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Ion Mixing and the Numerical Simulation of Different Ions Produced in the ECR Ion Source

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Abstract

This paper is the continuation of theoretical investigations and numerical simulations in the physics of ECR ion sources within the CERN programme of heavy ion acceleration. The gas (ion) mixing effect in ECR sources is considered here. It is shown that the addition of light ions to the ECR plasma has three different mechanisms to improve highly charged ion production: the increase of confinement times and correspondingly charge states of highly charged ions as the result of ion cooling; the concentration of highly charged ions in the central region of the source with high energy and density of electrons; the increase of electron production rate and accordingly the density of plasma.

The numerical simulations of lead ion production in the mixture with different light ions and different heavy and intermediate ions in the mixture with oxygen are carried out to predict the principal ECR source possibilities for LHC applications.

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1. Introduction

Lead ions were accelerated in the PS and SPS of the CERN accelerator complex last year. An Electron Cyclotron Resonance (ECR) source for lead ions was constructed in GANIL (France) and installed two years ago in the PS Division. The Large Hadron Collider project was adopted at the end of 1994 at CERN. The physics program of LHC will include investigations with beams of protons and lead ions. The acceleration of some other heavy and intermediate ions in the LHC is under consideration.

A program of theoretical investigations into the physics of ECR ion sources was started in the Joint Institute of Nuclear Research, Dubna in 1993 and was continued last year at CERN, Geneva. The recent results of this program included[1,2)] the development of the physical model of ionization and accumulation of ions in the ECR source, the creation of a computer code library for the numerical simulation of heavy ion production in the static and dynamic regimes of the ECR ion source, the computer simulation of the highly charged ion production in the ECR source and proposals for the improvement of highly charged ion output from the ECR ion source.

Like some ECR ion sources the source at CERN operates in the afterglow mode (pulse regime) using a gas (ion) mixture with oxygen. The gas mixing is an effective method of source operation and highly charged ion production. A study of the gas mixing effect and the numerical simulation of production of different ions in the ECR source is the subject of this paper.

2. The condition of ECR plasma neutrality

The ECR plasma has a density in the range of 10^{12} cm^{-3}. The condition of electromagnetic wave propagation limits the electron density in the plasma

$$n_e \leq \frac{\omega_{ce}^2}{4\pi r_e c^2} \approx 1.24 \cdot 10^{-8} f^2 \qquad (1)$$

with ω_{ce} being the rotation frequency of the electron in the magnetic field; r_e the classical radius of electron; c the velocity of light; f corresponds to the plasma heating frequency in Hertz. The limit (1) is more than 10^{12} cm^{-3} for the radio frequency of heating in the range of 10 GHz. This value can be used for the rough estimation of plasma density in the ECR source.

Positive ions neutralize the space charge of electrons to prevent the appearance of high electrical and magnetic fields in the plasma. One can consider the plasma as neutral or quasineutral in every point of its volume. This follows from the condition:

$$\sum_{i=1}^{Z} i\, n_i - n_e = 0 \tag{2}$$

here n_i are densities of ions with different charged states i, Z is the maximum charge of ions in the plasma. If there is a mixture of ions of different elements in the plasma then it is necessary to sum up all ion species and in a case of several electron components with different parameters all electron densities as well.

The time conservation of condition (2) in the static case is the cause of equal flows of ions and electrons from the plasma:

$$\sum_{i=1}^{Z} \frac{d(i\, n_i)}{dt} - \frac{dn_e}{dt} = 0 \tag{3}$$

The particle losses are determined by lifetimes or confinement times of particles in the plasma. The complete set of balance equations of ion and electron densities in the ECR source[3] gives us the following well known expression

$$\sum_{i=1}^{Z} \frac{i\, n_i}{\tau_i} - \frac{n_e}{\tau_e} = 0 \tag{4}$$

with τ_i being confinement times of ions and τ_e electron confinement time correspondingly. These values were determined earlier in Ref. 1,2,3.

3. Ion Mixing

It has been discovered experimentally that the addition of light ions increases the extraction of multiply-charged heavy ions in the ECR sources (for example Refs. 4 - 7). The role of light ions in the plasma is not completely clear at the moment and they probably have a number of roles. Let us consider the most important of them.

Ion cooling. The Maxwellian velocity and Boltzman energy distributions are established in the plasma due to the intensive elastic Coulomb collisions among the ions. It has been shown[3,8,9] that the ion energy redistribution and temperature stabilization times have a microsecond time scale, much less than the millisecond time scale of ion lifetimes in the ECR plasma.

The ions have much less average energy or temperature T_i than the electron temperature T_e in the source and their confinement conditions in magnetic mirrors are worse. A negative plasma potential U appears when ions leave the trap and this regulates the rate of ion loss. Ions with an energy more than the potential barrier will be lost from the plasma volume. The different ion charge states of i have different values of the potential barrier ieU. So the various ions have equal temperature but different potential barriers in the plasma and different rates of loss from the source. The rate of ion losses can be described with the Pastukhov theory10).

This situation is shown schematically in Fig.1, where potential barriers are presented for different charged states with equal temperature.

The electrons heat the light ions more slowly than the heavy ions in the mixture of different ion species. But the light ions are heated due to the elastic collisions with highly charged heavy ions and their mean energy comes closer to the energy of heavy ions. The low charged ions have a low potential barrier and short lifetime in the plasma and, therefore, are lost from the source taking away the energy of the heavy ions. The decrease of the heavy ion temperature causes the rise of the heavy ion lifetimes and their mean charge grows correspondingly in the source. These are the principles of so called "ion cooling" effect9).

