contains the representation Γ_5 once, (A.1) is satisfied for T_{40}. From the table it is evident that $\langle\frac{3}{2}m|T_{40}|\frac{3}{2}n\rangle = -\langle\frac{3}{2}n|T_{40}|\frac{3}{2}m\rangle$; therefore the matrix elements of this operator are pure imaginary.

The authors express their deep gratitude to I. L. Fabelinskiĭ and to the participants in the seminar conducted by him for useful discussion of the research.

1)The saturation range, however, is not considered in this paper.

2)A large number of mechanisms of nonlinear autorotation of the polarization ellipse have been discussed earlier for various media (see, for example, Ref. 11 and references cited in that paper, and also Ref. 12). But the treatment was everywhere limited to stationary fields.

1P. S. Pershan, Phys. Rev. **130**, 919 (1963).

2A. G. Gurevich, in: Ferromagnitnyĭ rezonana (Ferromagnetic Resonance), ed. S. V. Vonsovskiĭ, Fizmatgiz, 1961.

3P. S. Pershan, J. P. van der Ziel, and L. D. Malmstrom, Phys. Rev. **143**, 574 (1966).

4A. A. Dabalyan, M. E. Movsesyan, and R. E. Movsesyan, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 586 (1979) [JETP Lett. **29**, 534 (1979)].

5B. A. Zon and Yu. N. Mitin, Zh. Tekh. Fiz. **49**, 1781 (1979) [Sov. Phys. Tech. Phys. **24**, 1001 (1979)].

6B. A. Zon and Yu. N. Mitin, Opt. Spektrosk. **43**, 535 (1977) [Opt. Spectrosc. (USSR) **43**, 314 (1977)].

7A. Abragam and B. Bleaney, Electron Paramagnetic Resonance of Transition Ions, Oxford, Clarendon Press, 1970 (Russ. transl., "Mir", 1972, Vol. 2).

8I. V. Aleksandrov, Teoriya magnitnoĭ relaksatsii (Theory of Magnetic Relaxation), Nauka, 1975.

9V. M. Agranovich and M. D. Galanin, Perenos energii élektronnogo vozbuzhdeniya v kondensirovannykh sredakh (Transfer of electronic excitation energy in condensed media), Nauka, 1978.

10M. Born, Optik, Springer, Berlin, 1933 (reprint, Edwards Brothers, Ann Arbor, 1943; Russ. transl., GNTIU, 1937).

11B. A. Zon and T. T. Urazbaev, Zh. Prikl. Spektrosk. **28**, 425 (1978) [J. Appl. Spectrosc. (USSR) **28**, 293 (1978)].

12S. A. Akhmanov and V. I. Zharikov, Pis'ma Zh. Eksp. Teor. Fiz. **6**, 644 (1967) [JETP Lett. **6**, 137 (1967)]; S. A. Akhmanov, B. V. Zhdanov, N. I. Zheludev, A. I. Kovrigin, and V. I. Kuznetsov, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 294 (1979) [JETP Lett. **29**, 264 (1979)].

13Yu. N. Mitin, Opt. Spektrosk. **47**, 1105 (1979) [Opt. Spectrosc. (USSR) **47**, 614 (1979)].

14L. Allen and J. H. Eberly, Optical Resonance and Two-Level Atoms, Wiley, 1975 (Russ. transl., Mir, 1978).

15D. T. Sviridov and Yu. F. Smirnov, Teoriya opticheskikh spektrov ionov perekhodnykh metallov (Theory of the optical spectra of transition-metal ions), Nauka, 1977.

Translated by W. F. Brown, Jr.

Polarization of characteristic x rays excited by proton impact

N. M. Kabachnik, V. P. Petukhov, E. A. Romanovskiĭ, and V. V. Sizov

Nuclear Physics Research Institute of the Moscow State University

(Submitted 22 November 1979)

Zh. Eksp. Teor. Fiz. **78**, 1733–1742 (May 1980)

The degree of polarization of the x-ray lines L_l, $L_{\alpha 1,2}$, and $L_{\beta 2,15}$ of a proton-excited silver atom was measured. It is established that the measured degree of polarization of the L_l line decreases from 29 to 8% when the proton energy is increased from 150 to 500 keV. The degree of polarization of the radiation of the investigated lines, calculated in the Born approximation with allowance for the Koster-Kronig transitions, agrees well with experiment. The effect of the polarization on the measurements of the cross sections of the generated x-ray lines is analyzed.

