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THE K-SHELL IONIZATION OF HEAVY ELEMENTS INDUCED BY LOW ENERGY PROTONS

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1986

1. INTRODUCTION

This paper is an extension of our experimental studies of the K -shell ionization of high-Z elements induced by heavy, charged particles. In these investigations, we apply the method proposed by Celler et al.[1]. Originally this method assumed measuring cross sections σ_{KI} for the K -shell ionization relative to the well-known cross sections σ_C for the Coulomb excitation of deformed double-even target nuclei by protons. Such measurements for the $_{64}Gd$, $_{74}W$, $_{90}Th$ and $_{92}U$ targets were described by Celler et al.[1], Hornshøj et al.[2] and Gocłowski et al.[3]. In the study by Pfuetzner et al.[4] this method was extended to the odd-A nuclides: $^{165}_{65}Ho$, which exhibits nuclear deformation, and $^{197}_{79}Au$ with the nucleus of a rather spherical shape.

The present work describes the experimental cross section data for the proton induced K -shell ionization of neodymium, samarium, terbium, thulium and tantalum for energy range of 2.6 MeV to 3.8 MeV. The present experiments are the continuation of our previous measurements performed in Warsaw with lower proton energies ((0.8-2.6 MeV) ref.[5]).

The accurate knowledge of the ionization cross section data induced by protons for wider energy range offers an experimental basis for the understanding of the ion-atom collision mechanism and the inner shell ionization process. On the other hand the accurate cross section data are very important for quantitative analysis of elements in various kinds of samples (PIXE method[6]).

2. EXPERIMENTAL METHOD

The proton beam was produced by the EG-5 Van de Graaff accelerator at the Laboratory of Neutron Physics of the Joint Institute for Nuclear Research in Dubna. The beam was collimated to 4 mm in diameter before entering the aluminium target chamber. The target chamber was electrically insulated what permitted the measurement of the proton beam hitting the thick target backings in such a way that chamber behaved as a Faraday-cup. The investigated targets were placed perpendicularly with respect to the incident beam. The target thicknesses were 2.3, 1.8, 1.9, 2.4 and 2.5 mg/cm^2 for Nd_2O_3, Sm_2O_3, Tb_2O_3 ,

Tm_2O_3 and Ta respectively. The Nd, Sm, Tb and Tm targets used in these measurements consisted of oxides of natural elements which were deposited by sedimentation from suspension in isopropyl alcohol on a thick graphite backing. The Ta target was in a form of selfsupporting foil.

The electromagnetic radiation passing from the target through a 0.1 mm Cu absorbent (to cutt of L_x -rays) and a 25 μm Mylar window, was recorded by a 0.25 cc HPGe detector with a FWHM resolution of 350 eV and 450 eV at 5.9 keV and 80 keV, respectively. The HPGe detector was positioned outside the target chamber at a distance of about 8 cm from the target and to minimize the influence of the γ-ray angular distribution it was placed at an angle of 125° with respect to the incident proton beam direction. The HPGe detector was calibrated for energy and efficiency by placing γ-sources of ^{133}Ba, ^{152}Eu and ^{169}Yb in the target position. These sources simulated the actual geometry of X-γ radiation emission from the studied targets. In our method it was only necessary to calibrate the relative detector efficiency. Thus our experimental uncertainties were free from the contribution of errors in γ-sources emission rates certification. Figure 1 presents the relative efficiency curve of the used HPGe detector.

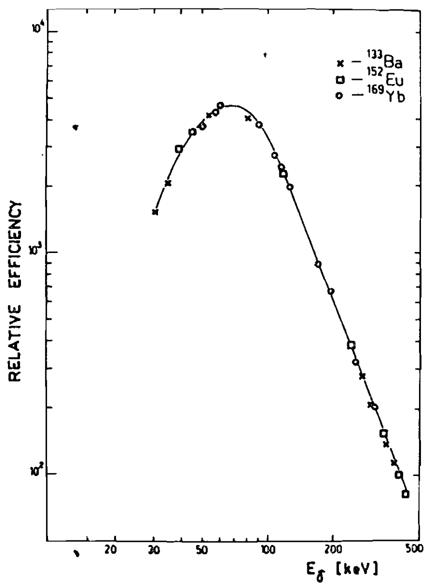


Fig.1. HPGe detector relative efficiency curve.

A silicon surface barrier detector Si(SB), located at an angle of 150° with respect to the proton beam and at a distance of about 15 cm from the target was used to detect the protons that were elastically backscattered from the target nuclei. The spectra of the backscattered protons were used to determine the thickness of the targets and the effective energy of the protons. The effective energy we defined as $E_{eff} = E_p - \frac{1}{2}\Delta E_p$, where E_p was the proton incident beam energy and ΔE_p was the total energy loss in the target.

