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E7 - 11546

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Исследование эффекта Пеннинга в плазменном ионном источнике магнетронного типа

Изучался вопрос влияния эффекта Пеннинга на увеличение ионизации атомов ртути в ионном источнике магнетронного типа в нескольких инертных газах (He, Ar, Xe).

Произведен анализ полученных экспериментальных данных и проведено сравнение с теоретическими предпосылками. Сделаны выводы, имеющие практическое значение для разделения изотопов на электромагнитном сепараторе.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1978

Mączka D., Gromova I.I., Žuk W. E7 - 11546

Investigation of the Penning Phenomenon in Magnetron Ion Source Plasma

The influence of the Penning phenomenon on He atom ionization in the plasma of a magnetron ion source has been studied by means of an electromagnetic isotope separator at the Laboratory of Nuclear Problems, JUNR, Dubna [1]. The analyses of processes taking place in the source have been carried out and the obtained results compared with theoretical predictions.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1978

1. INTRODUCTION

In a number of cases and particularly in the separation of radioactive isotopes, as a rule, it is necessary to supply the source - apart from the material subject to separation - with a gas carrier to secure stable discharge conditions in a discharge chamber [2]. This fact offers a possibility of increasing separation efficiency by utilizing not only electron ionization, but also other kinds of collisions, e.g., the collision of atoms of a separated sample with metastable atoms of the gas carrier

$$A^m + B \to A + B^+ + e + \Delta E, \qquad (1)$$

where A^m is a metastable atom of the gas carrier, B is an atom of the separated sample.

The process represented by eq. (1) is called Penning ionization and it takes place when the ionization energy of sample atoms is less than that of the metastable state of atoms of the gas responsible for stable discharge in the ion source [3].

The aim of this experiment was to investigate the influence of the Penning effect on the currents of Hg^+ ions emitted from discharge plasma burning in He or Ar mixtures. Similar measurements were carried out for the source operating on Xe, i.e., gas with which additional Hg ionization as a result of the Penning effect is impossible (see the *table*).

Table

Atom	Ionization energy (eV)	Ionization cross section with electrons of E=230 eV (cm^2)		Metastable state energy (eV)	
Hg	10.4	4.5×10^{-16}	/4/		
He	24.6	2.79×10^{-17}	/5/	20.6	($2\ ^1S_0$)
				19.8	($2\ ^3S_1$)
Ar	15.7	1.85×10^{-16}	/5/	11.5	($3P_2$)
		1.97×10^{-16}	/6/	11.7	($3P_0$)
Xe	12.1	3.44×10^{-16}	/5,7/	8.3	($3P_2$)
				9.5	($3P_0$)

2. *THE ANALYSIS OF PROCESSES IN THE ION SOURCE*

Let us assume that as a result of the ionization of neutral atoms of the gas carrier as well as of the sample atoms stable plasma is produced in the source where the ion concentration of the sample and the gas carrier is n_d^+ and n_n^+, respectively.

Assume also that ion losses through the extraction of the source are negligible and that plasma is poorly ionized, i.e., $n_d^+ \ll n_d$ and $n_n^+ \ll n_n$. In such a case the state of the plasma thermodynamic equilibrium can, in the first approximation, be formulated as follows:

for ions of the sample:

$$\left(\frac{j_e}{e}\sigma_d n_d + \alpha\, n_n^m n_d\right) v = \frac{j_d^+}{e} S \qquad (2a)$$

for ions of the gas maintaining the discharge:

$$\frac{j_e}{e}\sigma_n n_n v = \frac{j_n^+}{e} S, \qquad (2b)$$

where j_e is density of electron current, σ_d, σ_n are ionization cross sections with electrons, n_d, n_n are concentrations of atoms of the sample and the gas carrier, α is the coefficient of the Penning effect, v is volume of the discharge chamber, S is the surface of the sheath around the hot cathode.

In eqs. (2a) and (2b) j^+ denotes ion current density which can be expressed by appropriate ion current emitted from the source:

$$j^+ = \frac{J^+}{a}, \qquad (3)$$

where a is the surface of a plasma meniscus.