PACS numbers: 34.50.Hc, 32.30.Rj

1. INTRODUCTION

Excitation of atoms by a directional beam of particles produces an aligned state, and the light emitted in the course of its decay is linearly polarized. However, only relatively recently[1] was it understood that the an ion with a vacancy in the inner shell and with total angular momentum $j \geq 3/2$, produced when the atom is ionized by electron or proton impact, should also be in an aligned state. This alignment is due to the fact that the cross sections for the ionization are different for states with different values of the modulus of the projection of the angular momentum on the direction of the particle beam. Therefore the x rays accompanying the filling of the vacancies should be anisotropic and polarized. The first successful measurement of the polarization of the characteristic x rays was carried out in Ref. 2, where polarization of the L_{α_1} line of mercury excited by an electron beam was observed.

A theoretical analysis[3,4] has shown that the polarization of the x rays when atoms are ionized by protons can be much larger than the maximum polarization reached in ionization by electrons. A high degree of polarization was predicted in the proton relative velocity region $v/v_0 < 1$ (v_0 is the electron velocity on the given subshell, and v is the velocity of the incident

 0038-5646/80/050869-06$02.40

particle), which is energywise forbidden to ionization by electrons.

Until recently the polarization of the x rays generated when protons collide with atoms was measured only for several K_α satellite lines[5-7] connected with multiple ionization of Si and Al atoms. Schöler and Bell[8] determined the degree of polarization of the total emission of the three lines L_α, L_η, and L_l generated when protons of energy 100 keV collide with copper and germanium atoms by measuring the angular distribution of this emission.

Measurements of the degree of polarization of x rays of the diagram lines of the L spectrum of silver atom were reported in Refs. 9 and 10. The dependence of the degree of polarization on the energy of the incident proton was investigated there for the first time ever. Measurements of the degree of alignment of the ions Au^+ and Xe^+ on the energy of the incident proton was recently reported by Jitschin *et al.*[11]

We report and analyze here the results of measurements of the degree of polarization of the lines L_1, $L_{\alpha_{1,2}}$ and $L_{\beta_{2,15}}$ of a silver atom excited by protons of energy from 150 to 500 keV. In addition we discuss the influence of the anisotropy of the x rays on the measured ratios of the intensities of the different lines and generation cross sections.

2. EXPERIMENTAL PROCEDURE

To measure the ionization of the x rays excited by heavy ions we developed a large-transmission diffraction spectrometer-polarimeter.[12] In this instrument (Fig. 1), a proton beam of 2–4 mm diameter is aimed on target *1* at an angle 45°. The x rays excited in the target pass through a Soller collimator *2*, mounted at an angle 90° relative to the proton beam, and after a reflection from the analyzer crystal *3* is registered by a flow-through proportional counter *4* with a long narrow window (60×6 mm). The analyzer crystal is rotated during the plotting of the spectrum through a worm gear *5* by a stepping motor *6*. The Soller collimator, the analyzer crystal, the counter, the stepping motor, and the preamplifier 7 are mounted inside a cylinder *8*, which can be rotated through 360° around the *AA* axis in the measurements of the polarization of the x rays. The cylinder is mounted with the aid of bearings on a flange *9* in vacuum chamber *10*.

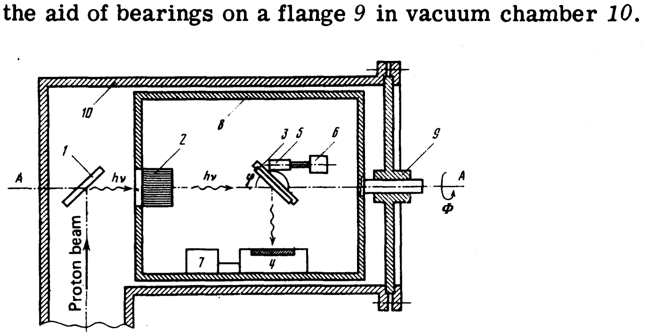

FIG. 1. Construction of spectrometer-polarimeter: 1—target, 2—Soller collimator, 3—analyzer crystal, 4—counter, 5—worm gear, 6—stepping motor, 7—pre-amplifier, 8—cylinder, 9—flange, 10—vacuum chamber.

The pressure in the vacuum chamber is maintained at 10^{-5} Torr.