Concentration of heavy ions in the center of ECR plasma. The recent X-ray measurements11,12) have shown that electrons in the ECR source have maximum energies and density in the central region of the plasma. According to the above consideration and numerical simulation, the energies of cooled highly charged ions are much less than the potential barrier in the plasma. Therefore the amplitudes of heavy ion oscillations in the potential well are much less than the plasma dimensions. This means that highly charged ions are concentrated at the bottom of the potential well in the middle of the ECR source where the density and energy of electrons are higher. This can be an additional factor that is able to explain the improvement of highly charged ion production in the mixture of heavy and light ions.

Electron production in the plasma. The electron density is one of the most important parameters in the plasma that determines the sources capability for ion production. It depends strongly on the rate of electron production in the plasma.

The electrons are generated as the result of electron impact ionization of neutral gas and ions in the source chamber. A set of coupled balance equations describes the rate of electron production as well as ion production in the source[3)]. The balance equation for electron component in the plasma is:

$$\frac{dn_e}{dt} = \sum_i n_e v_e \overset{i}{\sigma_i} (v_e)\, n_{i-1} - \frac{n_e}{\tau_e}, \qquad (5)$$

where $\overset{i}{\sigma_i} (v_e)$ are the cross-sections of electron impact ionization as a function of electron velocity. It is necessary to use the average value $< \sigma_i v_e >$ here. One can obtain it as a result of the integration with the distribution function of electron energy. The rate of electron production depends on ionization cross section and density of ions and neutrals in the plasma according to the equation (5).

Different theoretical models are in use for calculation of ionization cross-section for highly charged ions as well as for low charged ions and neutral atoms or molecules too. Lotz's formula is one of the most useful for calculating cross-sections for low energies[13)].

$$\overset{k}{\sigma_i} = \frac{4.5 \cdot 10^{-14}}{E_e} \sum_{j=1}^{m} \frac{n_j}{I_j} \ln \frac{E_e}{I_j} \qquad (6)$$

with m being the number of atomic subshells occupied in the ion, n_j the number of electrons in the sub-shell considered and I_j the ionizing energy of actual sub-shell in eV.

The calculated cross sections of electron impact ionization of Pb, Xe, Kr, Ar and O using the Lotz's formula are presented in Fig.2. The calculations were made for the Maxwellian distribution of electron energy with the temperature $T_e = 5000$ eV. One can see, that the dependence of impact ionization cross-section on the ionic charge state is very marked.

The typical energy of electrons in the ECR plasma, in the range of several keV, is enough to produce heavy ions of 20+, 30+, 40+ and even higher charge states[2)]. The average charge state $<i>$ of ions increase after the plasma ignition due to the step-by-step ionization. Here

$$<i> = \sum_{i=1}^{Z} i\, n_i \,/\, \sum_{i=1}^{Z} n_i$$

The total density of ions n ($n = \sum_{i=1}^{Z} n_i$) in the plasma decreases simultaneously to satisfy the condition of plasma neutrality (2). Therefore the rate of electron production dramatically decreases with the increasing of $<i>$ due to the reduction of ionization cross-section and total ion density. The electron density in plasma decreases after reaching a maximum before seting to an equilibrium in the static regime of source operation. The equilibrium electron density is much less than the limit of wave propagation in the plasma (1). According to numerical simulations this effect is very strong especially for the plasma of pure heavy ions. This is why different sources of additional electrons are used to increase the plasma density and improve the highly charged ion production. The most effective are biased electrodes and ion mixing with light ions.

Light ions increase the electron production in plasma. In the mixture of heavy highly charged ions and light low charged species the heavy ions are cooled and light ions are heated due to the elastic Coulomb collisions[9]. Thus the ion cooling effect acts as a heating effect for light ions. Therefore light ions have very low lifetimes and keep a low average charge state $<i_l>$ in the equilibrium plasma. According to our numerical simulations the $<i_l>$ is in the range of 1+ to 3+ depending on the relation of atomic masses of light and heavy ions. Low charged ions also have a high ionization rate and produce a lot of secondary electrons to feed the plasma.

Fig. 3 and Fig. 4 show the calculated total number of light (series 1) and heavy (series 2) ions in the source chamber. These figures also present the relative factor of plasma neutralization by heavy ions F, with

$$F = \sum_{i=1}^{Z} i\, n_i \,/\, n_e$$

Densities of heavy ions only are summed up here. All calculations were done for ECR4 ion source parameters. This type of source is used for Lead ion production in CERN. It has the following parameters: Length of the plasma volume l = 20 cm; diameter of the plasma volume d = 6.5 cm; magnetic field mirror ratio R = 2.5. The values of the electron temperature T_e = 5000 eV and electron density $n_e = 5 \cdot 10^{11}$ cm^{-3} were used in the calculations. The density of heavy neutrals outside the plasma volume was $2 \cdot 10^{8}$ cm^{-3} and light neutrals $4 \cdot 10^{10}$ cm^{-3}.

One can see in Figures 3 and 4 that light ions with low charge states are the main component of the ions in the plasma. The ionization of light ions and neutrals is the main source of electrons in the plasma according to equations (5) and (6) and Fig.1. Light ions have low life times (in the range of 0.1 to 0.3 ms) in keeping with conditions (3) and (4). On the other hand, the space charge of heavy ions dominates and regulates the neutrality of plasma according to the condition (2) as it is possible to see with series 3 in Figures 3 and 4. It is necessary to keep the density of light ions much higher than the density of heavy neutrals for good ion cooling and electron refilling in the plasma.

4. Numerical simulation of ion production in the different mixtures

The calculation of charge state distribution (CSD) of Lead ions in the so-called afterglow mode of source operation is shown in Fig. 5 in comparison to the one of typical experimental CSD of the ECR source at CERN. These calculations and the above parameters of the source were used as a "base variant" for numerical simulations in Ref.2, which shall be used to present calculated data.

