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An Atomic Beam Apparatus with a Magnetoelectric High Sensitivity Microbalance (10^{-7}G) for Measuring Structure Parameters by the Absorption Method

The design of an atomic beam apparatus and a high sensitivity magnetoelectric balance installed in the apparatus and used to atomic beam density determinations have been described. The results of measurements of electron transition probabilities for the resonance doublet of the indium arc spectrum obtained with the help of the apparatus are reported and a possible adaptation of the apparatus to other research fields indicated.

The present work discusses the construction of an atomic beam device for measuring electron transmission probabilities in atoms with the help of an absorption method and an experimental determination of the value of oscillator power f for the transmissions $5^2P_{3/2,\,1/2}-6^2S_{1/2}$ of the indium atomic spectrum. ($\lambda_1 = 4101.76$ Å and $\lambda_2 = 4511.31$ Å).

The measured values f for the above-mentioned transitions in the indium arc spectrum are $f_1 = 0.12$ and $f_2 = 0.13$, respectively, with an error of several percent; the principal responsibility for this lies with the error determining the density of absorbing atoms. This error has consequently been reduced by perfecting the apparatus — to be described below.

At present, works are carried out on the determination of the value f for the resonant transitions in the atomic spectrum of bizmuth. The method was first applied at the University of Göttingen [5,] [6], [7] and [8]. It is well known that the absorption of the monochromatic light transmitted by the atomic beam is proportional to the product of the atom density N [atoms/cm^3] in the beam and the oscillator power f for the given spectrum line and thus the probability of electron transition.

This dependence is expressed by the formula:

$$A = \frac{\sqrt{\pi}e^2NLf\alpha}{mc}\left\{\frac{1}{\sqrt{1+\frac{\alpha^2}{\beta^2}}} - \frac{C}{2!\sqrt{2+\frac{\alpha^2}{\beta^2}}} + \right.$$

$$\left. + \frac{C^2}{3!\sqrt{3+\frac{\alpha^2}{\beta^2}}} - \ldots + \right\},$$

where

$$C = \frac{\sqrt{\pi}e^2NLf\beta}{mc}.$$

L — length of the light trajectory within the stream equal to 112 mm,

α — denotes the Doppler widening of the emitted line,

β — denotes the line widening due to absorption and is calculated from the beam geometry and the furnace temperature,

e — electron charge,

m — electron mass,

c — light velocity.

Having determined the oscillator power f from the formula we can easily calculate the probability of electron transitions [6], [7], [8], [12].

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In the first stage of the work the value of N has been determined on the base of the vapour pressure curve for indium and the temperature measurement [2], [20], [29]. The next stage includes the elaboration of a method of immediate registration of atomic density in the beam by an exact measuring of the mass of the stream deposited on the scale of the microbalance of high sensitivity.

A general measuring setup can be seen in Fig. 1. A collimated light beam from the stabilized Schiller lamp enters the measuring chamber K through the diaphragming window after having been reflected by prism P. The light of the beam is then absorbed by the vertically oriented atom beam (the light beam and the atomic beam are perpendicular to each other). When the light beam leaves the measuring chamber it passes through a focussing system f_2, the diaphragm D_2 and the spectral system unit Sp and fall on the slit of the photomultiplier unit, which analyses the beam and registers the absorbed part of the light.

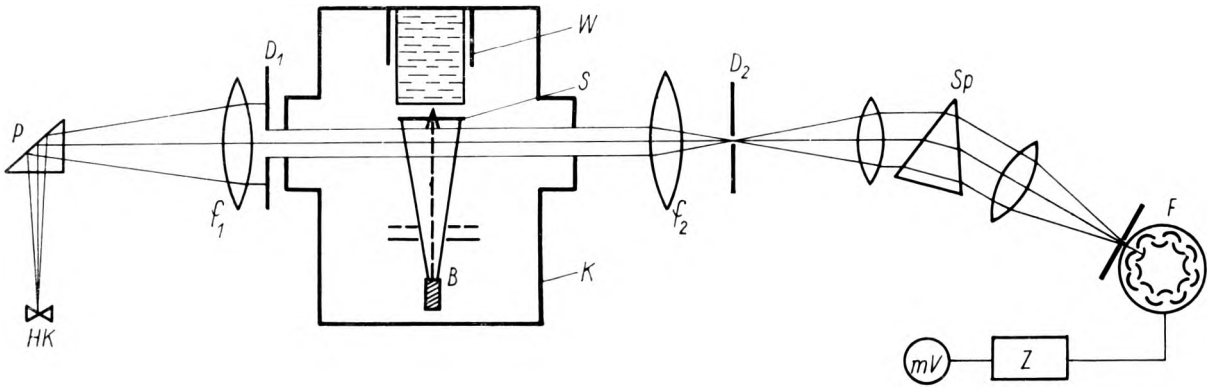

Fig. 1. Scheme of the measuring system
HK – hollow cathode, *SP* – spectral system, *F*, *Z*, *mV* – photomultiplier assembly, *B* – the source of the atomic beam, f_1, f_2 – lens, *P* – prism, *D* – diaphragm, *W* – gap with liquid nitrogen, *S* – microbalance scale, *K* – measuring chamber