The polarization measurement is based on the use of the polarization dependence of the intensity of the Bragg reflection from the crystal. The crystal, mounted at 45° to the direction of the incident x-ray beam reflects the radiation in a narrow spectral interval, for which the Bragg condition is satisfied; it reflects furthermore only that component of the radiation whose polarization plane is perpendicular to the plane of the incident and reflected rays. The component whose polarization plane is parallel to the plane of the incident and reflected rays is absorbed. If the crystal is rotated around the incident x-ray beam, then the polarization of this radiation manifests itself in a change of the intensity of the reflected beam as a function of the angle of rotation of the instrument about this axis (the *AA* axis in Fig. 1). The spectrometer has an energy resolution 20–30 eV in the x-ray energy range from 0.7 to 7 keV. The transmission of the apparatus, depending on the employed analyzer crystal, ranges from 5×10^{-2} to 10^{-5} count/photon. The analyzer crystals are single crystals of lithium fluoride ($2d=4.02$ Å), quartz ($2d=6.66$ Å), graphite ($2d=6.76$ Å) and rubidium biphthalate ($2d=26.6$ Å).

This instrument was used to measure the spectra of the L lines excited in collisions of protons with a solid target, at two positions of the analyzer crystal: in the first position the direction of the proton beam was parallel to the plane of the incident x rays and the x rays reflected from the analyzer crystal (the angle between the beam axis and this plane is $\Phi=0°$). In the second position the direction of the proton beam was perpendicular to this plane ($\Phi=90°$). The target was a foil 300 $\mu g/cm^2$ thick. The angular divergence of the proton beam incident on the target did not exceed 1°. Estimates based on the distribution of multiply scat-

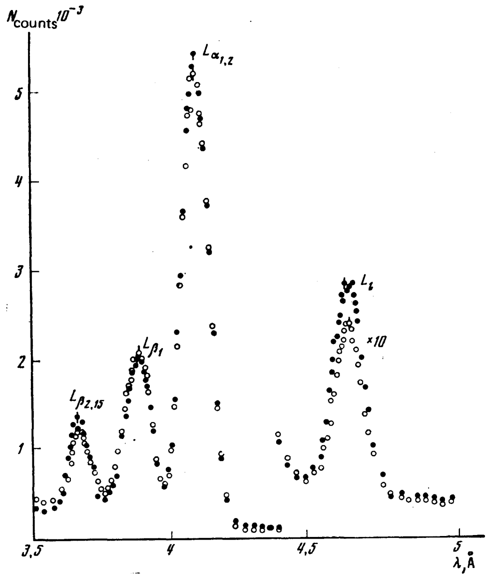

FIG. 2. Spectra of x-ray emission produced when the L shell of Ag atoms is ionized by 400-keV protons. The spectra were registered at two positions of the analyzer crystal relative to the proton-beam axis: ●—$\Phi=0°$; ○—$\Phi=90°$.

tered protons in the given target[13] have shown that the beam divergence angle in the target does not exceed 5°.

A typical spectrum of the L emission of silver atoms excited by protons of energy 400 keV is shown in Fig. 2. As seen from this figure, when the line L_{β_1} is registered the intensity of the beam reflected from the analyzer crystal is independent, within the limits of the measurement accuracy, of the analyzer-crystal orientation relative to the proton-beam axis, while the registered intensities of the lines L_l, $L_{\alpha_{1,2}}$, and $L_{\beta_{2,15}}$ vary noticeably, depending on the orientation of the analyzer crystal.

In connection with the definition of the degree of polarization

$$P=(I_\parallel-I_\perp)/(I_\parallel+I_\perp)$$

(where $I_\parallel$ and $I_\perp$ are the intensities of the radiation in the direction perpendicular to the proton-beam axis with electric vectors parallel and perpendicular to this axis), the linear polarization of the x rays for a Bragg angle φ is given by

$$P=\frac{(J_\parallel-J_\perp)(1+\cos^2 2\varphi)}{(J_\parallel+J_\perp)(1-\cos^2 2\varphi)}, \tag{1}$$

where $J_\parallel$ and $J_\perp$ are the intensities of the radiation reflected from the analyzer crystal when the reflection plane is perpendicular and parallel to the proton-beam axis, respectively.

The accuracy with which the polarization is determined from formula (1) depends on the accuracy at which the registration efficiency is known for the indicated two orientations of the instrument. Any misadjustment leads to a systematic error that can predominate over all the errors in the measurement. To exclude the systematic errors in the polarization measurements, due to errors in the adjustment of the instrument, they measured simultaneously with the intensities of the lines L_l, $L_{\alpha_{1,2}}$ and $L_{\beta_{2,15}}$ the intensity of the L_{β_1} line, the radiation of which is not polarized; when the degree of polarization of the emission of these lines was determined from formula (1), their intensities were normalized to the intensity of the L_{β_1} line. The statistical error in the measurements of the degree of polarization did not exceed 2% as a rule.

