Scattering of slow electrons by xenon atoms in various quantum states

A.I. Korotkov, G.M. Sorokin, and A.N. Podshivalin

Chuvashskii State University, Cheboksary

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The spectra of scattering of slow electrons by standard and metastable xenon atoms are investigated. The excitation functions of resolved peaks are studied. New information on efficient cross sections of scattering of electrons by xenon atoms is obtained.

New developments in the electron-atom collision physics – the spectroscopy of negative ions, had begun from the middle of 1960s. Schulz and others[1,2] have made an important contribution into the development of this problem. However, the processes of excitation and deactivation of atoms and molecules in the dense plasma occur, mainly, not from the ground state, but from the metastable and resonance levels. Therefore to carry out experiments on interaction of electrons with the metastable atoms becomes an urgent problem. Today the knowledge of the energy dependences of the differential cross sections of electron scattering has been obtained for the lower metastable states of O_2 (see Ref. 3) and resonance levels of Na (Ref. 4) and Ba (Ref. 5). From the set of atoms of the noble gases the spectra of electron scattering have been studied[6] for the case of scattering on metastable atoms of He.

The goal of this paper was to investigate scattering of slow electrons by the normal and metastable xenon atoms and to study the excitation functions of the resolved peaks.

The experimental technique

The experimental setup consisted of a vacuum chamber, source of metastable atoms, and a system for counting separate electrons (Fig. 1).

The vacuum chamber is made from the 1X18H9T stainless steel and is pumped out by two oil-vapor pumps P_1 and P_2 with the total rate up to 3000 l/s. It allowed one to provide, with using nitrogen traps, the residual pressure in the chamber of $\leq 10^{-7}$ Torr. A beam of xenon atoms was created by the metal multi-channel former (ABF) (with 100 channels, of 10-μm diameter, and the length of 1 mm) and was directed into the spectrometer to study the metastable atoms.

The spectrometer to study the metastable atoms consisted of a high-intensity electron gun, a block of capacitors, and two 127-degs electron selectors. Basic elements of the spectrometer are made from polished steel and a Ni-Cr alloy.

The electron gun with an oxide cathode and three plane electrodes having conical nozzles allowed one to obtain a beam with the intensity of 10^{-5}–10^{-3} A and energy of electrons from 0.6 to 30 eV with the half-width of the electron energy spread ΔE from 0.6 to 1.5 eV.

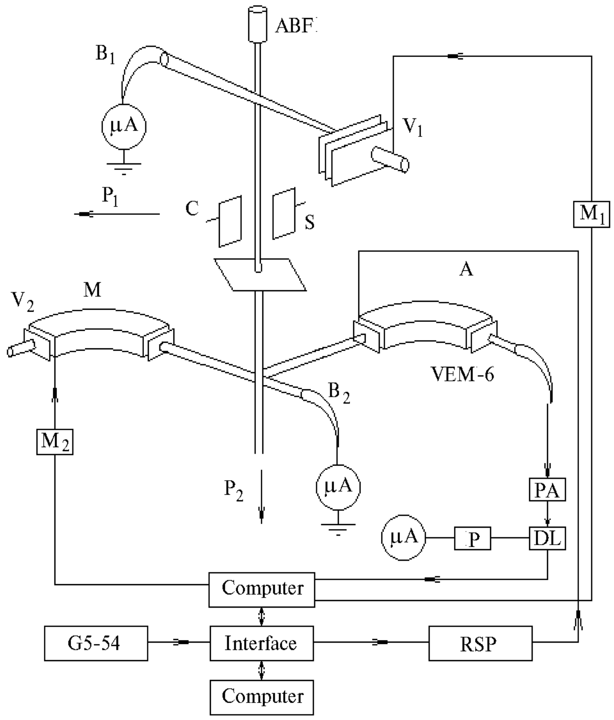

Fig. 1. Block-diagram of the experimental setup.