According to West[14)] the ion current density for the different charge states leaking through the end of the source can be evaluated as

$$j_i = e\, i\, n_i\, V / (2\, S\, \tau_i)\ (A\ cm^{-2}) \qquad (7)$$

Here S is the surface area of the end and V the volume of the plasma. This formula gives the extracted current for a source extraction hole of 1 cm diameter as

$$I_i = e\, i\, n_i\, l / (2\, \tau_i)\ (A) \qquad (8)$$

where l is the length of plasma region. And the output current in the afterglow can be estimated accordingly

$$I_i = e\, i\, n_i\, l / (2\, \tau_p)\ (A) \qquad (9)$$

where τ_p is the duration of afterglow pulse.

The numerical simulations of afterglow regime in Ref. 2 are in good agreement with the experimental data (Fig. 5), but the shape of the calculated pulse of ion current is not the same as the best experimental pulses of stable afterglow[15)]. These experimental pulses have a long tail with decay time of 2 to 3 ms. The calculated pulses of heavy ion afterglow have a duration of less than 1 ms and an amplitude that is 2 or 3 times greater.

The duration and shape of the ion pulse in the afterglow are determined by the plasma destruction time as a result of electron loss without RF heating. The electron confinement time in the open magnetic trap and loss from the source depends strongly on the electron energy. The model for numerical simulation uses the Maxwellian distribution for electrons with fixed temperature of several keV. The real energy distribution in the ECR plasma is rather complicated and is not thoroughly determined at the moment. X-ray spectra measurements show the presence of electrons with energies of up to 100 keV. These high energy electrons have a long life time in the open magnetic trap and probably determine the long tail of the output ion current in afterglow. It will be necessary to use the electron energy distribution with different electron components as the next step in the improvement of the model.

When the RF power is switched off and the electrons begin to be lost then the electron density reduces, the negative potential which traps the ions disappears and ions escape from the trap as so-called afterglow. The CSD of the output ion current in afterglow reflects the CSD of accumulated ions in the equilibrium plasma before the switch off of the RF power. The numerical simulation of ion ionization and accumulation in this plasma gives us information on ion densities or total number of ions of all charge states in the source and enables us to estimate how many ions the source will produce during the afterglow.

Numerical simulation of lead ion production in the mixture with different light ions. Different light ions have different abilities to cool heavy ions and produce secondary electrons to feed the plasma. Different light neutrals have different ionization potentials and accordingly different rates of charge exchange with highly charged ions. According to a previous paper$^{2)}$, the charge exchange process is very dangerous for heavy ions and limits the production of highly charged ions. A series of numerical simulations of the lead ion accumulation in the CERN-like ECR source was carried out to study the effect of different light ions in the mixtures. Figures 6 to 13 present the CSD of lead ions in ECR source in the mixture of different light ions from He up to Ar. All CSD are given in comparison with the "base variant" of Pb - O mixture$^{2)}$. It is necessary to note that we do not discuss here the technical problems of the experimental realization these ion mixtures, for example Pb + F or Pb + Al mixtures.

Figures 6 to 13 show the dependence of lead CSD on the type of second light ion in the source. The location of the CSD maximum depends on the rate of charge exchange processes in the plasma according to the Ref.2. Neon and argon mixtures give the highest charge states due to the high ionization potential of the neutral atom. The improvement of production of highly charged lead ions has been investigated during a short experimental test of "neon cooling" in August 1995 at CERN ECR source[16] but confirmation of this result is needet.

On the other hand, the amplitude of CSD, or the number of ions in the maximum of distribution, decreases with the increase of the average charge state $<i>$. Two factors are able to explain this phenomenon: the higher value of $<i>$ require a lower value of total ion number n according to the condition of neutrality of plasma (2) and the CSD with higher values of $<i>$ are usually wider and therefore have a lower density in every charge state.

Numerical simulation of heavy and intermediate ion production in the mixture with oxygen ions. The accelerator complex at CERN produces lead ion beams for experimental application in high energy physics. Oxygen and sulphur were used for this purpose some years ago. The new LHC project at CERN foresees ion beams of different heavy and intermediate elements. A series of numerical simulations of different ion production in the ECR4 type source were carried out to predict the possibilities. Figures 14 to 23 present the CSD of different ions from Ca up to U in the ECR source in the mixture with oxygen. All CSD are given in comparison with our "base variant" of Pb - O mixture.

Figures 14 to 23 show the strong dependence of CSD on the type of ions in the source. The heavier ions have higher charge states and lower number of ions in the charge state with maximum density. For example, the ECR source is able to produce 3 or 4 times more ions of calcium or iron with charge states of 12-15 than uranium, thorium or lead ions with 26-28. The explanation used above could be used here to explain this phenomenon.

5. Conclusions

The continuation of theoretical investigations and numerical simulations in the physics of ECR ion sources according to the CERN program of heavy ion acceleration is presented here. The ion mixing effect in ECR sources is considered in this paper using a new approach. It was shown that the addition of light ions to the ECR plasma improves highly charged ion production not only due to the well known ion cooling effect, but also due to the increase of electron production rate and consequently the density of plasma. The concentrating highly charged ions in the central region of the source where there is a high energy and density of electrons also has an effect.

The numerical simulations of the production of different heavy and intermediate ions in the ECR source have shown the difference in CSD and source efficiency for different ions and will be probably useful in the ionic part of LHC project at CERN.