3. THEORY

The angular distribution and polarization of the characteristic x radiation generated by bombardment of atoms with a beam of charged particles are determined by the degree of alignment of the produced vacancies. Since the alignment is possible only for states with total angular momentum $j>1/2$, the x radiation connected with the filling of vacancies in the L_1 and L_2 subshells ($j=1/2$) is isotropic and unpolarized. The only radiation that can be polarized is the one connected with the filling of the vacancies in the L_3 subshell ($j=3/2$), the filling of which is accompanied by emission of the lines L_l, $L_{\alpha_{1,2}}$, $L_{\beta_{2,15}}$, etc.

For a quantitative description of the alignment it is convenient to introduce the alignment parameter $\mathcal{A}_{20}$.[14] This parameter can be expressed in terms of the cross sections $\sigma(jm)$ of ionization of the given subshell of atoms with different projections of the angular momentum m on the direction of the primary beam. For example, for the L_3 subshell

$$\mathcal{A}_{20}=\frac{\sigma(^3/_2\ ^3/_2)-\sigma(^3/_2\ ^1/_2)}{\sigma(^3/_2\ ^3/_2)+\sigma(^3/_2\ ^1/_2)}. \tag{2}$$

If we neglect the spin-orbit interaction, then $\mathcal{A}_{20}$ can be expressed in terms of the cross section for the production of vacancies with definite values of the projection of the angular momentum $\sigma(lm_l)$. Thus, for $l=1$ we have

$$\mathcal{A}_{20}=\frac{\sigma(11)-\sigma(10)}{2\sigma(11)+\sigma(10)}. \tag{3}$$

The angular distribution and the degree of polarization of a definite x-ray line are expressed in terms of the alignment parameter in the following manner:

$$W(\gamma)=\frac{W_0}{4\pi}[1+\alpha\mathcal{A}_{20}P_2(\cos\gamma)],$$
$$P(\%)=\frac{3\alpha\mathcal{A}_{20}}{\alpha\mathcal{A}_{20}-2}\cdot 100. \tag{4}$$

Here γ is the angle between the direction of the incident proton beam and the radiation, and α is a coefficient that is characteristic for the given x-ray line and is determined only by the angular momentum of the initial and final states of the ion. The values of the coefficient α, taken from Ref. 14, are listed in the table for the cases of interest to us. As seen from the table, the largest polarization at a given alignment should be expected for the line L_1 (the transition $M_1\to L_3$).

A comparison of the theoretical and experimental ionization cross sections shows that the Born approximation describes well the experiment at proton velocities $v/v_0>0.2$.[15] This approximation is therefore used to calculate the vacancy alignment for ionization of the inner shell of an atom by electron impact. The general formulas for the calculation of $\mathcal{A}_{20}$ in the Born approximation are given in Ref. 4. The Born matrix elements were calculated by us in three models: hydrogen like (HL), hydrogen like model with allowance for external screening (SHL)[16], and the Hartree-Slater model (HS). These atomic models are widely used in the analysis of the cross sections for ionization and generation of x rays in ion-atom collisions.

The results of the calculation of the degree of alignment for the case of ionization of the L_3 subshell of the silver atom are shown in Fig. 3. In the calculations in the SHL model the external screening is taken into

TABLE I. The coefficient α for different values of the total angular momentum of the final state of the ion j_f. The initial state of the ion is a vacancy in the L_3 subshell ($j=\frac{3}{2}$).

Line	j_f	α
L_l	$1/2$	$1/2$
L_{α_2}, $L_{\beta_{15}}$	$3/2$	$-2/5$
L_{α_1}, L_{β_2}	$5/2$	$1/10$

account by introducing the parameter $\theta = 4I/I_0 Z^{*2}$, where I is the experimental binding energy of the removed electron,[18] $Z^* = Z - 4.15$ is the effective charge of the nucleus, and $I_0 = 13.6$ eV. It is seen from the figure that the HS and the SHL models given close result that differ quite considerably from the case $\theta = 1$. We used these data to calculate the degree of polarization for the lines L_l, $L_{\alpha_{1,2}}$, and $L_{\beta_{2,15}}$.