The capacitor and the diaphragm served to trap the charged particles, electrons and ions, from the atomic beam.

Two 127-degs electron selectors form the monochromator M and analyzer A, which are located at a 90° angle with respect to each other. The spread of slow electrons at the output of M equals to about 0.07 eV. The minimal energy of the electrons that passed the analyzer A equals to 0.1 eV with the angular resolution of 2.9°.

The scattered electrons passed the 127-degs selector were detected by a VEM–6 channel electron multiplier and were amplified by an amplifier (PA).

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The upper and lower discrimination levels (DL) were chosen to provide for the highest signal-to-noise ratio. From the output of the discriminator the pulses arrived at the electron computing device (ECD). The electron flux passed the analyzer contains electrons scattered by the Xe atoms in the ground state, Xe atoms excited into the metastable state, and molecules of residual gases. To separate the electron flux caused by scattering on metastable atoms, the pulsed control over the setup blocks was used. The pulse generator controlled the operation of the ECD and modulators M_1 and M_2. The rectangular shaped pulses from the generator were transmitted to the ECD control module, which initiated the modulators M_1 and M_2. The count of electron pulses from the output of the VEM–6 was carried out during the time set by the special generator (strobe-pulses) as it is shown in Fig. 2. If the control pulses correspond to Fig. 2 then 4 variants are available to perform counting of electron pulses from the VEM–6.

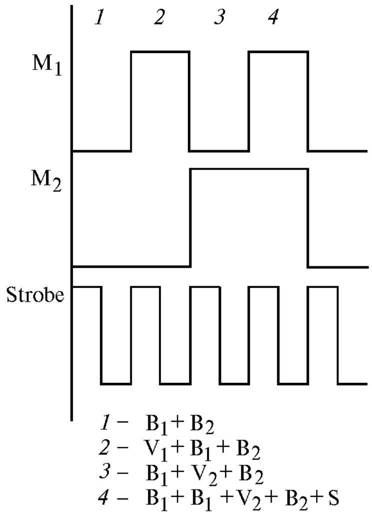

Fig. 2. The diagram of operation of the modulators and strobe to obtain a signal.

For example, if the modulator M_1 is off while the modulator M_2 is switched on (*3*), the signal accumulated at the strobe frequency corresponds to the electron scattering by normal Xe atoms and residual gas. The separation of a valid signal and total background B_1+ B_2 was carried out in the arithmetic module of the ECD during multiple cycles (minimum 8 cycles, maximum 8192 cycles) at the preset values of the energy of the electron spectrum scanning in M and A. The valid signal was received by the module of the ECD counter and through the interface entered into the online memory of the computer.

To test the serviceability of the experimental setup, the measurements have been carried out:

– the spectra of the energy losses of electrons by He atoms at the energies of collisions 10 to 50 eV;

– the energy dependences of the differential cross sections of the elastic scattering of electrons by He atoms (DSES) from the threshold value to the ionization boundary;

– the cross sections of the elastic scattering of electrons by He atoms with the calibration of energy scale by resonance at the energy of 19.35 eV (Fig. 3).

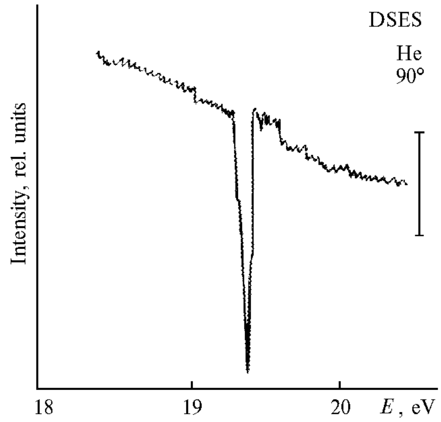

Fig. 3. The resonance $(1s2s^2)^2s$ in helium for the scattering angle of 90°.

The reliable reproducibility of the measurement results in He and agreement of the obtained data with another investigations allowed us to conclude that the designed setup corresponds to the general requirements to the experiment and provides a possibility of obtaining reliable information.