Simultaneously with the help of a magnetoelectric microbalance S the atom density N in the stream is measured. A scheme of the atom beam arrangement is presented in Fig. 2. The source of the atom beam, which is an atom beam furnace, is a fundamental element of the entire measuring system. Its design is described in the paper [16]. The construction of the furnace guarantees an offusion of molecules with sufficiently great free paths. The latter may be regulated immediately by changing the width of the furnace slit as well as the pressure of the vapour in the furnace, effectuated by furnace temperature.

The main part of the furnace is a graphite head *1*. In the middle of the heating element of the crucible there is a graphite interface with a graphite crucible *2* located on it and closed with the help of a molybdenum cover *3* which is with the furnace slit. The sizes of the crucible are fitted in such a way that it could oosely enter the heating element and that the furnace slit be positioned in the region of uniform temperature field.

The furnace is fed with a.c. stabilized by an assembly of transformers; the power provided to the heating element of the furnace amounts to 2 kW under stationary conditions. The temperature inside the furnace was measured with the help of a thermoelement Pt, Rh–Pt. The head was mounted in a steel vacuum housing cooled with water. The temperature is read out on a millivoltmeter of class 0.5, which measures the temperature with the accuracy up to 5°.

A freezer with liquid nitrogen is mounted in the upper part of the measuring chamber [12]. The surface of the freezer bottom on the one hand plays: the part of a condensing target located close to the microbalance scale and out-of-the-way of the atomic stream, or, on the other, cools the surface of the microbalance scale from the upper side in its normal position.

A scheme of the high sensitivity magneto-microelectrical microbalance for determining the atom density N in the beam as well as the velocity v_z of atoms in the direction of the z-axis is shown in Fig. 3, while Fig. 4 illustrates the block scheme of the electric circuit of the microbalance. The microbalance is on an original device constructed with the cooperation of the Institute of Physics, Technical University of Warsaw [17].

The application of the high sensitivity balance for the absorption measurement in the atomic stream allows to determine with great accuracy the absolute values of the spectral line oscillator power. The real sensitivity of the balance 10^{-7} G is reduced in our case to the value 10^{-6} G because of the mechanical vibrations in the laboratory, which are often difficult to avoid. This reduced sensitivity was, however, sufficient for our measurements.

The measurement of the mass of the substance deposited on the microbalance scale determines directly