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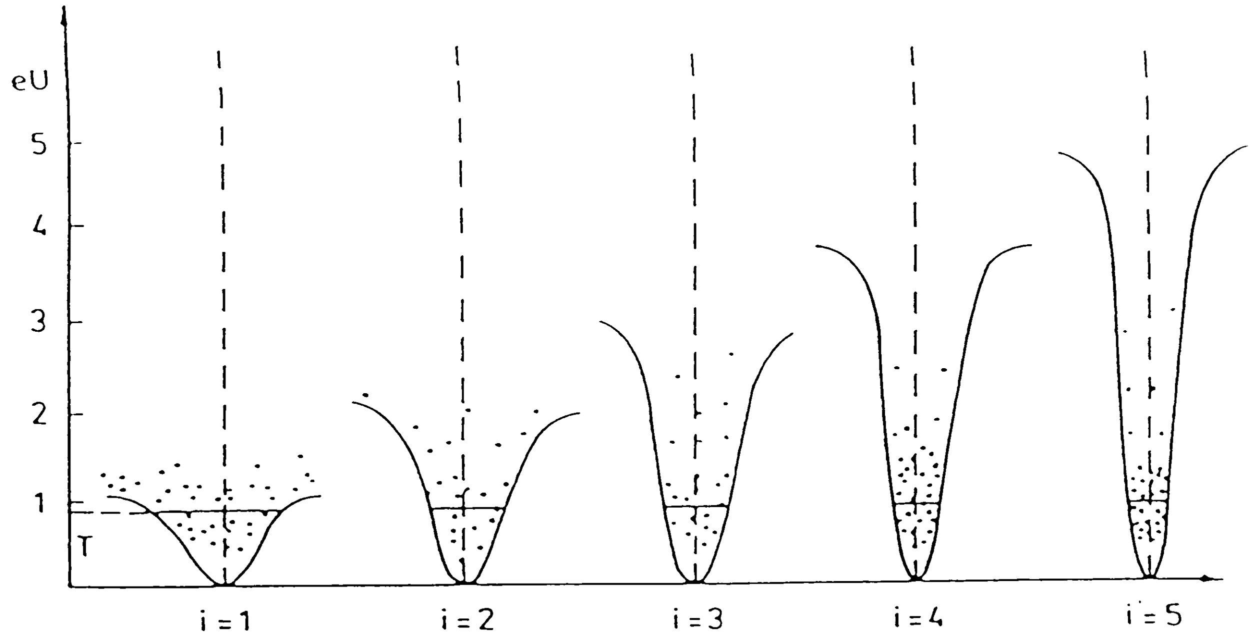


Figure 1. Relative position of ions with charge states i =1,2,3,4,5 at equal temperature T_i in a potential well of depth U.

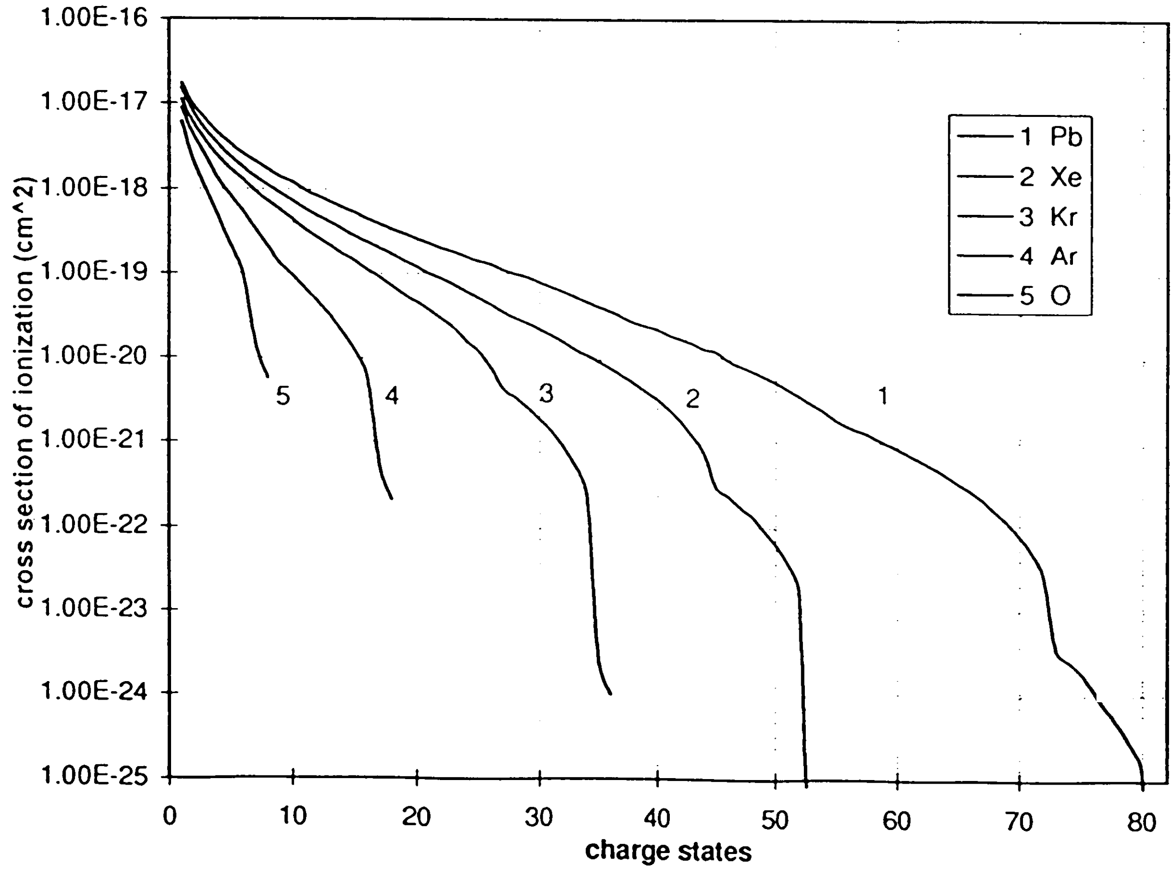


Figure 2. Calculated cross sections of electron impact ionization of Pb, Xe, Kr, Ar and O