Results and their discussion

The typical spectrum of energy losses of electrons on the Xe atoms is presented in Fig. 4 where the elastic peak and the group of discrete lines are shown. The location of these lines is associated with the excitation of low levels of xenon atoms up to the ionization potential. The resolution of levels with the $n = 6$ is distinct, and the following maxima form groups of levels.

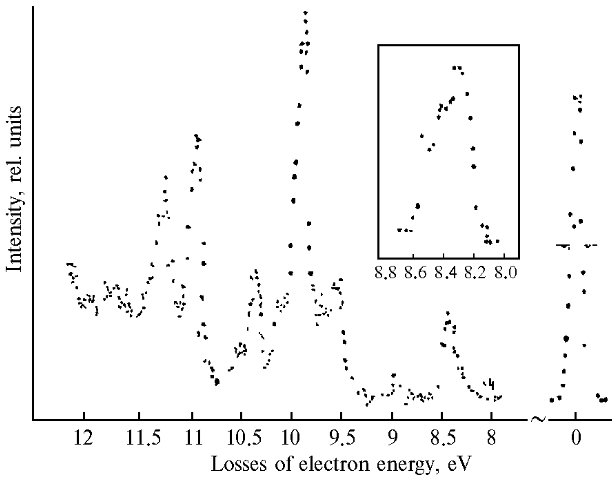

Fig. 4. The spectrum of energy losses of electrons on the Xe atoms.

For the isolated lines of the loss spectrum the relative differential scattering cross sections are measured. Figure 5 presents the differential cross section of the elastic scattering of electrons by the xenon atoms over a wide range of energies.

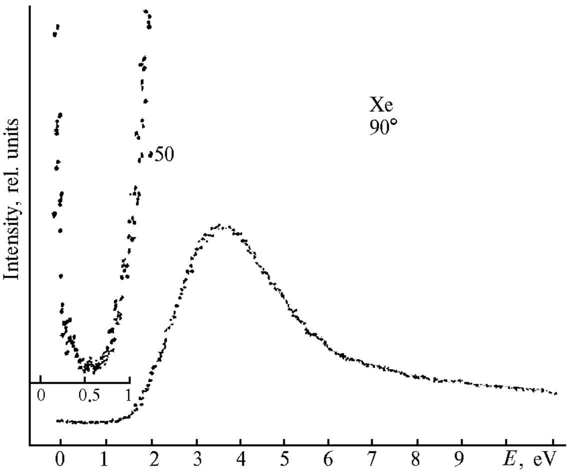

Fig. 5. The differential cross section of the elastic scattering of electrons by Xe atoms at the 90° angle.

In the region of low energies the resonance is isolated that forms a deep minimum. Its energy position equals to 0.51 eV. The initial state of this resonance is apparently an unexcited state of a xenon atom. In the differential cross sections of the inelastic scattering of the isolated levels the entire set of the resonance peculiarities is detected, which are revealed as maxima and their alternation. As an example the excitation function of the lower metastable level of Xe(6^3P_2) is presented in Fig. 6.

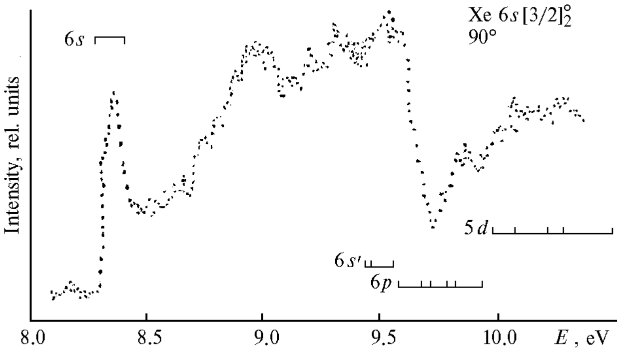

Fig. 6. The differential excitation cross section of the Xe($^3P_2$) level.