4. RESULTS AND DISCUSSION

The experimental values of the degree of polarization of the L lines of silver are shown in Fig. 4. It is seen that the degree of polarization of L_l changes from 29 to 8 when the proton energy E is increased from 150 to 500 keV. The polarization of the radiation of the lines $L_{\alpha_{1,2}}$ and $L_{\beta_{2,15}}$ does not exceed 4% in this case and is practically independent of the proton energy.

Before we proceed to compare the experimental and calculated results, we note two circumstances. In our experiments the lines L_{α_1} and L_{α_2}, as well as L_{β_2} and $L_{\beta_{15}}$, cannot be resolved, and what is measured in this case is a certain average polarization $\bar{P}$, which is expressed in terms of the polarization of each line P_i and their radiative widths Γ_i (Ref. 8):

$$\bar{P} = \sum g_i P_i \Big/ \sum g_i, \qquad g_i = \Gamma_i (1 - P_i/3). \tag{5}$$

In the calculation of $\bar{P}$, the radiative widths were taken from Ref. 19 ($\Gamma_{\alpha_1} = 0.0946; \Gamma_{\alpha_2} = 0.0107$, $\Gamma_{\beta_2} = 0.00098$, $\Gamma_{\beta_{15}} = 0.0086$).

The second circumstances connected with the possibility of indirect formation of a vacancy in the L_3 subshell. In fact, when the atom is bombarded with protons, vacancies are produced also in the L_1 and L_2 subshells, which then decay via the Koster-Kronig transitions and increase the number of the L_3 vacancies. The alignment of the L_1 and L_2 vacancies is equal to zero, so that this two-step process leads to a decrease of the alignment of the L_3 vacancy:

$$\bar{\mathscr{A}}_{20} = k\mathscr{A}_{20}, \quad k = \sigma_3 / [\sigma_3 + \sigma_2 f_{23} + \sigma_1 (f_{13} + f_{12} f_{23})]. \tag{6}$$

Here $\sigma_{1,2,3}$ are the cross sections of the ionizations of the $L_{1,2,3}$ subshells, f_{ij} are the Koster-Kronig factors.

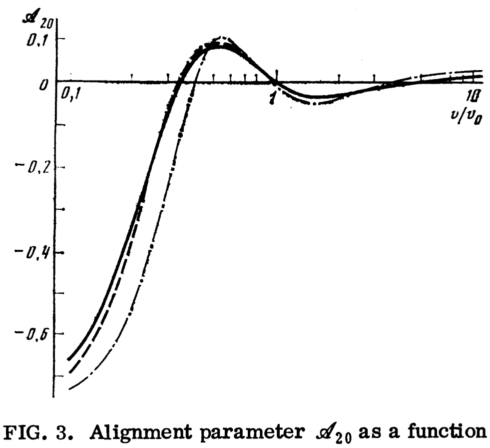

FIG. 3. Alignment parameter $\mathscr{A}_{20}$ as a function of the relative velocity of the protons v/v_0, for ionization of the $2p_{3/2}$ subshell of Ag. Solid line—calculation in the HS model; dashed—in the SHL model, $\theta = 0.54$; dash-dot—in the HL model.

In the calculation of the alignment $\bar{\mathscr{A}}_{20}$ with allowance for the Koster-Kronig transitions, the cross sections $\sigma_{1,23}$ were calculated in the Born approximation, and the factors f_{ij} were taken from Ref. 20 ($f_{23} = 0.152$; $f_{13} = 0.756$; $f_{12} = 0.052$).

Figure 4 shows the results of the calculation of the radiation polarization of the L lines of silver in various models, with allowance for the Koster-Kronig transitions. For comparison, the figure shows the calculated polarization of the L_1 line in the HS model, without allowance for the two-step process. It is seen that the influence of the latter is noticeable in the entire investigated energy range, but is particularly large in the region of low velocities ($E \leq 300$ keV). This is understandable, for it is precisely in this proton-energy region, in view of the singularities of the ionization of the $2s$ and $2p$ subshells,[21] that the state of ionization of the L_1 subshell becomes larger than the cross sections for the ionization of the $L_{2,3}$ subshells. This results in an increase in the number of vacancies produced in the L_3 subshell on account of the Koster-Kronig transitions, and leads to a considerable decrease of the alignment, and consequently also of the polarization of the emission of the L_l line. We note that the measurements of Jitschin *et al.*[11] show that at low velocities the alignment is much smaller than predicted by the theory without allowance for the Koster-Kronig transitions.