Proton beam current of the order of 150-200 nA was applied. The total charge collected during irradiation ranged from 0.5 mC to 2.6 mC depending on proton energy and target. The incoming charges were integrated by a digital current integrator.

Because of the relative character of our experimental method [1] the errors arising from the target heterogeneity, beam instability, etc., are negligibly small.

The backscattered protons and X-γ ray energy spectra were recorded simulatenously in the multichannel analysers system. The photon spectra induced by 3 MeV protons on Nd, Sm, Tb, Tm and Ta targets are shown in Fig.2.

3. RESULTS

The K -shell ionization cross sections σ_{KI} were measured for incident proton energies ranging from 2.6 to 3.8 MeV in 0.2 MeV steps. The cross sections were calculated from the formula [1]:

$$\sigma_{KI} = \frac{I_{Kx}}{I_\gamma (1 + \alpha_T)\, \omega_K}\, p\, \sigma_c ,$$

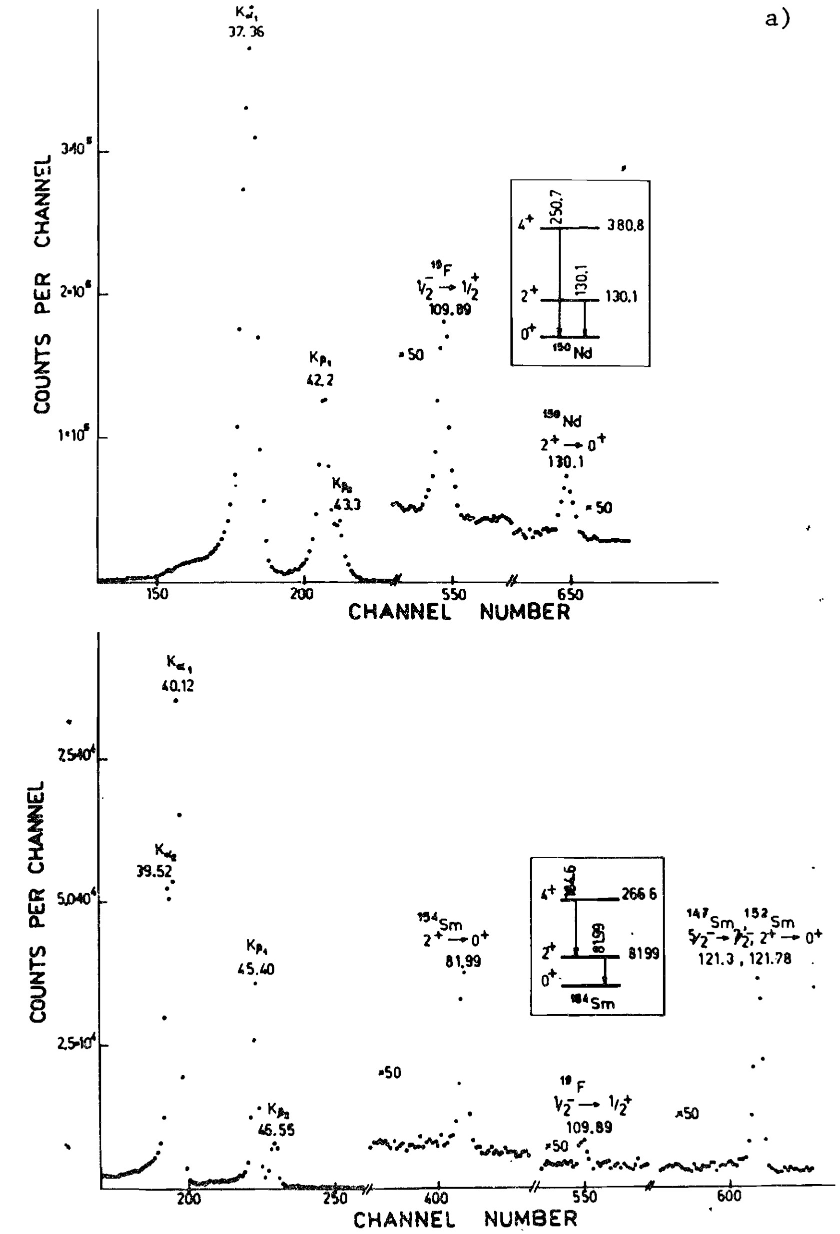
where I_{KI} is the total intensity of all K_x -ray lines from the ionization of target atoms corrected for the detector efficiency and for the contribution from K conversion of all gamma transitions in all isotopes of the investigated element ($\sum_\gamma N_\gamma \alpha_K$), I_γ is the intensity of the γ-transition from the Coulomb excited level in the target nuclei corrected for the detector efficiency and angular distribution, α_T is the total internal conversion coefficient for this γ-transition, ω_K is the target element K -shell fluorescence yield and p is the percentage atomic abundance of the considered isotope in the natural target. Also self-absorption in the target was accounted for both X and γ radiation though its influence was less than 1%.