It is characteristic of the curve in Fig. 6 the presence of a sharp threshold maximum, which has a tendency to be split into 2 peaks. After the threshold of excitation and up to the ionization potential the entire groups of resonances are observed. The energy position of these resonances can be compared with the data of transmission measurements[1] and experiments by the threshold spectroscopy. The classification of the resonances has been carried out for the xenon atoms in Ref. 7. In this case within the jLS-connections the energies of states of negative ions were calculated. After that these energies were compared with locations of the observed resonances. The resonance classification was carried out using known spectra of the alkaline elements with the same number of electrons as the discussed ions. Five basic types of resonances were isolated: $np^5(n+1)s^2$, $np^5(n+1)s(n+1)$, $np^5(n+1)p^2$, $np^5(n+1)s(n+1)p$, and np^5ml^2. The resonance at the energy $E = (8.49 \pm 0.01)$ eV recorded in our experiments is classified as relating to the configuration of negative ions of the type $np^5(^2p_{3/2,1/2})(n+1)s(n+1)$. The Xe atom has a strong connection between the pair of the excited levels $ns[3/2]_2$–$np[1/2]_1$ and $ns[3/2]_2$–$np[3/2]_3$ because of both the short distance between them and their weak connection with the ground level. The large values of the matrix elements correspond to this case, it causes the resonance in cross section of the excitation of the $ns[3/2]_2$ level of xenon.

The next distinct resonance at the energy (9.64 ± 0.01) eV can be classified as relating to the configuration $np^5(^2p_{3/2,1/2})(n+1)p^2$. This resonance has a much complicated behavior, moreover, this resonance is split into 3 peaks, what is explained by the change of the interference contribution of the direct and resonance scattering cross sections.

The interpretation of the abundant structure in the presented excitation cross section within other energy ranges also indicated to the principle role of negative ions in the collision of electrons with the xenon atoms in the ground state. Note that more reliable results have been obtained by Rea et al.[7] with the method of threshold spectroscopy which was developed at the Manchester University for measuring the total scattering cross section of metastable atoms using the computer processing of the experimental results. First, the positions of the isolated resonances have been recorded with the accuracy up to 0.001 eV and then a set of new states of negative ions of the noble gas atoms has been isolated. Certain deviations in the energy positions of maxima as compared with our curve are explained by the angular dependence in the differential scattering cross sections. The abundance of resonances in Ref. 7 is obtained by processing the portion of the spectrum from 10 to 13 eV with the computer by the method of the square function of two curvatures, although at the experimental curve there were observed much less number of maxima. A plot of characteristic electron spectrum obtained for the electron scattering by the metastable atoms of Xe($^3P_{2,0}$) is shown in Fig. 7 by dots.

The spectrum presented is a result of three passes in which the spikes of signal intensity, which are caused by the failures in the recording device, are automatically detected and removed. A spread of the experimental points is at the level of a valid signal. Therefore, the solid resultant curve is presented at the same plot. This curve is obtained by the method of smoothing the spectrum portion involving five points to separate true signal from the ordinary statistical noise.

We interpret the obtained spectrum in the following way. The maximum in the energy region near zero corresponds to the elastic scattering of electrons by metastable xenon atoms. The maximum which is located at the energy 8.5 eV corresponds to the hyper-elastic collision: $Xe(6^3P_{2,0}) + e \to Xe(5^1S_0) + e + E$. To obtain high concentrations of an electron beam, the monochromator transmission for electrons has been especially increased in these experiments, therefore no other processes and transitions were observed. The experiments carried out at the energies of an electron beam, which are more than 19 eV show that with the increase of energy a considerable reduction of a signal from the hyper-elastic collision is observed. It is connected with a general regularity in the behavior of the cross sections of the collisions of the second kind as function of energy. Note that the intensity of a signal from the collisions of the second kind is ten times smaller than the intensity of the signal due to elastic scattering of electrons by the metastable xenon atoms. The value of the amplitude of the elastic peak decreases with the increase of the energy of slow electrons following the law of $q_{el} \sim E^{-3}$, that does not contradict the theoretical calculations by Robinson.[8]