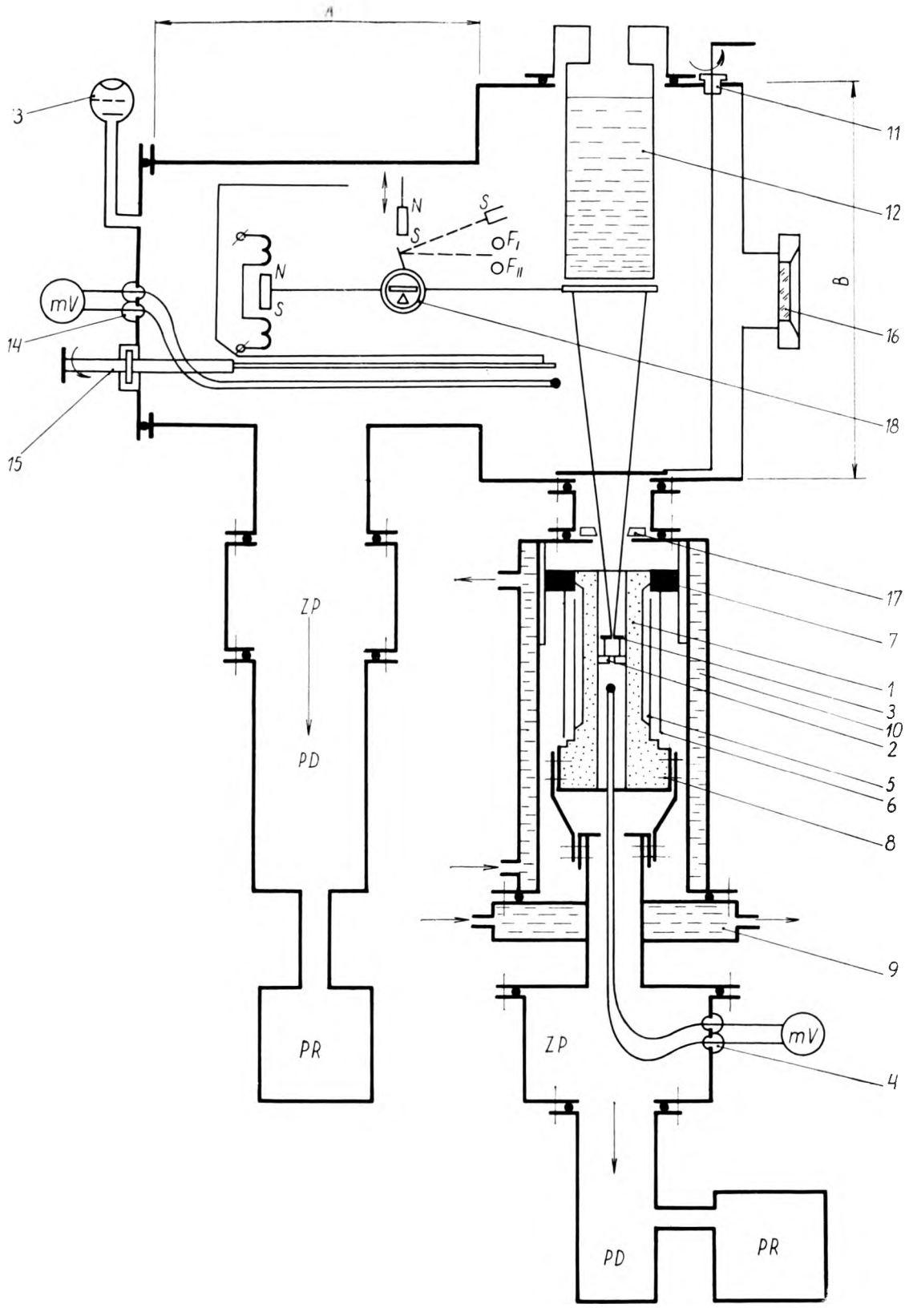

Fig. 2. Scheme of the atomic beam apparature with microbalance
1 — graphite furnace, *2* — graphite crucible, *3* — molibden cover, *4* — Pt, Rh-Pt thermocouple, *5* — graphite screen, *6* — tantalium screen, *7* — steel ring, *8* — lower steel pipe, *9* — two-wall furnace bottom, *10* — furnace chamber, *11* — vacuum pass for the operating the shutter, *12* — gap with liquid nitrogen, *13* — ionization lamp, *14* — chromel-kopel termocouple, *15* — vacuum Wilson pass, *16* — plexiglas windows, *17* — colimation slit, *18* — microbalance, *ZP* — vacuum valve, *PD* — diffusion pump, *PR* — rotation pump

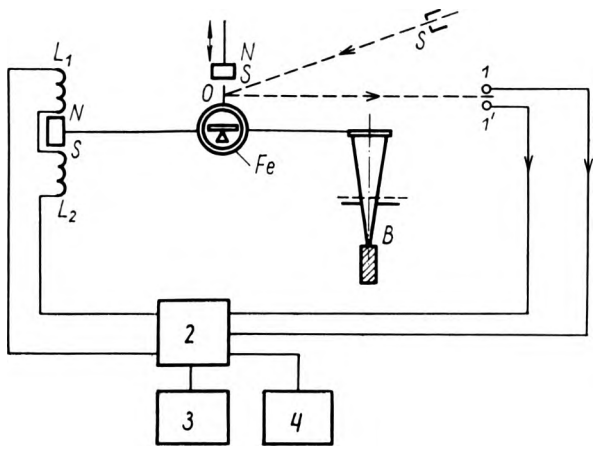

Fig. 3. Block diagram of the apparature with microbalance S — light source, O — mirror, B — atomic beam, L_1 L_2 — coils, 1, $1'$ — photocells, 2 — amplifier, 3 — magnetoelectric gauge, 4 — supply unit

When ϱ[g/cm³] is known the number N [atoms/ /cm³] may be easily estimated. The value $\bar{v}$ may be measured immediately with a great accuracy or be calculated on the base of the kinetic theory of gases from the formula:

$$\bar{v} = \frac{3}{4}\sqrt{\frac{2\pi kT}{M}},$$

where:

k — Boltzman constant,

T — temperature of atoms [in K],

M — atomic mass.