The Coulomb excitation cross section σ_c can be calculated with the application of lowest order perturbation formalism given by Adler et al. [7]

$$\sigma_c^{E\lambda} = C_{E\lambda} E_{MeV}^{\lambda-2} (E_{MeV} - \Delta E'_{MeV})^{\lambda-1}\, B(E\lambda) f_{E\lambda}(\eta_i \xi),$$

where: $C_{E\lambda} = 4.819(1 + A_1/A_2)^{-2} A_1/Z_2^2$ barn (for $\lambda = 2$), A_1, A_2, Z_1, Z_2 are the mass and atomic numbers of the projectile and target, respectively; $\Delta E' = (1 + A_1/A_2)\Delta E$, where ΔE is the excitation energy of a given level. The reduced transition probability $B(E\lambda)$ is measured in units of e^2b^2. The function $f_{E\lambda}(\eta_i \xi)$ is defined and tabulated in paper [7]. For E2 excitation the angular distribution of the γ-rays is given [7]

$$W(\theta) = 1 + a_2^{E2}(\eta_i\,\xi)\,A_2P_2(\cos\theta) + a_4^{E2}(\eta_i\,\xi)\,A_4P_4(\cos\theta).$$



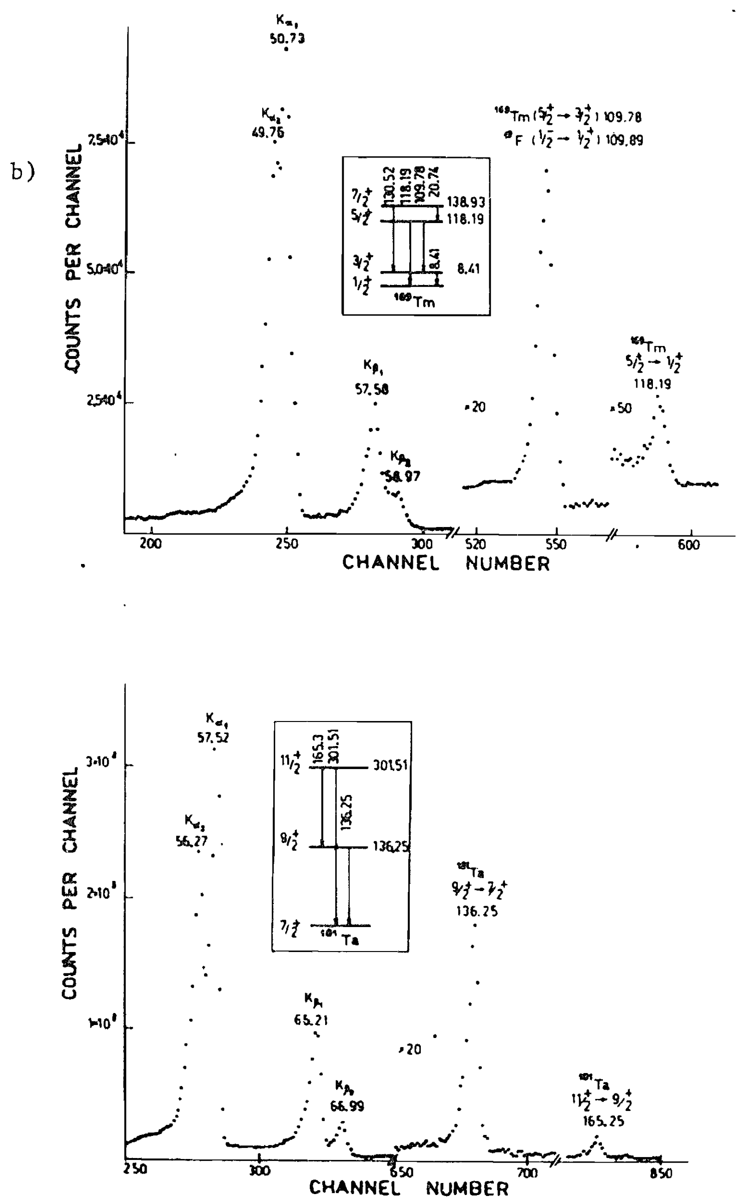


Fig. 2a, b. Proton spectra observed in the bombardment of natural Nd_2O_3, Sm_2O_3, Tm_2O_3 *and* Ta *targets with 3 MeV protons. Inserts: fragments of the* ^{150}Nd, ^{154}Sm, ^{169}Tm *and* ^{181}Ta *level scheme.*

