the sample; d - thickness of the sample;* $K_i(E_r)$ *- the factor considering absorption in a film for quantum of exciting radiation and fluorescence of chemical elements of a film, and also geometry of measurements:*

$$K_i(E_r) = \frac{\mu(E_r)}{\sin\varphi} + \frac{\mu(E_i)}{\sin\psi} \quad ;$$

μ (E) is mass factor of absorption in the sample for quantum with energy E; φ, ψ - angles of sliding of exciting and registered quantum.

Measurement of composition and optical thickness of flat and profile film samples

X-ray absorptive analysis

At known element composition a film thickness is determined by means of expressions:

- monolayer film sample

$$m = -\frac{\sin\varphi \ln(\frac{I_j}{I_j^0})}{\mu(E_j)} \qquad ,$$

- two-layer film sample

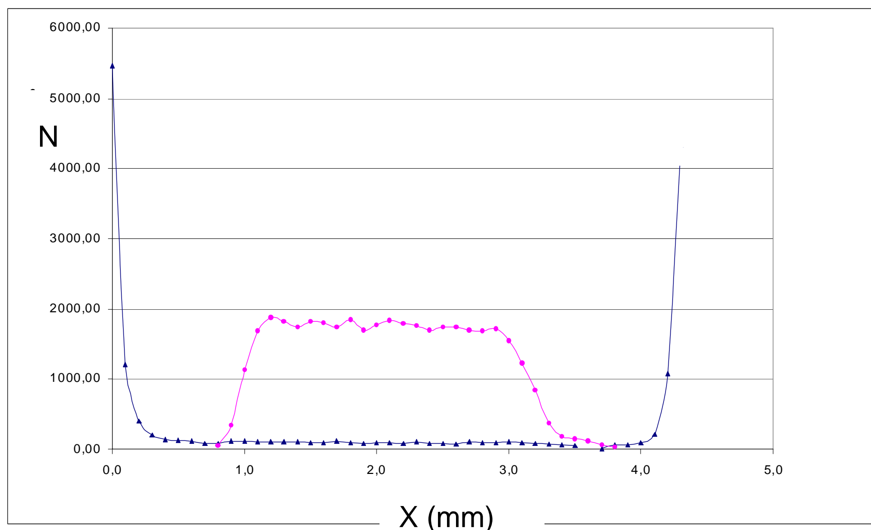
$$\mu_i(E_1)\cdot m_i + \mu_j(E_1)\cdot m_j = -\ln\left\{\frac{I(E_1)}{I_0(E_1)}\right\}$$

$$\mu_i(E_2)\cdot m_i + \mu_j(E_2)\cdot m_j = -\ln\left\{\frac{I(E_2)}{I_0(E_2)}\right\}$$

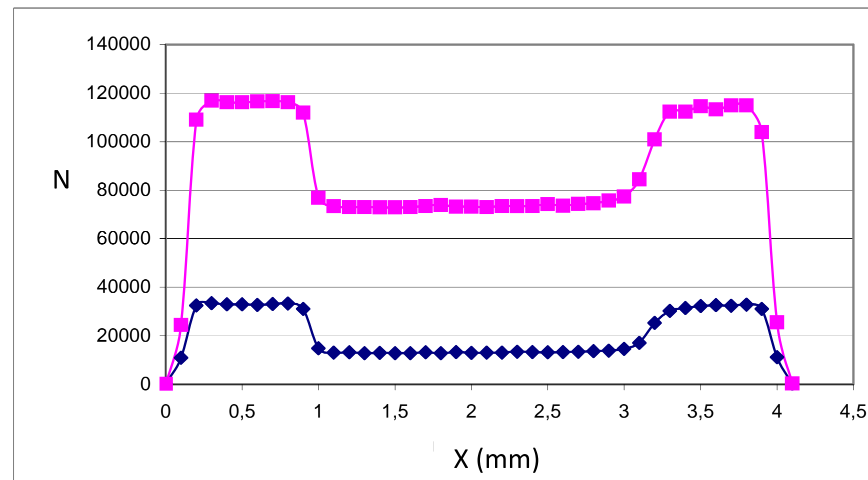
$I\,(E_1)$ and $I_0\,(E_1)$ are intensities of quantum with energy E_1 past by sample and in absence of the sample, accordingly; $m_i\,(E_1)$ and $m_j\,(E_1)$, loss factors of quantum with energy E_1 in films consisting from i-th and j-th elements, accordingly; m_i and m_j - thickness of a film from i-th and from j-th element.

Measurement of composition and optical thickness of flat and profile film samples

Scanning of samples. Diameter of a beam is 0.2 mm, step of scanning is 0.1 mm.

