Polarization of the characteristic x-ray lines excited by proton collisions

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A diffraction spectrometer-polarimeter was used to measure for the first time the degree of polarization of x radiation of the L_l-, $L_{\alpha 1,2}$- and $L_{\beta 2,15}$- lines of a silver atom excited by protons. We show a reduction in the L_l-line polarization from 29 to 8% for an increase in the proton energy from 150 to 500 keV.

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Ions produced in the course of ionization of the inner shells of atoms with a total angular momentum $j > \frac{1}{2}$ by means of a particle beam are aligned with respect to the beam as a result the ionization cross sections being different for the states with different projections of the momentum onto the particle beam direction.[1] Thus, X-rays which accompany the filling of vacancies in the subshells with the quantum number $j > \frac{1}{2}$ should be polarized. A study of polarization of X-rays yields information concerning the degree of orientation of the produced ions and the population of states with different values of the total and differential ionization cross sections.

The authors are aware of only a single work[2] in which the degree of polarization of the aggregate radiation of the three lines L_α, L_η and L_l—produced as a result of a collision between 100–keV protons and the atoms of copper and germanium—was determined indirectly from a measurement of the angular distribution of this radiation.

In this work a diffraction spectrometer–polarimeter[3] with graphite crystal-analyzer ($2d = 6.76$ Å) and a resolution of ~ 30 eV was used to measure the degree of polarization P of the L_l-, $L_{\alpha_{1,2}}$- and $L_{\beta_{2,15}}$-X-ray emission lines excited by protons with energies from 150 to 500 keV. Measurement of the degree of polarization of X-rays is based on the use of the polarization dependence of intensity of a Bragg reflection from a crystal. As a target we used a foil 300 μg/cm^2 thick which was placed at an angle of 45° with respect to proton beam and X-rays were recorded at a 90-degree angle with respect to the beam. The angular divergence of the proton beam incident on a target was not greater than 1°.

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TABLE I.

E_p, keV / line	150	200	250	300	400	500	$\frac{1+\cos^2 2\theta}{1-\cos^2 2\theta}$
L_l	29 ± 4	25 ± 4	22 ± 4	17 ±2	14 ±2	8 ± 2	1,002
$L_{\alpha_{1,2}}$	—	4 ±2	—	3 ± 2	2 ±1,5	2 ±1	1,13
$L_{\beta_{2,15}}$	—	4 ±2	—	3 ±2	2 ±2	2 ± 2	1,38

In conjunction with determination of the degree of polarization the linear polarization of X-rays measured at a Bragg angle θ is expressed as follows:

$$P = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} \frac{1 + \cos^2 2\theta}{1 - \cos^2 2\theta}, \tag{1}$$

where $I_{\parallel}$ and $I_{\perp}$ are intensities of radiation reflected from the crystal-analyzer when the reflection plane is respectively perpendicular and parallel to the proton beam.* To avoid a systematic error in the polarization measurements due to errors associated with instrumental adjustment, intensity of the L_l-, $L_{\alpha_{1,2}}$- and $L_{\beta_{2,15}}$- lines was concurrently measured with the intensity of the L_{β_1}-line which emits unpolarized radiation. The L_β-line intensity was used to normalize the intensities of the above lines as their degree of polarization was being determined from Eq. (1).

The results of measurement of the degree of polarization of the L emission lines of a silver atom excited by protons are shown in Table I.

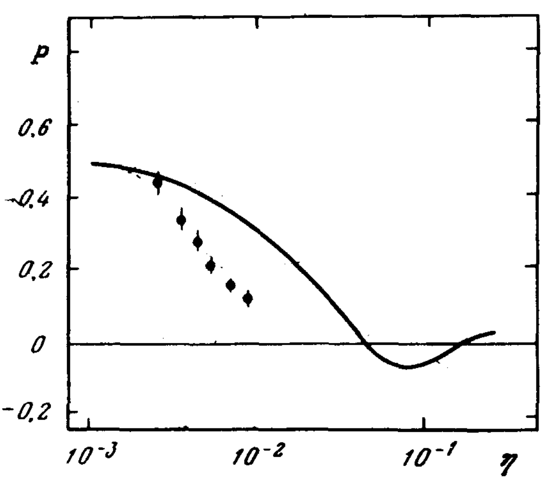

FIG. 1. Dependence of a degree of polarization P of L_l-line emission on the relative velocity of collision η. Solid line represents calculations in the Born approximation.

As may be seen from Table I, the degree of polarization of line emission is the greatest in comparison to the remaining lines and it varies from 29 to 8% as the proton energy E_p increases from 150 to 500 keV. Moreover, emission polarization of the $L_{\alpha_{1,2}}$ and $L_{\beta_{2,15}}$ lines does not exceed 4% and is practically independent of the proton energy.

As we utilize the results of calculations for the dependence of the degree of alignment of atoms with vacancies in the L_3 subshell on the relative collision velocity $\eta = (v/v_0 Z)^2$ (v is proton velocity, Z is nuclear charge of target atom, $v_0 = 2.19\times 10^8$ cm/sec) which were carried out in the Born approximation,[4] we may calculate the degree of polarization of the L_l-line emission excited by protons (Fig. 1). The results of our calculations coincide with similar calculations carried out elsewhere.[2] As can be seen from Fig. 1, the calculated values of the degree of polarization of the L_l-line emission exceed the experimental in the range of collision velocities $3\times 10^{-3} < \eta < 10^{-2}$, and this deviation deteriorates with increasing relative velocity of collision. The contribution of the Koster-Kroenig transitions from the L_1 and L_2 subshells to the formation of vacancies in the L_3 subshell—the filling of which is characterized by a unpolarized emission—was not taken into consideration in the calculations[2,4]; as a result of this Fig. 1 shows experimental data for polarization of the L_l-line of a silver atom which have been corrected for an increase in a number of subshell vacancies due to these transitions. The ionization cross sections of the L_1 and L_2 subshells were determined from the intensity measurements of the L_{β_1} and L_{β_3} lines. A better quantitative agreement between the theory and experiment may, clearly, be attained if the calculations were to be conducted by means of more precise models.

Thus, we have established by means of direct measurement that the characteristic X-ray lines emitted by an atom in the course of filling a vacancy created in the L_3 subshell by a proton collision are polarized and the degree of polarization increases with decreasing proton energy. Since the results of the measured intensity of emitted X-radiation of individual lines depend on the degree of its polarization which, as we showed, may attain 30% and vary as a function of the proton energy, this result must be taken into account in both the measurement of X-radiation spectra and the determination of cross sections for the excitation of X-radiation by heavy particles.

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