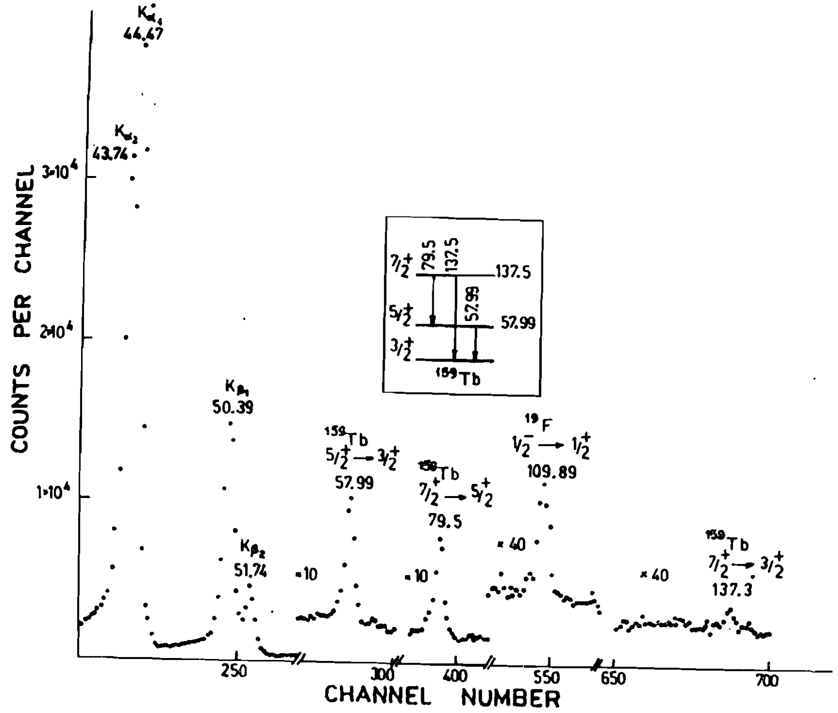


Fig.2c. Photon spectrum observed in bombardment of natural Tb_2O_3 *target with 3 MeV protons. Insert: fragment of the* ^{159}Tb *level scheme*

For $\theta = 125°$ the $P_2(\cos\theta) = 0$ and a small correction proportional to $P_4(\cos\theta)$ must be introduced to isotropic distribution of the γ-rays.

To calculate the σ_c values, one needs information about the nuclear transitions in those isotopes which are present in the target. For studied targets the experimental information about the reduced transition probabilities B(E2), total α_T and K-shell α_K internal conversion coefficients are presented in Table 1 together with respective references. The uncertainty of the Coulomb excitation cross section σ_c is determined mainly by the uncertainty of the reduced transition probability B(E2) and the projectile effective energy of the incident protons.

First order perturbation procedure is sufficiently accurate because the probability of double and higher order Coulomb excitation by low energy protons is negligibly small. In ^{169}Tm nuclei it is necessary to use the multiple Coulomb excitation formalism. This follows from the fact that an excited level with a very low excitation energy (8 keV) exists in the thulium nuc-

Table 1

Compilation of the literature data on the relevant target isotopes

isotope	level: excitation energy (keV)	level: spin parity	γ-transition energy keV	multipolarity	B(E2) (e^2b^2)	δ	α_T	α_K	ω_K	references
$^{150}_{60}$Nd	130.1	2+	130.1	E2	2.72 ± 0.04	-	0.865	0.552	0.92	[10]
	380.8	4+	250.7	E2	1.51 ± 0.11	-				
$^{154}_{62}$Sm	82.0	2+	82.0	E2	4.36 ± 0.05	-	4.93	1.97	0.928	[11]
	266.6	4+	184.6	E2	2.13 ± 0.32	-	0.276	0.193		
$^{159}_{65}$Tb	57.99	5/2+	57.99	M1 + E2	2.81 ± 0.06	0.122 ± 0.013	11.2	9.15	0.937	[12]
	137.5	7/2+	79.5	M1 + E2	1.66 ± 0.06	0.126 ± 0.008	4.42	3.67		
			137.5	E2	1.44 ± 0.06		0.84	0.48		
$^{169}_{69}$Tm	8.4	3/2+	8.4	M1 + E2	2.86 ± 0.32	0.033 ± 0.001	270	0	0.948	[13,14]
	118.2	5/2+	109.8	M1 + E2	0.59 ± 0.05	-0.160 ± 0.004	2.395	2.07		
			118.2		3.42 ± 0.21	-	1.619	0.692		
	138.9	7/2+	20.7	M1 + E2	0.224±0.004 a)	0.027 ± 0.007	53.3	0		
			130.5	E2	3.24 ± 0.18	-	1.125			
$^{181}_{73}$Ta	136.25	9/2+	136.25	M1 + E2	2.1 ± 0.2	0.41 ± 0.03	1.756±0.013	1.388±0.020	0.956	[15]
	301.51	11/2+	165.26	M1 + E2		0.44 ± 0.06	0.991±0.019	0.792±0.023		
			301.51	E2	0.53 ± 0.04		0.081	0.056		

a) Calculated within rotational model using intrinsic quadrupole moment value taken from Taras et al. /14/.