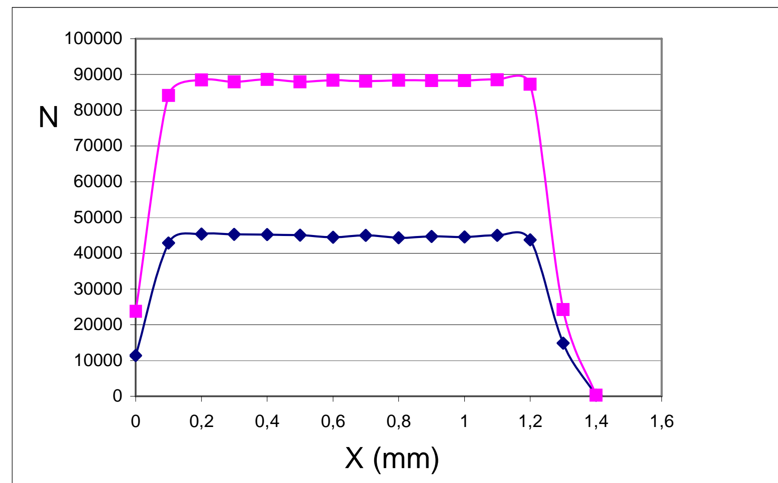


Intensity of fluorescence of a lead film strip (the top curve) and copper mandrel (the bottom curve) in various points of scanning (excitation from a lead film).



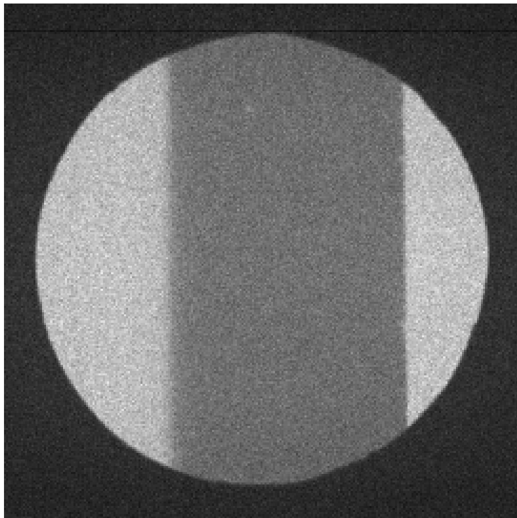
Intensity of quantum of characteristic radiation of a secondary target past the Pb strip on Al sample depending on scanning coordinate. The bottom curve - a target from nickel ($E_{K\alpha}$=7.472 кэВ), the top curve - a target from zirconium ($E_{K\alpha}$=15.746 кэВ)

Intensity of quantum of characteristic radiation of a secondary target past the Cu-Al sample depending on scanning coordinate. The bottom curve - a target from nickel ($E_{K\alpha}$=7.472 кэВ), the top curve - a target from germanium ($E_{K\alpha}$=9.876 кэВ)

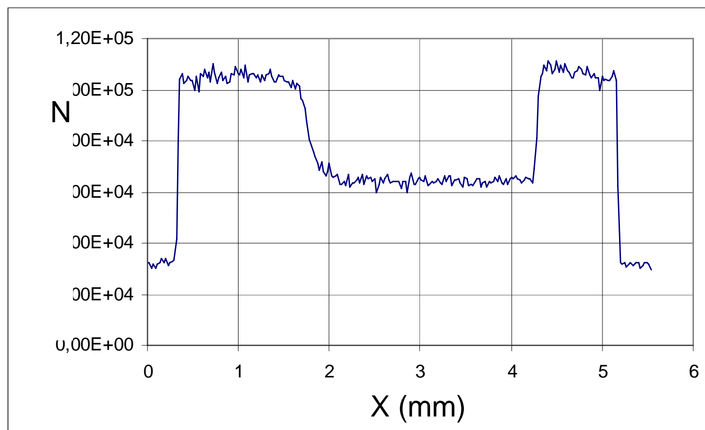


Measurement of composition and optical thickness of flat and profile film samples

Using of CCD-chamber



For reception of the image the mode of accumulation of 3000 consecutive frame with an exposition of each frame of 3 s was used. The probing beam formed on a secondary target was limited to an exit diaphragm.



The roentgenogram and distribution of intensity on diameter of the sample of the past X-ray radiation. X-raying of the sample is developed by radiation of a secondary target from Ni.

Conclusion

- *Measurement of composition of the targets containing tritium is possible by techmiques of the X-ray fluorescent analysis. Definition of amount of any element including tritium with use only fundamental parameters gives a greater mistake and qualitative value of the measured parameter. It is connected with difficulties of the adequate description of β-electron passage in the multicomponent multilayered environment. Use reference element or data about brake radiation allows improving accuracy of measurements considerably.*
- *Definition of composition of targets without tritium by means of the X-ray fluorescent analysis with use a reference element allows receiving accuracy up to 10 %. Application of monochromatic radiation for fluorescence excitation (a secondary target) gives reduction of a measurement mistake in 2-5 times.*
- *Complex application of techniques of X-ray fluorescent and absorptive analysis allows to define element composition and thickness both single-layered and multilayered films applied to microtargets manufacturing. By a choice of optimum energy of the quantum raying the sample or exciting fluorescence it is possible to achieve the beautiful accuracy of optical thickness measurement for film samples in a wide range. The method of the fluorescent analysis gives greater sensitivity and high accuracy for small thickness, and the absorptive method has high accuracy at average and greater thickness. Their joint use allows to measure optical thickness of films in a range of* $6 \cdot 10^{-7}$*-0.1 g/cm*^{2} *(*$6 \cdot 10^{-4}$*-100 microns) with accuracy of 1-2 %. Use of a probing exciting X-ray beam of small diameter or a beam with the slot-hole form allows developing scanning measurements on the sample area. Application of the X-ray CCD-chamber allows defining position and thickness of layers of different elements on a surface and depth of multilayered samples.*

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