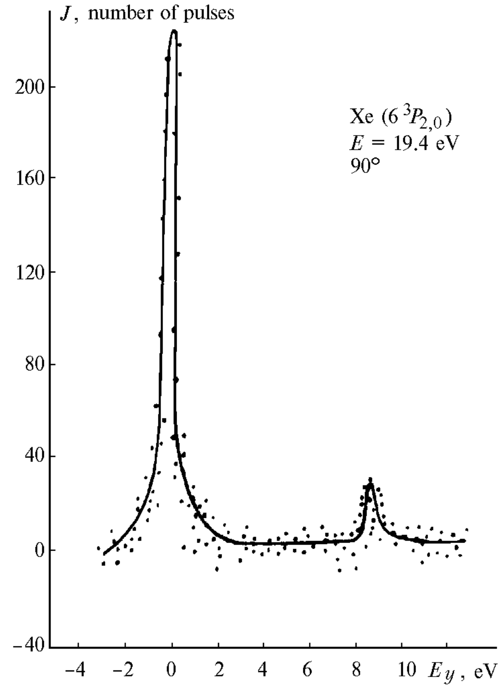

Fig. 7. The energy spectrum of electrons scattered by the lower metastable atoms Xe ($^3P_{2,0}$) at the angle 90°.

To automate the processing of the obtained data, a complex of programs has been developed. It allowed us to filtrate the data of a plot, digitize a plot, and smooth the data by numerical methods. Then the obtained data array has been processed by formula of detailed equilibrium (Klein and Rosseland formula)

$$Q_{21} = Q_{12}\, g_1(E_{ex} + E)/(g_2 E),$$

where Q_{21} is the effective cross section of the inelastic collisions of the second kind; Q_{12} is the effective cross section of the inelastic collisions of first kind; g_1 is the statistic weight of the ground level; g_2 is the statistic weight of the metastable level; E is the energy of slow electrons; E_{ex} is the excitation energy of the metastable level.

Figure 8 presents the de-excitation cross-section calculated for the angle 90° by the Klein and Rosseland formula based on the measured differential excitation cross section of the level $Xe(6^3P_2)$.

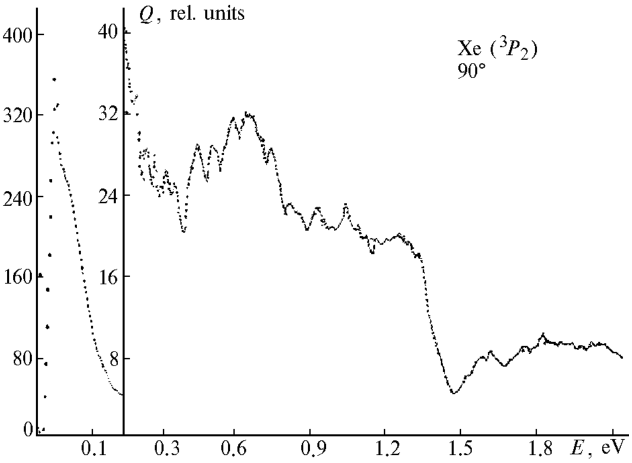

Fig. 8. The de-excitation cross section of $Xe(6^3P_2)$ for the angle 90°.

One can see from Fig. 8 that in the energy dependence of the de-excitation cross section the resonance structure is revealed, it is explained by the rise of negative ions and their decay into the lower states. It is confirmed by the data of their life times, which were determined by the width of resonance at the curve of the de-excitation cross section. Note that the obtained values of the resonance position allow them to be classified as well as the Feshbach resonances and the shapes proposed by Schulz in the transmission experiments on electron scattering by the atoms in the ground state.

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