As seen from Fig. 4, calculations, in the HS and the SHL ($\theta = 0.54$) models agree well with experiment in the entire investigated energy interval. At the same time, the degree of polarization of the L_l line, calculated using the HL model, differs markedly from the experiment. Unfortunately, the experimental conditions did not make it possible to verify the prediction of the

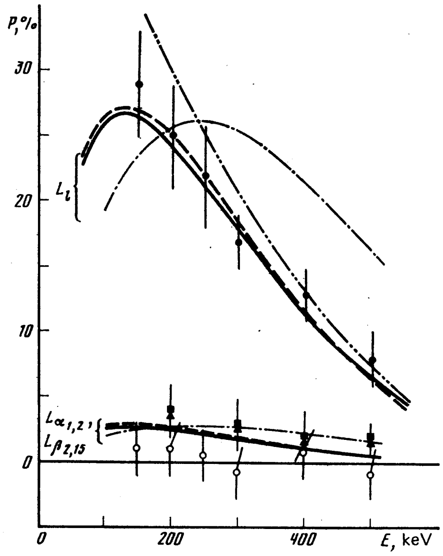

FIG. 4. Degree of polarization of the L radiation of Ag atoms as a function of the proton energy. Experimental results: ●—L_l; ■—$L\alpha_{1,2}$; ▲—$L\beta_{2,15}$; ○—$L\beta_1$. Results of calculations in the Born approximation: solid line—in the HS model; dashed—in the SHL model ($\theta = 0.54$); dash-dot—in the HL model ($\theta = 1$). Dash and two dots—in the HS model without allowance for the Koster-Kronig transitions.

theory that the polarization of the L_l line decreases in the low-velocity region. It would be of interest also to determine experimentally the energy at which the polarization reverses sign. The theory predicts a sign reversal at $E \approx 750$ keV.

5. INFLUENCE OF X-RAY POLARIZATION ON THE RESULTS OF MEASUREMENTS OF THE GENERATION CROSS SECTIONS

In the preceding sections it was demonstrated theoretically and experimentally that the emission of certain characteristic lines is polarized and anisotropic. Let us examine how this anisotropy can influence the results of measurements of the cross sections for the generation of x rays in ion-atom collision. As a rule, the x-ray yield is measured at a single angle (90°) to the direction of the primary beam, and the total generation cross section is determined under the assumption that the x rays are isotropic. The x-ray anisotropy observed by us can lead to an error in the determination of the cross section of generation of certain lines.

It was observed in measurements of the intensities of individual lines of the L series of lead atoms excited by proton impact[22] that the ratio of the intensities of the lines L_α and L_l depends on the energy of the protons and has a pronounced minimum in the proton energy region 0.5 MeV $\leq$ 2 MeV. At the same time, according to the universally accepted premises, the ratio of the intensities of the two lines should be determined only by the ratio of the radiative widths of the decay of the L_3 level via the respective channels. No explanation was found for this phenomenon. We shall show that the experimentally observed decrease of the ratio of the intensities of the L_α and L_l lines can be explained by taking into account the anisotropy of the emission of the L_l line. In fact, when formula (4) is taken into account the ratio of the intensities of the L_α and L_l lines, registered at an angle 90° to the direction of the proton beam, can be written in the form

$$\frac{I_\alpha}{I_l}=\frac{\Gamma_\alpha[\sigma_3(1-\frac{1}{2}\alpha_\alpha\mathcal{A}_{20})+\sigma_2 f_{23}+\sigma_1(f_{13}+f_{12}f_{23})]}{\Gamma_l[\sigma_3(1-\frac{1}{2}\alpha_l\mathcal{A}_{20})+\sigma_2 f_{23}+\sigma_1(f_{13}+f_{12}f_{23})]}. \quad (7)$$

If we neglect the anisotropy of these lines, i.e., assume that $\mathcal{A}_{20}=0$, then $I_\alpha/I_l=\Gamma_\alpha/\Gamma_l$[22] (Ref. 22) and does not depend on the proton energy. However, since actually the emission of the L_l line is strongly anisotropic and $\mathcal{A}_{20}$ increases with decreasing energy, the ratio I_α/I_l should also depend on the energy.

Analysis shows that the anisotropy of the L_α line can be neglected ($\alpha_\alpha \ll 1$). Then, dividing the numerator and denominator of expression (7) by the total cross section for the production of the L_3 vacancy, we obtain

$$\frac{I_\alpha}{I_l}=\frac{\Gamma_\alpha}{\Gamma_l(1-\frac{1}{2}\alpha_l\mathcal{A}_{20})}. \quad (8)$$

In the high-energy region, the alignment $\mathcal{A}_{20}$ is positive and the ratio I_α/I_l should exceed Γ_α/Γ_l slightly. With decreasing energy, the alignment reverses sign and increases in amplitude and magnitude; this leads to a decrease of I_α/I_l.