Now assume that the losses of metastable atoms in the discharge plasma are the results of collisions with sample atoms and gas carrier atoms only. In this case we can write

$$\left(\frac{j_e}{e}\sigma_n^m n_n + \sum_{i=1}^{k} A_{im} n_i\right) v = (\alpha n_n^m n_d + \beta n_n^m n_n)\, v, \qquad (4)$$

where σ_n^m is the cross section to excite metastable state with electrons, A_{im} is a probability that the gas carrier atom in the i-state passes to the metastable m-state, β is a destruction coefficient of metastable atoms as a result of collisions with gas carrier atoms, n_i is the concentration of gas carrier atoms in the i-state.

Dividing equations 2a by eq. 2b and taking into account eqs. (3) and (4) we obtain the following:

$$\frac{J_d^+}{J_n^+} = C\frac{\sigma_d}{\sigma_n} + \frac{\gamma\cdot C}{\sigma_n\left(C+\frac{\beta}{\alpha}\right)}, \qquad (5)$$

where γ - is the summed cross section to excite metastable atoms in discharge plasma, $C = n_d/n_n$.

3. *APPARATUS AND EXPERIMENTAL RESULTS*

The studies of the influence of the Penning phenomenon on sample ionization were carried out by means of an ion source of magnetron type whose schematic view is shown in *Fig. 1*. The basic part of this source is a molybdenum discharge chamber. In the discharge process the chamber functions as anode. Inside the chamber there is a tungsten cathode K supplied with direct current. The whole system if placed into a magnetic field whose lines run parallel to the cathode filament. Ions produced in the source diffuse through the hole S and after acceleration and the analysis in the magnetic field of the separator, are gathered on the Faraday' s cup collector.

The measurements of ion currents of the gas carrier (Xe , Ar , He) were performed as well as of ion currents of the sample, i.e., mercury, which in a stable flow was supplied to the source from the container P. The gas carrier was introduced into the discharge chamber from the container M. The amount of the supplied gas was measured by means of the measuring system U.

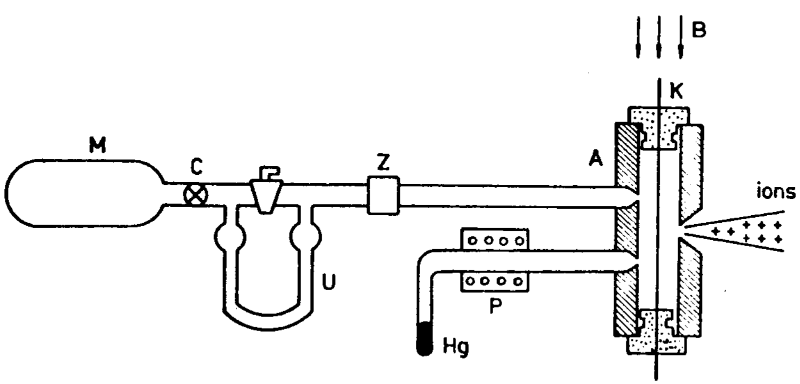

Fig. 1. Schematic view of the magnetron ion source.
K - cathode, A - anode, M - gas container, U - measuring system.