Table 2

Experimental and Theoretical Cross Sections for the Proton-Induced K -Shell Ionization

E_p^{eff} (MeV)	σ_{KI}^{exp} (mb)	$\sigma_{KI}^{SCA-LAL}$ (mb)	σ_{KI}^{CPSSR} (mb)	σ_{KI}^{ECPSSR} (mb)	$\sigma_{KI}^{exp}/\sigma_{KI}^{SCA-LAL}$
$_{60}Nd$					K_β/K_α = 0.232 ± 0.009
0.88[a]	2.02 ± 0.I6	2.25	2.I0	2.87	0.90 ± 0.07
I.I0[a]	6.I ± 0.5	6.7I	6.08	7.50	0.9I ± 0.07
I.3I[a]	I3.8 ± 0.9	I4.6	I3.3	I4.5	0.95 ± 0.06
I.5I[a]	25.4 ± I.6	26.6	24.I	25.5	0.95 ± 0.06
I.72[a]	43 ± 3	43.5	38.9	4I.0	0.99 ± 0.07
I.93[a]	6I ± 4	65.6	58.0	6I.0	0.93 ± 0.06
2.I3[a]	89 ± 6	92.9	83.I	82	0.96 ± 0.06
2.33[a]	I20 ± 8	I25	II3	II5	0.96 ± 0.06
2.54[a]	I54 ± I0	I64	I48	I52	0.94 ± 0.06
2.55	I68 ± 22	I68	I5I	I54	I.00 ± 0.I0
2.75	I94 ± I6	2I2	I92	I97	0.92 ± 0.08
2.95	264 ± 22	262	240	243	I.0I ± 0.08
3.I5	330 ± 29	3I9	292	298	I.03 ± 0.09
3.35	405 ± 44	382	354	358	I.06 ± 0.II
3.55	459 ± 50	452	420	424	I.02 ± 0.II
$_{62}Sm$					K_β/K_α = 0.236 ± 0.009
0.74[a]	0.6I0 ± 0.043	0.5I2	0.5I	0.75	I.I9 ± 0.08
0.95[a]	2.39 ± 0.I5	2.I6	2.04	2.8	I.II ± 0.07
I.I6[a]	5.65 ± 0.35	5.74	5.23	6.3	0.98 ± 0.06
I.37[a]	II.3 ± 0.7	I2.I	II.I	I2.2	0.93 ± 0.06
I.56[a]	I8.9 ± I.I	2I.0	I9.0	20.5	0.90 ± 0.05
I.76[a]	3I ± 2	33.2	29.4	33.2	0.93 ± 0.06
I.97[a]	47 ± 3	49.6	44.3	47.5	0.95 ± 0.06
2.I7[a]	66 ± 4	70.0	62.8	66.0	0.94 ± 0.06
2.37[a]	90 ± 6	94.5	84.5	87	0.96 ± 0.06
2.57[a]	II8 ± 8	I23	III	I80	0.96 ± 0.07
2.56	I33 ± I4	I22	I09	II8	I.09 ± 0.II
2.76	I66 ± I8	I54	I40	I43	I.08 ± 0.I2
2.96	I96 ± 2I	I92	I74	I78	I.02 ± 0.II
3.I6	257 ± 28	234	2I5	2I9	I.09 ± 0.I2
3.36	303 ± 33	280	256	265	I.08 ± 0.I2
3.56	37I ± 4I	332	308	3II	I.I2 ± 0.I2
3.77	4I7 ± 59	389	36I	362	I.07 ± 0.I5
E_p^{eff} (MeV)	σ_{KI}^{exp} (mb)	$\sigma_{KI}^{SCA-LAL}$ (mb)	σ_{KI}^{CPSSR} (mb)	σ_{KI}^{ECPSSR} (mb)	$\sigma_{KI}^{exp}/\sigma_{KI}^{SCA-LAL}$
$_{65}Tb$					K_β/K_α = 0.235 ± 0.011
0.73[a]	0.I97 ± 0.020	0.2I4	0.224	0.42	0.92 ± 0.09
0.94[a]	I.06 ± 0.I2	I.05	I.02	I.52	I.0I ± 0.II
I.I5[a]	3.2I ± 0.27	3.03	2.83	3.75	I.06 ± 0.09
I.36[a]	6.90 ± 0.55	6.69	6.24	7.40	I.03 ± 0.08
I.56[a]	I2.5 ± 0.80	I2.I	I0.9	I2.5	I.03 ± 0.07
I.76[a]	I8.5 ± I.7	I9.7	I7.9	I9.6	0.94 ± 0.09
I.96[a]	29.5 ± I.9	29.6	26.6	28.5	I.00 ± 0.06
2.I6[a]	4I.6 ± 2.6	42.2	37.7	40.5	0.99 ± 0.06
2.36[a]	56.I ± 3.3	57.4	5I.5	53.0	0.98 ± 0.06
2.56[a]	72.6 ± 4.3	75.4	67.4	70.0	0.96 ± 0.06
2.56	83 ± 9	75.4	67.4	70.0	I.I0 ± 0.I2