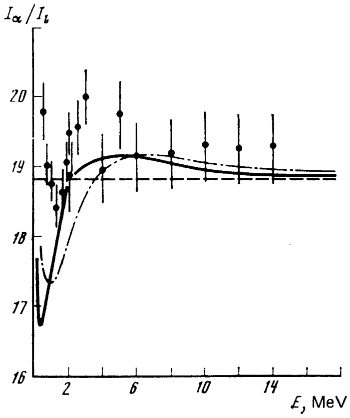

FIG. 5. Ratio of the intensities of the emission of the lines L_α and L_l of Pb atoms as a function of the proton energy. Solid line—calculation in the HS model; dash-dot—calculation in the HL model; dashed—ratio Γ_α/Γ_l; the experimental data were taken from Ref. 22.

Finally, at still lower energies the alignment decreases because of the increase of the role of Koster-Kronig transitions, and the ratio I_α/I_l again increases (Fig. 5). This was precisely the picture observed in Ref. 22. Figure 5 shows the theoretical plot of the ratio of the intensities of proton-excited L_α and L_l lines of a lead atom as a function of the energy, as calculated by us in the Born approximation. The theory and experiment are seen to agree qualitatively. The absence of quantitative agreement is due apparently to the fact that in the calculation of the intensity ratio we used the theoretical ionization cross sections, radiation widths, and Koster-Kronig factors, which can differ somewhat from the true ones. It appears that the anisotropy effects explain similar anomalies observed also in other experiments.[23-25]

CONCLUSION

Direct experiments have established that the characteristic x-ray lines emitted upon filling of a vacancy produced by proton impact in the L_3 subshell are polarized, and that the degree of polarization increases with decreasing proton energy. The experimental dependence of the degree of polarization on the proton energy agrees with that calculated in the Born approximation. A decrease of the alignment and of the polarization of the x rays at low velocities, due to the influence of Koster-Kronig transition, is predicted.

Since the measured intensities of the emission of the individual lines depend on the degree of the polarization of the radiation which, as established here, can reach 30% and varies with the proton energy, this circumstance must be taken into account both in the measurement of the spectra of the x rays, and when the cross section of generation of this radiation, excited by heavy particles, is determined.

Measurement of x-ray polarization is a new and important method of investigating the ionization of the inner shells of atoms and makes it possible to study the population of the magnetic sublevels of x-ray levels.

[1]W. Mehlhorn, Phys. Lett. 26A, 166 (1968).
[2]J. Hrdy, A. Henins, and J. A. Bearden, Phys. Rev. A 2, 1708 (1970).
[3]E. G. Berezhko, N. M. Kabachnik, and V. V. Sizov, J. Phys. B 11, L421 (1978).
[4]V. V. Sizov and N. M. Kabachnik, J. Phys. B 13, 1708 (1980).
[5]K. A. Jamison and P. Richard, Phys. Rev. Lett. 38, 484 (1977).
[6]K. A. Jamison, P. Richard, F. Hopkins, and D. L. Mattews, Phys. Rev. A 17, 1642 (1978).
[7]K. A. Jamison, J. Newcomb, J. M. Hall, C. Schmiedekamp, and P. Richard, Phys. Rev. Lett. 41, 1112 (1978).
[8]A. Scholer and F. Bell, Z. Phys. A 286, 163 (1978).
[9]V. P. Petukhov, E. A. Romanovskiĭ, and S. V. Ermakov, Pis'ma Zh. Eksp. Teor. Fiz. 29, 385 (1979) [JETP Lett. 29, 348 (1979)].
[10]V. P. Petukhov, E. A. Romanovsky, N. M. Kabachnik, V. V. Sisov, and S. V. Ermakov, Eleventh ICPEAC, Abstracts, Kyoto, 1979, p. 668.
[11]W. Jitschin, H. Kleinpoppen, R. Hippler, and H. O. Lutz, Eleventh ICPEAC, Abstracts, Kyoto, 1979, p. 675.
[12]V. P. Petukhov, E. A. Romanovskiĭ, and A. M. Borisov, 7th All-Union Conf. on the Physics of Electron and Atom Collisions, Abstracts, Petrozavodsk, 1978, p. 151.
[13]P. Sigmund and K. B. Winterbon, Nucl. Instrum. Methods 119, 541 (1974).
[14]E. C. Berezhko and N. M. Kabachnik, J. Phys. B 10, 2467 (1977).
[15]J. D. Garsia, R. J. Fortner, and T. M. Kavanagh, Rev. Mod. Phys. 45, 111 (1973).
[16]E. Merzbacher and H. W. Lewis, Handbuch der Physik 34, 166 (1958).
[17]F. Herman and S. Skillman, Atomic Structure Calculation, Prentice Hall, 1963.
[18]J. A. Bearden and A. F. Burr, Rev. Mod. Phys. 39, 125 (1967).
[19]J. H. Scofield, Phys. Rev. 179, 9 (1969).
[20]W. Bambynek, B. Crasemann, R. W. Fink, H. U. Freund, H. Mark, C. D. Swift, R. E. Price, and P. Venugopala Rao, Rev. Mod. Phys. 44, 716 (1972).
[21]V. P. Petukhov, V. S. Nikolaev, E. A. Romanovskiĭ, and V. A. Sergeev, Zh. Eksp. Teor. Fiz. 71, 968 (1976) [Sov. Phys. JETP 44, 508 (1976)].
[22]C. E. Busch, A. B. Baskin, P. H. Nettles, S. M. Shafroth, and A. W. Waltner, Phys. Rev. A 7, 1601 (1973).
[23]K. Ishii and S. Morita, Phys. Rev. A 10, 774 (1974).
[24]F. Abrath and T. J. Gray, Phys. Rev. A 10, 1157 (1974).
[25]F. Abrath and T. J. Gray, Phys. Rev. A 9, 682 (1974).