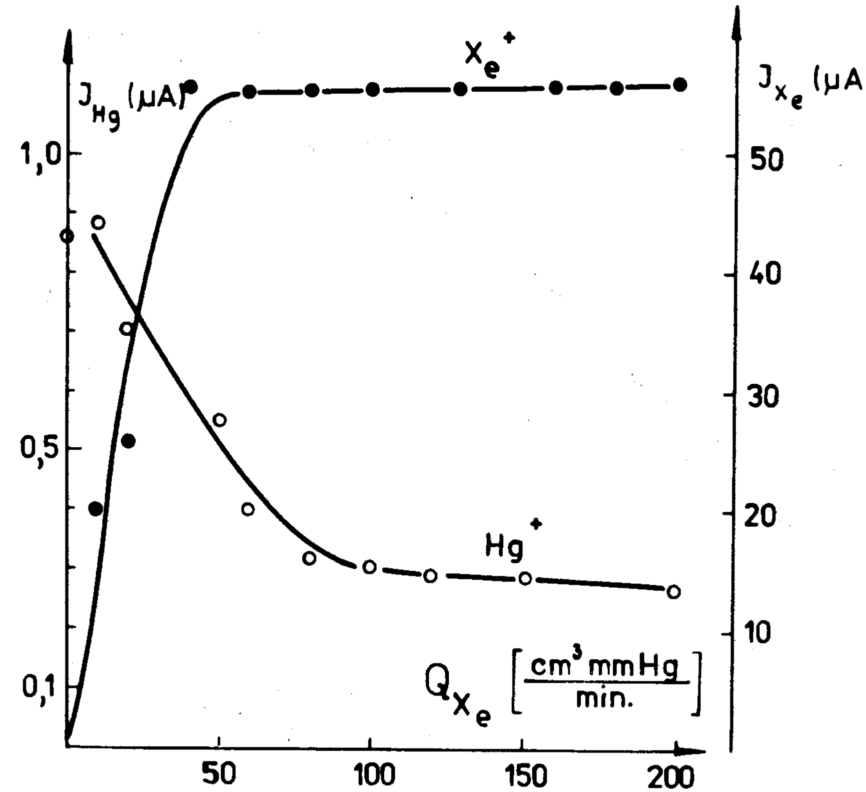

Fig. 2. Ion current of Xe^+ *and* Hg^+ *as a function of the* Xe *flow entering the ion source* (Q_{Hg} = const).

Figures 2,3 and *4* represent the dependencies of ion currents Hg and ions of the gas carrier Xe^+, Ar^+, He^+ as functions of flows of the corresponding gases to the source chamber.

All the measurements were performed under the same working conditions of the source. The anode voltage amounted to 230 *V*, while the current of the magnetic coil was 0.5 *A*, *the current* of the arc was 2*A* and the ion extraction voltage being 25 *kV*.

It follows from the presented diagrams that with all gas mixtures the current of Hg ions is decreased with