Table 2 (continued)

E_p^{eff} (MeV)	σ_{KI}^{exp} (mb)	$\sigma_{KI}^{SCA-LAL}$ (mb)	σ_{KI}^{CPSSR} (mb)	σ_{KI}^{ECPSSR} (mb)	$\sigma_{KI}^{exp}/\sigma_{KI}^{SCA-LAL}$
$_{65}Tb$					K_β/K_α = 0.235 ± 0.011
2.76	I02 ± II	96.I	86.4	90.5	I.06 ± 0.II
2.96	I2I ± I3	I20	I09	II0	I.0I ± 0.II
3.I6	I5I ± I6	I47	I33	I35	I.03 ± 0.II
3.36	I7I ± I8	I77	I6I	I65	0.97 ± 0.I0
3.56	209 ± 22	2I0	I93	I95	I.00 ± 0.I0
$_{69}Tm$					K_β/K_α = 0.295 ± 0.10
0.94[a]	0.629 ± 0.059	0.43	0.44	0.74	I.46 ± 0.I4
I.I4[a]	2.00 ± 0.I7	I.36	I.32	I.85	I.47 ± 0.I3
I.35[a]	4.24 ± 0.34	3.I4	3.93	3.85	I.35 ± 0.II
I.56[a]	7.60 ± 0.63	6.08	5.72	7.05	I.25 ± 0.I0
I.76[a]	I2.8 ± I.0	I0.I	9.I6	I0.9	I.26 ± 0.I0
I.96[a]	I8.3 ± I.5	I5.6	I4.2	I4.0	I.I7 ± 0.I0
2.I6[a]	29.7 ± 2.3	22.4	20.I	22.0	I.32 ± 0.I0
2.36[a]	37.5 ± 2.7	30.9	27.7	30.5	I.2I ± 0.09
2.56[a]	49.I ± 4.5	40.9	36.6	38.5	I.20 ± 0.II
2.55	48.5 ± 5.5	40.5	36.3	38	I.I9 ± 0.I4
2.75	62.I ± 7.2	52.5	46.9	49	I.I8 ± 0.I4
2.95	86.3 ± 9.6	65.9	59.3	62	I.30 ± 0.I5
3.I5	II0 ± I3	8I.2	72.9	77	I.35 ± 0.I6
3.35	I38 ± I4	98.3	89.3	92	I.40 ± 0.I4
3.56	I5I ± I8	II8	I07	II0	I.28 ± 0.I5
$_{73}Ta$					K_β/K_α = 0.245 ± 0.013
I.03[a]	0.459 ± 0.060	0.33	0.35	0.58	I.39 ± 0.I8
I.I9[a]	I.06 ± 0.I3	0.8I	0.82	I.I2	I.3I ± 0.I6
I.40[a]	2.34 ± 0.28	I.9I	I.85	2.43	I.23 ± 0.I5
I.62[a]	4.48 ± 0.54	3.78	3.64	4.30	I.I9 ± 0.I4
I.83[a]	7.I5 ± 0.84	6.43	5.95	6.80	I.II ± 0.I3
2.02[a]	II.3 ± I.4	9.63	8.9I	9.90	I.I7 ± 0.I5
2.I8[a]	I4.6 ± I.8	I3.0	II.8	I2.9	I.I5 ± 0.I4
2.38[a]	20.7 ± 2.5	I8.0	I6.3	I7.5	I.I5 ± 0.I4
2.58[a]	26.6 ± 3.5	24.0	2I.6	22.2	I.II ± 0.I5
2.55	26.7 ± 2.9	22.9	20.7	23.0	I.I6 ± 0.I3
2.75	36.3 ± 3.9	29.7	26.7	28.5	I.22 ± 0.I3
2.95	43.3 ± 4.7	37.7	33.9	35.7	I.I5 ± 0.I2
3.I5	53.7 ± 5.8	46.7	4I.9	43.9	I.I5 ± 0.I2
3.35	68.2 ± 7.4	57.0	5I.5	53.4	I.20 ± 0.I3
3.56	78.4 ± 7.4	68.4	6I.7	63.9	I.I5 ± 0.II
3.76	88.8 ± 9.6	8I.0	73.8	75.6	I.I0 ± 0.I2

a) The values taken from ref. /5/ for Ta from ref. /24/.