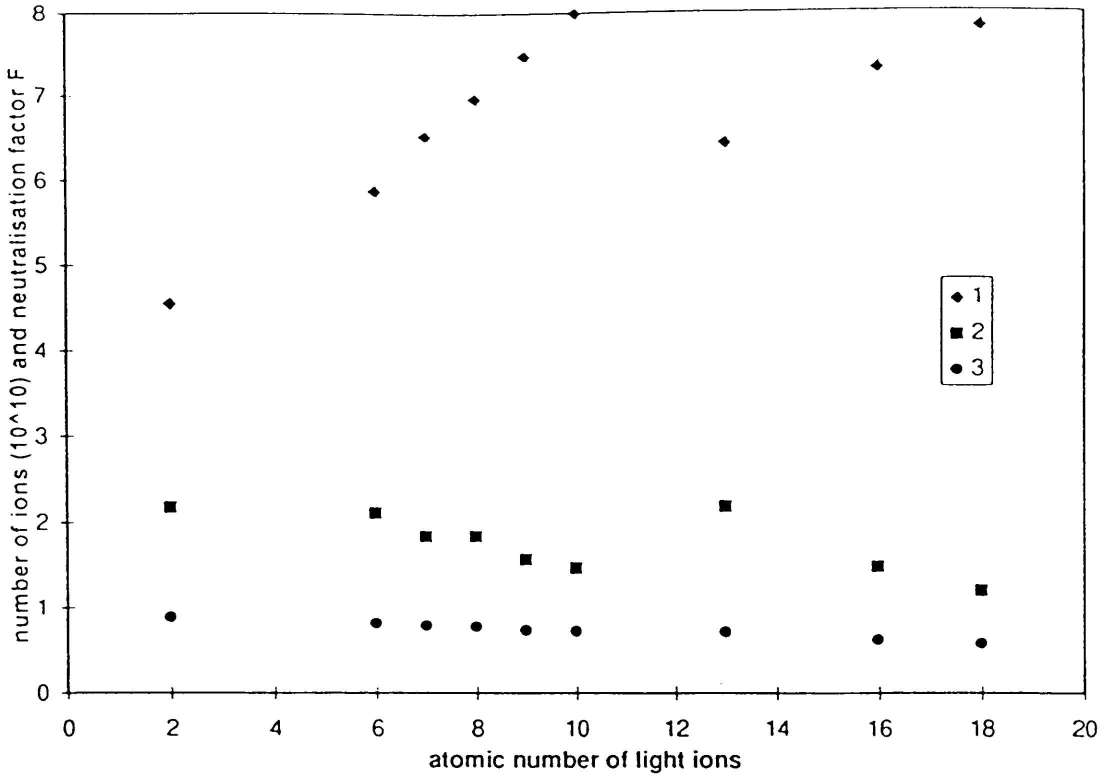


Figure 3. Calculated total number of light (series 1) and lead (series 2) ions in the source chamber. The relative factor of plasma neutralization by lead ions F (series 3).

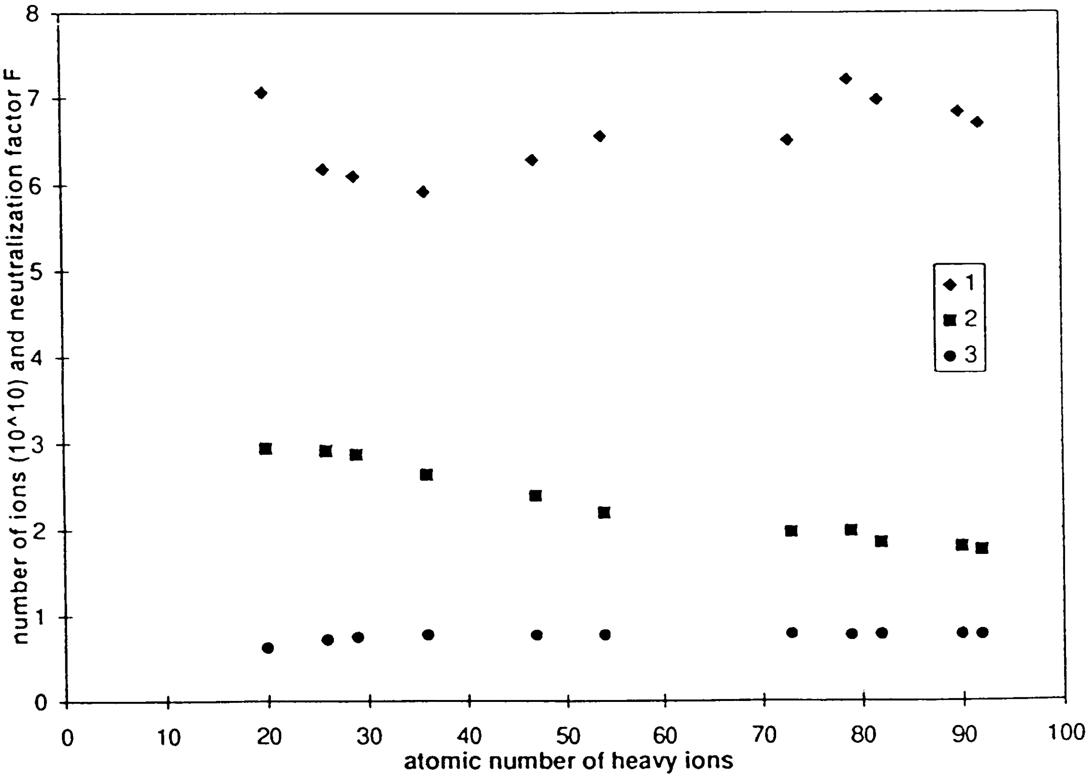


Figure 4. Calculated total number of oxygen (series 1) and heavy (series 2) ions in the source chamber. The relative factor of plasma neutralization by heavy ions F (series 3).