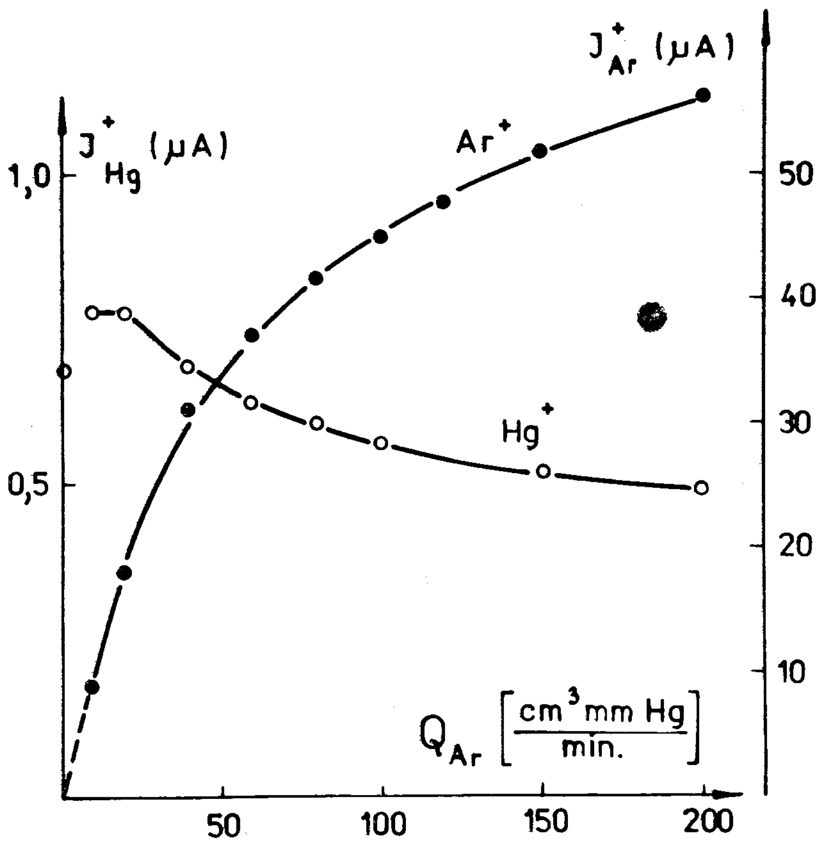

Fig. 3. Ion current of Ar^+ *and* Hg^+ *as a function of the* Ar *flow entering the ion source* (Q_{Hg} = const) .

increasing the pressure of the gas maintaining the stable discharge in the source. However, this discharge depends on the kind of a gas carrier and is the largest one with a Hg and Xe mixture, which can be explained by the fact that additional ionization of Hg atoms as a result of the Penning effect does not take place.

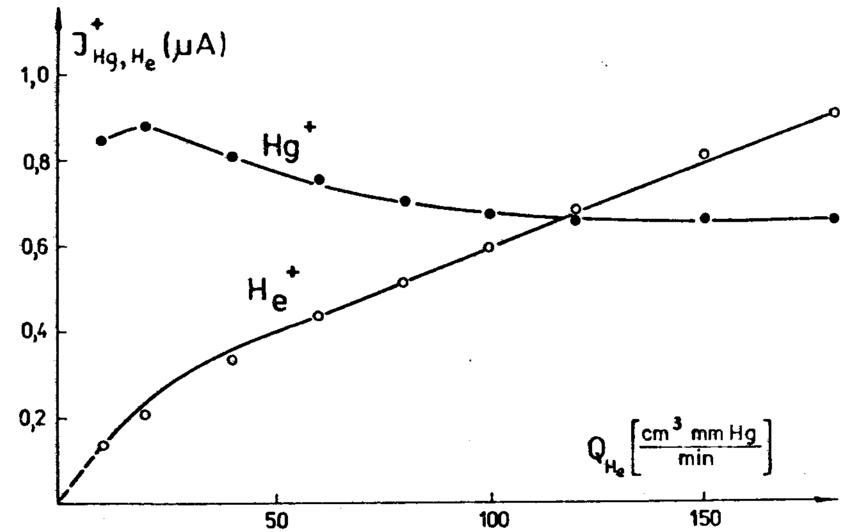

Fig. 4. Ion current He^+ *and* Hg^+ *as a function of the* He *flow entering the ion cource* (Q_{Hg} = const).

4. DISCUSSION OF RESULTS

In order to compare the experimental results with theoretical predictions, the ratio of currents of Hg ions and of the gas carrier has been drawn as a function of reverse Q_n, i.e., as a function of the ratio of appropriate concentrations C. The obtained data are shown in *Figures 5,6* and 7. From the presented diagrams it follows that in our experimental conditions the ratio is a linear function of C. The essential difference between the curves depends on the value of J_d^+/J_n^+ at $Q_n^{-1} \to 0$. Only in the case of a Hg–Xe mixture does the curve run through the beginning of the coordinate system. In the case of a Hg–Xe mixture the Penning effect is impossible and formula (5) can be written as