leus and this level becomes excited with high probability even by low energy protons and thus double excitations with this level as an intermediate state must be considered. The multiple Coulomb excitation calculations in paper [5] were performed using the computer code GOSIA written by Czosnyka et al. [8]. The results obtained for ^{169}Tm with the use of the GOSIA code differ up to about 25% from those found from the perturbation treatment. In the present paper for calculation the Coulomb excitation cross section σ_c in Tm nucleus we used only the first order perturbation procedure [7]. The calculation using code GOSIA will be performed later.

All applied proton energies are much lower than the relevant effective Coulomb barriers for our projectile - target systems and thus the nuclear interaction effects are completely negligible.

The numerical results for Nd, Sm, Tb, Tm and Ta are summarized in Table 2. In the first column of this table the effective proton energies are listed. The second column shows our experimental cross section data, while the next three columns display predictions of various theoretical models (see next section). Our experimental uncertainties in Tables 2 include also systematic errors of ω_K (~2%), B(E2) (1÷5%), α_T (2÷3%), detector efficiencies (~4%) and uncertainties of several keV in proton effective energy. These contributions have been quadratically added to the standard deviations of statistical errors (~4%), and thus the final uncertainties quoted in Table 2 are not purely statistical in their character. Table 2 contain also the mean values of the measured K_β/K_α ratios; these ratios agree with the values presented in the paper of Bambynek et al [9] .

4. COMPARISON WITH THEORETICAL MODELS

We have compared the experimental K-shell ionization cross sections with theoretical predictions calculated within the frame of the semiclassical approximation (SCA) and the plane-wave Born approximation (PWBA) models. The SCA model is applied in the version referred to as SCA-LAL which was proposed by Laegsgaard et al. [16]. The effects of the change of electron binding, Coulomb retardation of the projectile in the target nucleus field and relativistic electron velocity are treated here as corrections to the straight-line, non-relativistic SCA calculations.

The PWBA model is applied in two different versions. The first one we have used is the Coulomb Perturbed Stationaty State Relativistic (CPSSR) model. It was developed by Brandt and coworkers (Basbas et al. [17] and Brandt and Lapicki [18]). We have

decided to use the more realistic (Kocbach et al. [19]) Coulomb repulsion correction of Anholt [20] instead of the original one of Basbas et al. [17]. The second PWBA version is referred to as ECPSSR and it has been taken from the recently published tables of Cohen and Harrigan [21]. This model has been developed by Brandt

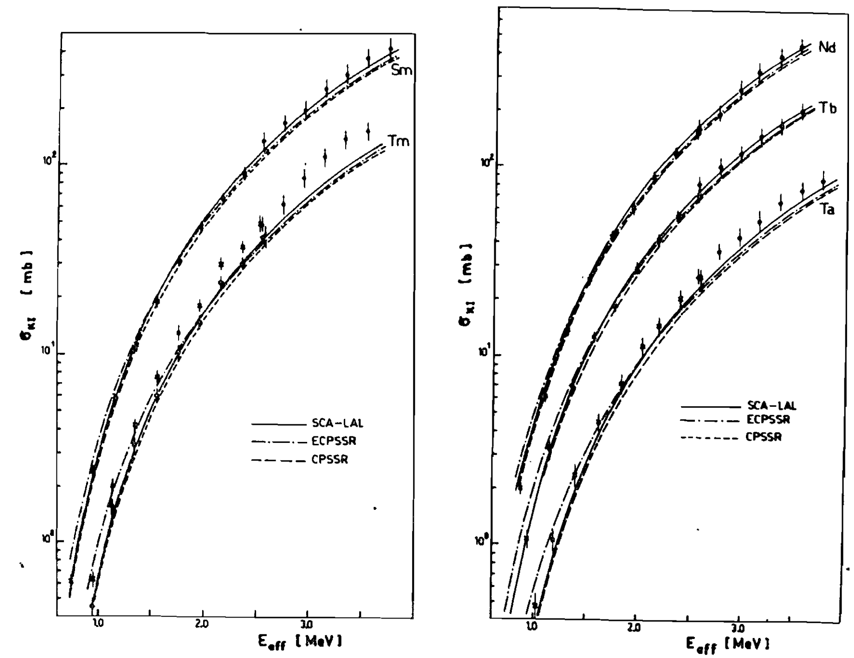


Fig.3. Experimental K*-shell ionization cross sections for* Sm, Tm, Nd, Tb *and* Ta *versus effective proton energy. The solid, dashed and dot-and-dash lines refer to predictions of the SCA-LAL, CPSSR and ECPSSR models, respectively. Dots - the present work, crosses - the Warsaw data [5]. Open circles - the* Tm *data with multiple Coulomb excitations [5].*