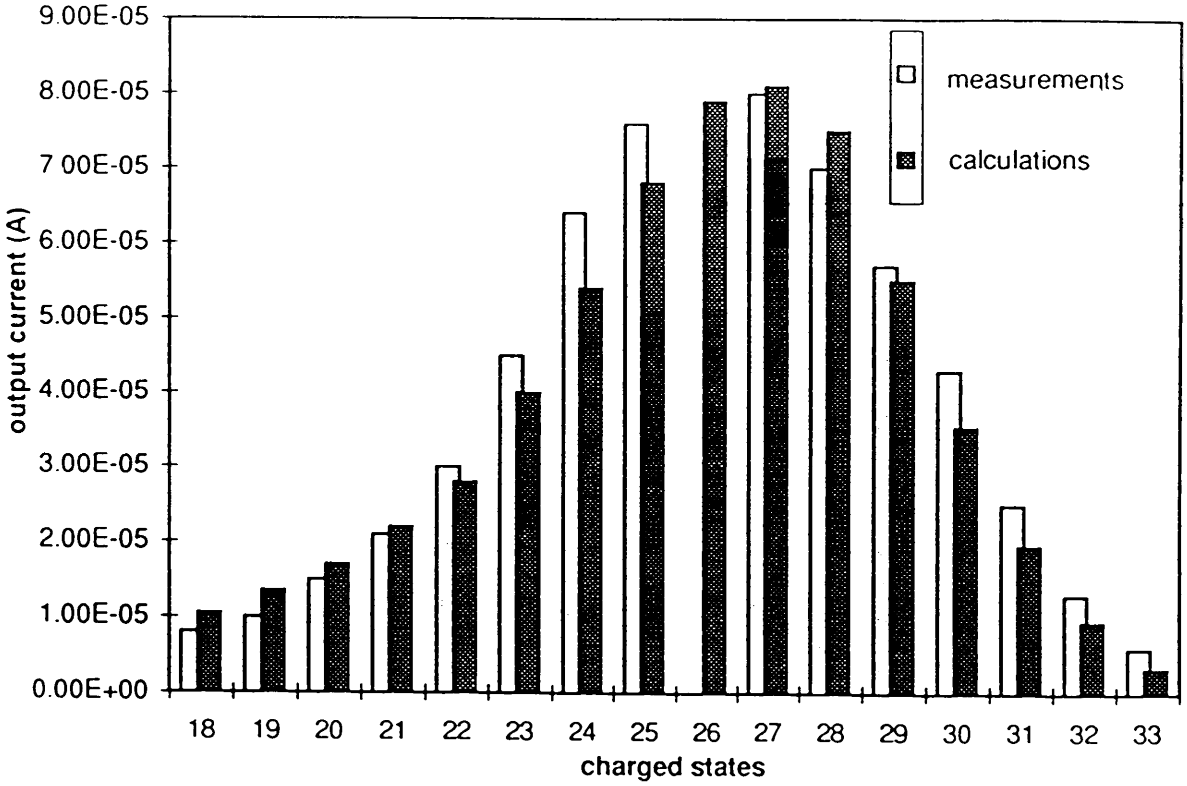
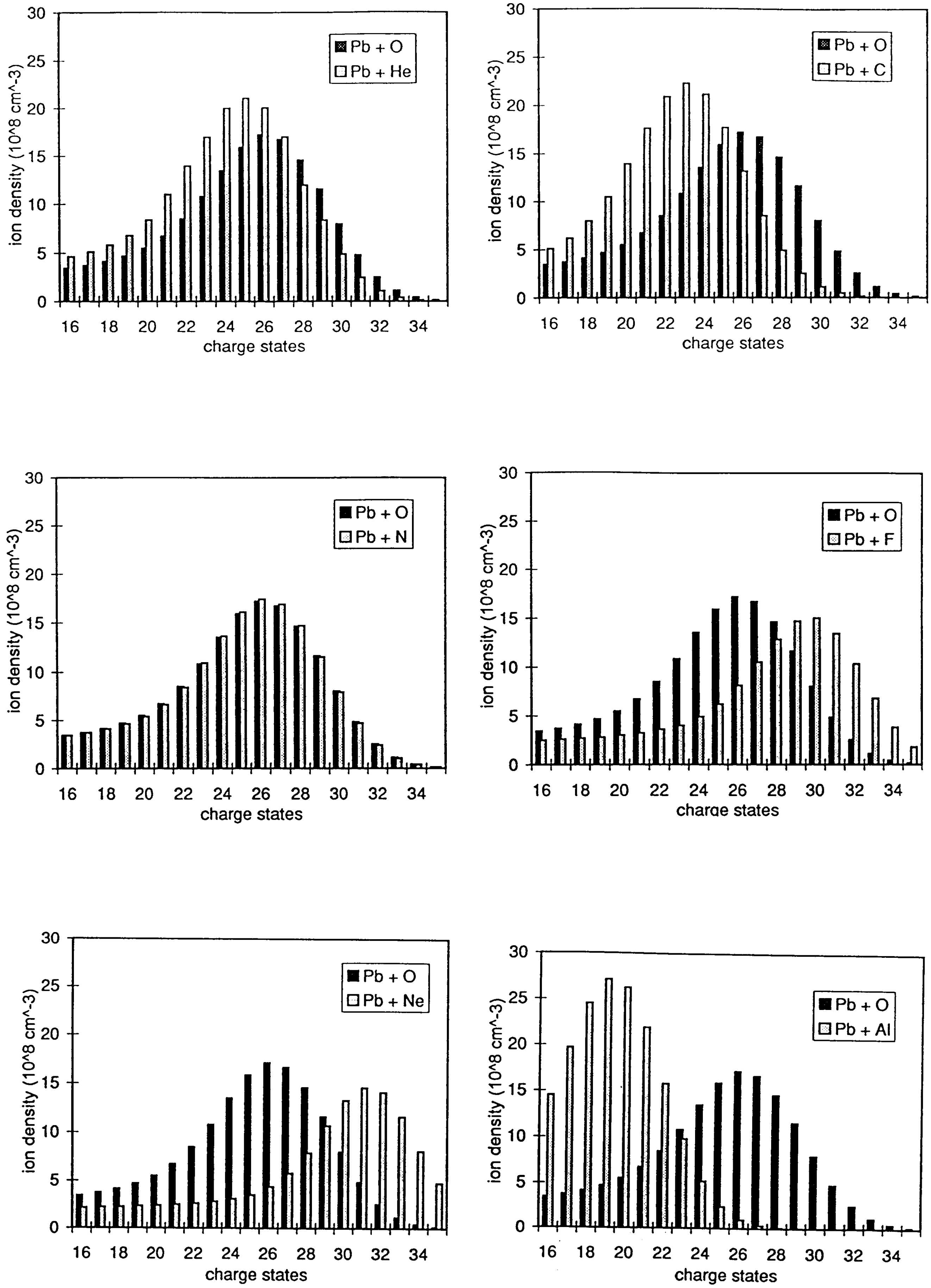
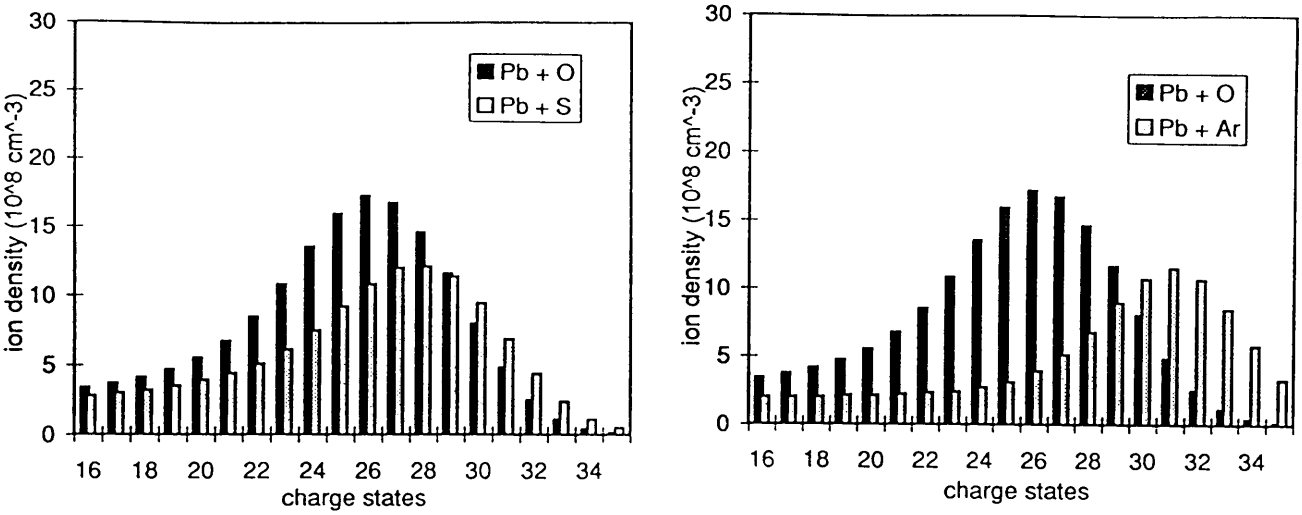