$$\frac{J_d^+}{J_n^+} = C\frac{\sigma_d}{\sigma_n} \qquad (6)$$

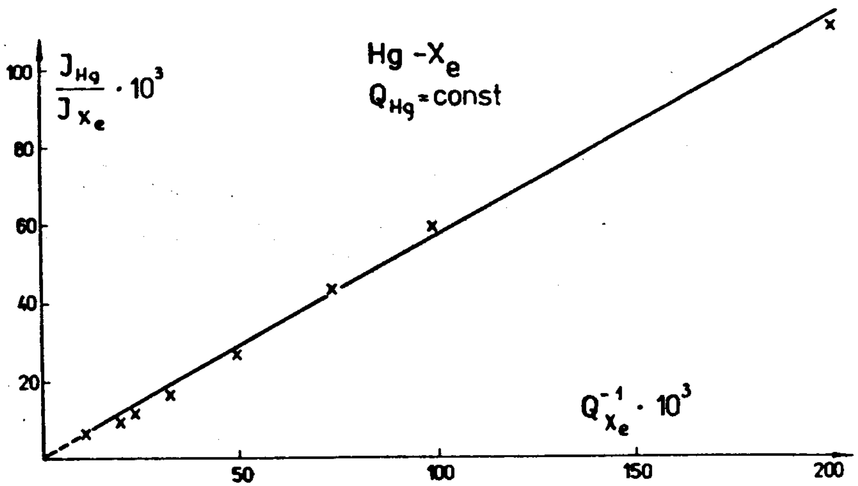

Fig. 5. Current ratio of Hg^+ *and* Xe^+ *as a function of* Q^{-1}_{Xe}.

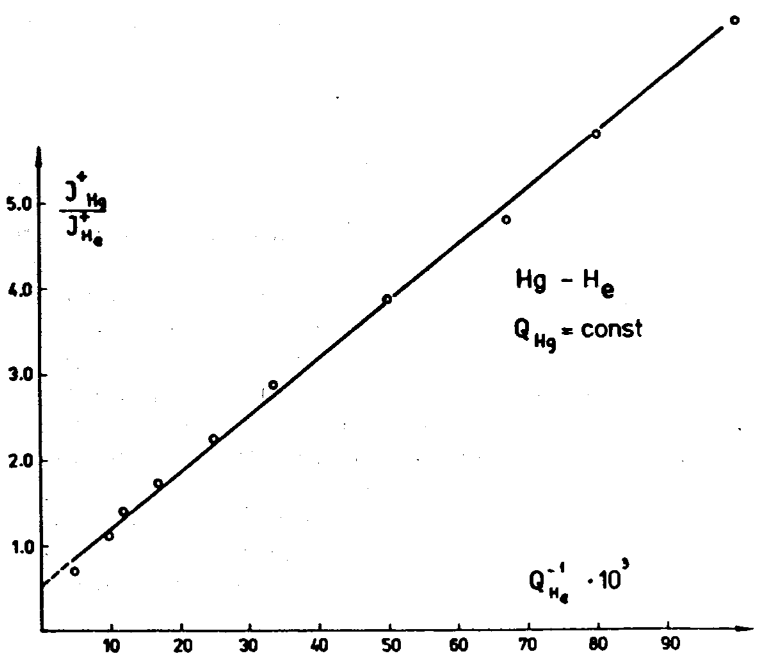

Fig. 6. Current ratio of Hg^+ *and* He^+ *as a function of* Q^{-1}_{He}.

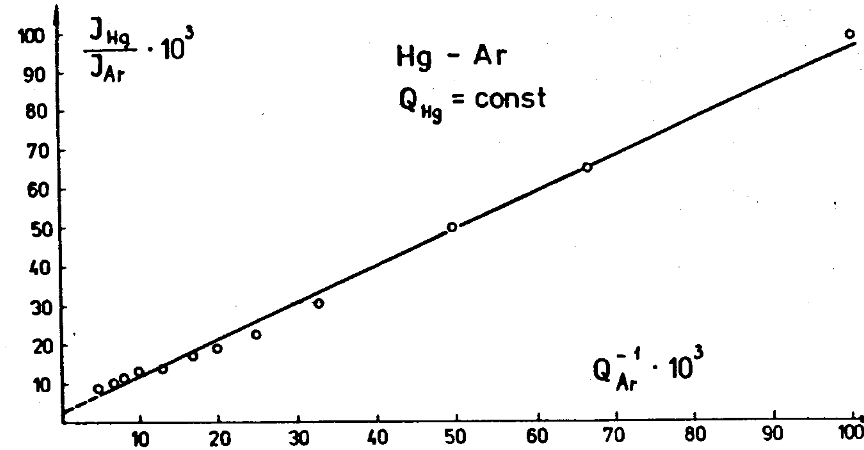

Fig. 7. Current ratio of Hg^+ *and* Ar^+ *as a function of* Q^{-1}_{Ar}.