Translated by J. G. Adashko

Oblique Langmuir solitons and their self-compression in the "free-flight" regime

S. V. Antipov, M. V. Nezlin, and A. S. Trubnikov

I. V. Kurchatov Institute of Atomic Energy
(Submitted 31 October 1979)
Zh. Eksp. Teor. Fiz. **78**, 1743–1751 (May 1980)

For the first time we have observed experimentally in a magnetized collisionless plasma, of the "beam afterglow", slow (approximately fixed relative to the plasma) oblique Langmuir solitons with an HF carrier on the branch of waves with the linear dispersion $\omega = \omega_p \cos\Theta$, which occur as a consequence of the modulational instability of the nonlinear waves. The longitudinal size of the solitons is less than the initial (beam) wavelength and it is impossible to call them envelope solitons. We show that after a time equal to their "free-flight" (along with the plasma) along the magnetic field—after the "pump beam" was switched off—the solitons experience appreciable self-compression. The solitons observed differ in priniciple from the well known, fast, soliton [H. Ikezi, P. J. Barrett, R. B. White, and A. Y. Wong, Phys. Fluids **14**, 1997 (1971); S. M. Krivoruchko, Ya. B. Faĭnberg, V. D. Shapiro, and V. I. Shevchenko, Sov. Phys. JETP **40**, 1039 (1975); V. D. Fedorchenko, Yu. P. Mazalov, A. S. Bakaĭ, A. V. Pashchenko, and B. N. Rutkevich, JETP Lett. **18**, 281 (1973)], which exists on the same branch of waves: the fast soliton moves several orders of magnitude faster, constitutes a potential hump without an HF carrier and arises as the result of another mechanism, such as a Korteweg–de Vries ion-sound or shallow-water soliton [H. Ikezi, R. P. H. Chang, and R. A. Stern, Phys. Rev. Lett. **36**, 1047 (1976); B. B. Kadomtsev, Collective Phenomena in a Plasma, Nauka, Moscow, 1976, Ch. 3, §3; Ch. 5, §5 (English translation published by Pergamon Press)]. The observed solitons with oscillation frequencies $\omega = (1/3 \text{ to } 1/2)\omega_p$ are as yet not described in the theory.

PACS numbers: 52.35.Mw

1. STATEMENT OF THE PROBLEM

The present paper is an extension of Refs. 1 and 2, in which we observed and studied Langmuir solitons in a magnetized collisionless plasma which was excited by an electron beam. In contrast to the preceding work[1] the aim of the present paper consisted in studying the evolution of the solitons *after* the "pump beam" was switched off, i.e., in the afterglow of the beam plasma. Such a study (if we neglect isolated observations in our first paper[2]) has not been made before. To carry it out it is necessary that the plasma be collisonless, i.e., that there be sufficiently low densities of both charged and neutral particles. It was just the high den-