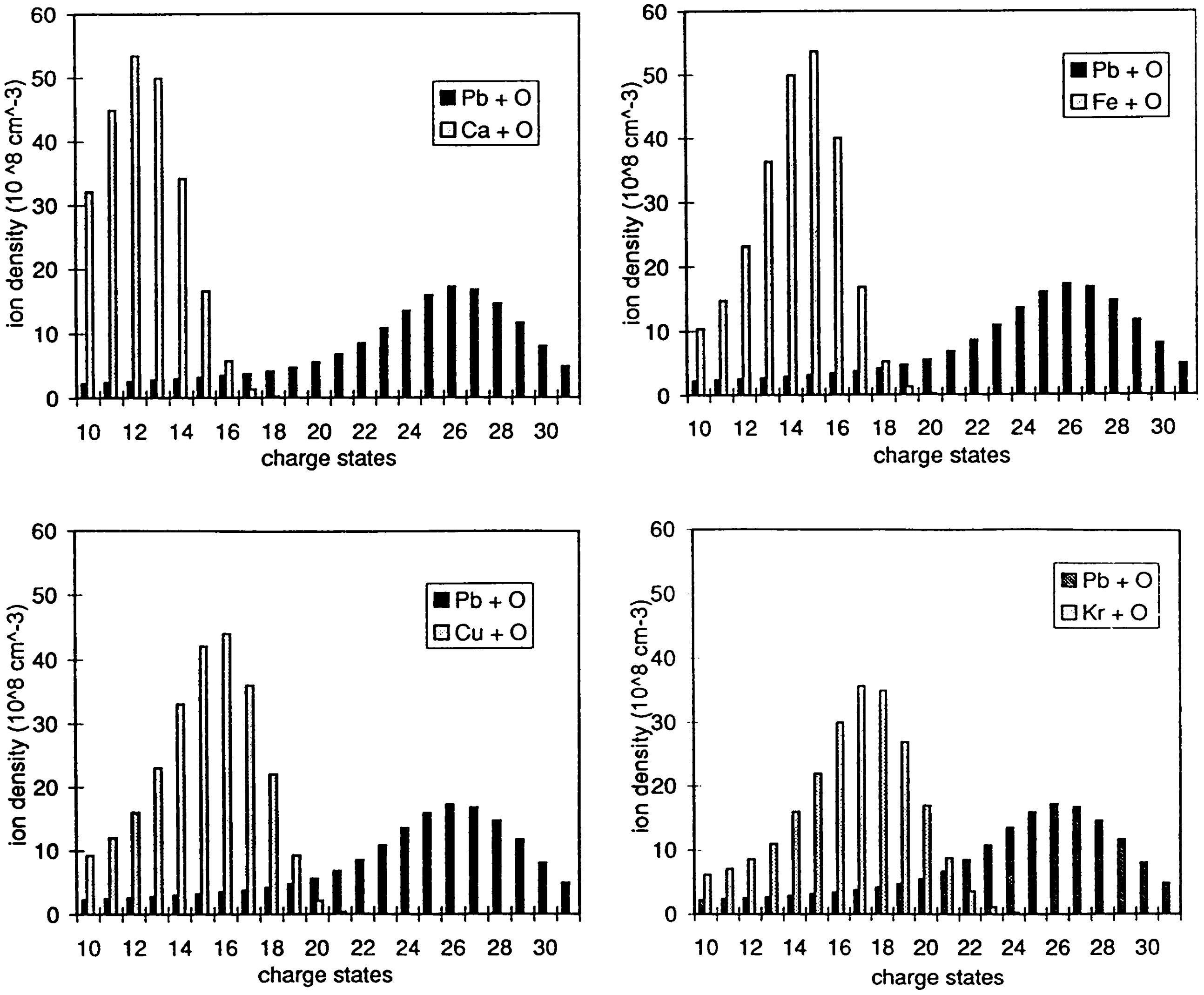
Figure 5. Calculated charge state distribution of lead ion in the afterglow mode of ECR ion source in comparison with experimental data