which is in good agreement with the experiment. For Hg–He and Hg–Ar mixtures formula (5) agrees with the diagrams if it is assumed that $C \gg \beta/\alpha$. When this assumption is taken into consideration, formula (5) is reduced as follows:

$$\frac{J_d^+}{J_n^+} = \frac{\gamma}{\sigma_n} + C\frac{\sigma_d}{\sigma_n} \qquad (7)$$

or assuming the molecular flow of gas from the source, to the following

$$\frac{J_d^+}{J_n^+} = \frac{\gamma}{\sigma_n} + \frac{\sigma_d}{\sigma_n}\sqrt{\frac{m_d}{m_n}}\,\frac{Q_d}{Q_n}, \qquad (8)$$

where m_d, m_n are the corresponding masses of sample atoms and gas maintaining the discharge, Q_d, Q_n are streams of atoms of the sample and the gas carrier to the source.

From formula (8) one can obtain the efficiency of the ion source:

$$\eta = \frac{J_d^+}{Q_d} = \frac{\sigma_d}{\sigma_n}\sqrt{\frac{m_d}{m_n}}\,\frac{J_n^+}{Q_n} + J_n^+\frac{\gamma}{\sigma_n}\,\frac{1}{Q_d}. \qquad (9)$$

Taking into account formula (8) from the presented diagrams it is possible to determine the value γ, i.e., the cross section for the production of metastable gas atoms in plasma as a result of electron collisions and radiation transitions. In the present experiments (2 *A*, 230 *V*) the cross section for He–γ=1.4×10^{-17} cm^2, for Ar – γ = =4.9×10^{-19} cm^2. Under the conditions of a known Hg stream supplied to the source, diagrams 7 and 8 make it possible also to estimate the ratio of the destruction coefficients of metastable atoms. The obtained value for the Ar–Hg mixture is $\beta/a \ll 2 \times 10^{-3}$, for a He–Hg mixture $\beta/a = 2 \times 10^{-2}$.

5. SUMMARY

1. The fact that the obtained experimental results are in good agreement with theoretical predictions indicates that under our conditions it is possible to apply formulas 7 and 8 to ionization processes and to assume simplifications resulting from low plasma density.

2. The values of cross sections for the production of metastable atoms of the gas carrier as a result of electron collisions and radiation transitions have been determined. Under our experimental conditions the γ values for He/2^3S_1, 2^1S_0 and Ar/$3P_2$; $3P_0$ / are 1.4×10^{-17} cm^2 and 4.9×10^{-19} cm^2, respectively.

3. The upper limit of the ratio of destruction coefficients of metastable atoms Ar and He as a result of Hg and Ar atom collisions have been estimated. They are 2×10^{-3} and 2×10^{-2}, respectively. The results agree with those obtained by other authors, e.g., for the Ar–Hg and N_2–He mixtures the ratios β/a are about 10^{-4} /8/.

4. It follows from *Figs. 2,3* and *4* that with decreasing the gas carrier pressure in the discharge chamber the ion current of the sample (Hg) and, at the same time, the efficiency of the source is increased. Hence, the high efficiency of the source requires low gas pressure in the discharge chamber.

5. The analysis of the curves in *Figs. 6* and *7* shows that with regard to electron ionization (cf. graph 5), the Penning effect in Hg ionization is increased with decreasing Hg atom concentration in the mixture. The result agrees with those obtained in ref. /9/.

6. Comparing the values γ for Hg–He and Hg–Ar mixtures and also the curves in *Figs. 3* and *4*, we may state that from the point of view of the efficiency of Hg ionization, He is a better gas than Ar to maintain a discharge in the source.

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Received by Publishing Department
on May 4 1978.