and Lapicki [18-22] and includes also the projectile energy loss correction, which is not accounted for in two previously mentioned models. The so-called reduced PWBA universal function F is for the first time calculated performing the proper double integration with exact limits. Thus the tables of Cohen and Harrigan [20] are actually a masterpiece from PWBA point of view.

The predictions of the SCA-LAL, CPSSR and ECPSSR models are listed in the referred above Tables 2 in columns 3,4 and 5, respectively.

In fig.3 we present the predictions of all three considered models together with our data for Nd, Sm, Tb, Tm and Ta targets. The experimental data obtained in Warsaw for lower proton energies[5,24] are also presented in the figures. It is seen that all theoretical models agree in general with the experimental data. The accuracy of our mesurements does not allow us to choose between the models. But it seems that the SCA-LAL model is slightly better (for the studied proton energy range) than the others.

The agreement between the SCA-LAL theory and empirical data is even better visible in fig.4 where the $\sigma_{KI}^{exp}/\sigma_{KI}^{SCA\text{-}LAL}$ ratios are plotted in the linear scale versus the effective proton energy.

It is worth noting that the agreement between theory and experiment for $_{69}$Tm target is possible only if the multiple Coulomb excitation procedure is applied for calculation of the reference σ_c cross section. These calculations were performed only below 2.6 MeV[5].

We also compare our data with earlier results reported by Divoux et al.[23] and Anholt[20]. Those data were obtained by a standard experimental method where the Rutherford backscattering cross sections were considered as the reference cross sections. Comparison is possible only for Nd, Sm and Ta nuclides and is

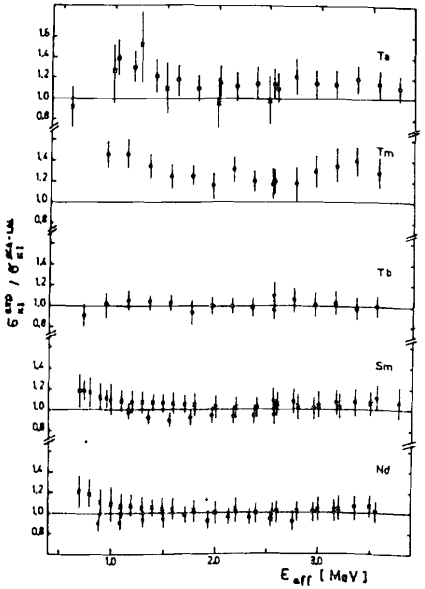


Fig.4. The ratio of the experimental and SCA-LAL model predicted K*-shell ionization cross sections for* Nd , Sm , Tb , Tm *and* Ta *versus effective proton energy. Dots - the present and Warsaw work. Crosses - Divoux et al.*[23] *and Anholt*[20].

displayed in fig.4 where the $\sigma_{KI}^{exp}/\sigma_{KI}^{SCA-LAL}$ ratios are plotted for both our and those of Divoux et al.[23] and Anholt[20] results. The agreement between these independent experiments is quite good.

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Ионизация K-оболочки тяжелых элементов протонами низких энергий

Измерялись сечения ионизации K-оболочки σ_{KI} для атомов Nd, Sm, Tb, Tm и Ta при возбуждении их протонами с энергией от 2,6 до 3,8 МэВ. Значения сечений σ_{KI} получались путем нормировки выходов характеристического рентгеновского излучения K-оболочки к известным сечениям кулоновского возбуждения для этих же ядер. Полученные результаты сравнивались с теоретическими расчетами в полуклассическом приближении (SCA) и борновском приближении плоских волн (PWBA) с учетом поправок на кулоновское отталкивание падающего иона, изменения энергии связи и релятивистский эффект для электронов атомов мишени.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

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The K-Shell Ionization of Heavy Elements Induced by Low Energy Protons

The K-shell ionization cross sections, σ_{KI}, have been measured for Nd, Sm, Tb, Tm, and Ta targets for incident proton energies of 2.6 MeV to 3.8 MeV. The absolute σ_{KI} values have been determined by normalization to the known Coulomb excitation cross sections σ_c of these target nuclei. The experimental results are compared with the predictions of the SCA, PWBA models including the electron binding, Coulomb repulsion and relativistic correction ones.

The investigation has been performed at the Laboratory of Neutron Physics, JINR.

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