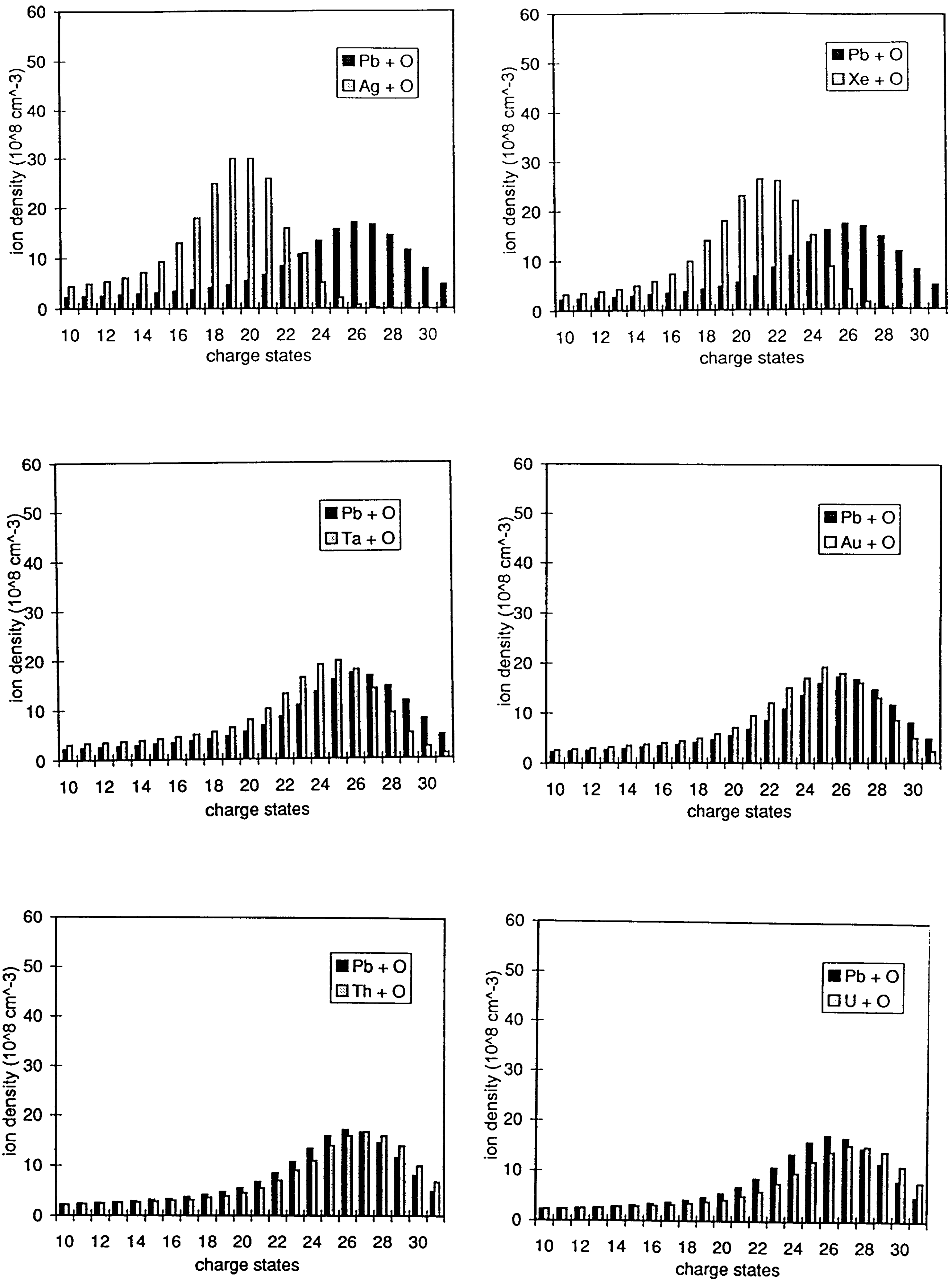
Figures 6 - 11. Calculated CSD of lead ions in the ECR source in the mixture with He, C, N, F, Ne and Al in comparison with “base variant” of Pb - O mixture.



Figures 12, 13. Calculated CSD of lead ions in the ECR source in the mixture with S and Ar in comparison with "base variant" of Pb - O mixture.



Figures 14 - 17. Calculated CSD of Ca, Fe, Cu and Kr ions in the ECR source in the mixture with oxygen in comparison with "base variant" of Pb - O mixture.



Figures 18 - 23. Calculated CSD of Ag, Xe, Ta, Au, Th and U ions in the ECR source in the mixture with oxygen in comparison with “base variant” of Pb - O mixture.