The measurement of the mean velocity of atom v_z consists in measuring the impulse of the force exerted on the microbalance scale by the atom beam, at the opening and closing of the diaphragm (5). After mak-

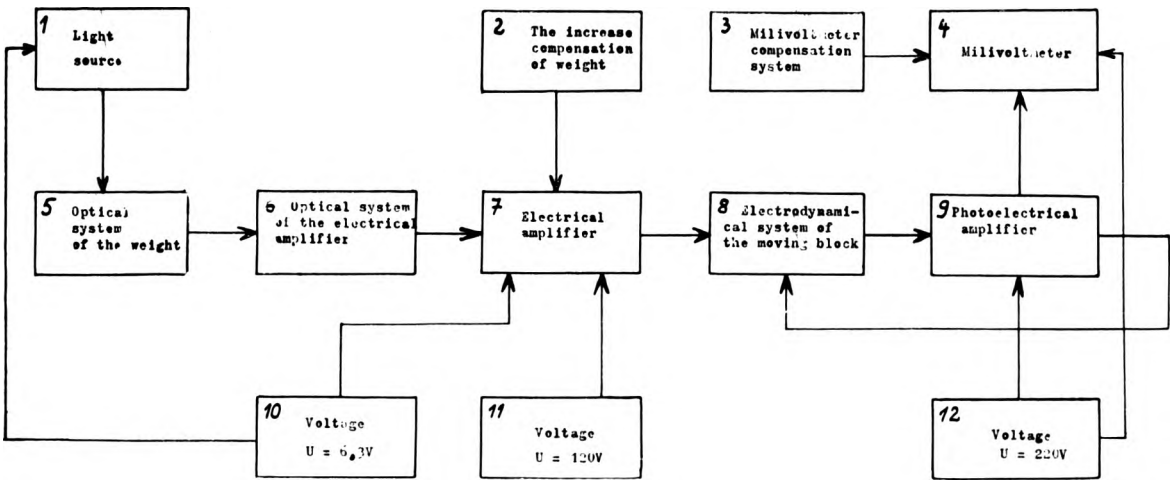

Fig. 4. Block diagram of the electrical microbalance system

the number of absorbing atoms, which makes it possible to avoid errors due to inaccurate knowledge of the temperature dependence on the vapour pressure. The vapouring material creates a stream of atoms or molecules, its shape being defined by two slits; the furnace slit and the collimation slit.

Denoting by:

m_1 — mass of the material deposited in the time 1 s [in g],

F — surface of the scale [in cm²],

$\bar{v}$ — mean velocity of the atoms in the beam [in cm/s],

ϱ — density [in g/cm³]

we can link the quantities with the help of the formula:

$$\varrho = \frac{m_1}{\bar{v}F}.$$

ing the required calculations the following formula may be employed.

$$v_z = \frac{g \cdot m_2 \Delta t}{m_1},$$

where:

m_2 — actual mass read on the millivoltmeter (scaled in units of mass) at the moment of beam opening,

m_1 — real mass deposited on the microbalance scale in the time of 1 s.

Δt — time interval, which is 1 s in our case,

$\bar{v}_z$ — vertical component of the velocity with reference to the balance scale,

g — acceleration of gravity.

The differences between the values $\bar{v}_z$ obtained

experimentally and those estimated theoretically are small and justified by the measurement error.

On the base of the above considerations it is possible to realize the following programme of research by measuring with the help of the compensation magnetoelectrical microbalance:

1. Measurement of the density ϱ [g/cm^3] of the absorbing atoms.

2. Measurement of the average velocity of the atoms in the z-axis direction.

3. Determination of the mass deposited on the scale as a function of temperature T of the furnace generating the atomic beam.

4. Determination of the average velocity of the molecules v [m/s] as the function the furnace temperature.

The balance is fixed as a whole inside a vacuum unit, the scale being positioned horizontally.

To increase the condensation coefficient the scale bottom is deposited from below with the chemical element under test and cooled with the help of a container filled with fluid nitrogen, the container being located as close as possible to the scale.

The design of the microbalance has the following features:

a) The balance is equipped with a magnetic suspention of the movable system.

b) The balance lever made of a quartz pipe and positioned horizontally is magnetically suspended, which makes the friction in the saphire-graphite bearings negligibly small.

c) The balance scale made of mica and located in a phosphor-bronze holder — dimensions 20×80 mm^2 — is replaceable. The scale sizes depend on the furnace slit and collimation slit magnitude as well as on the course of the experiment.

d) The compensation of the mass increment on the scale is made electrically by the corresponding interaction constant magnetic field of the coils on the constant magnet located on the other end on the lever (Fig. 3). The compensation is automatic with a possibility of registering measurement results. Increment of mass is read out from magnetoelectric gauge indications. Small increases may be measured very exactly by connecting parallelly a meter of greater current sensitivity. The field appears as a result of the output current flowing in the photoelectronic amplifier (Fig. 5).

The arrangement of photocells is controlled by a light beam reflected from a mirror mounted on the microbalance beam. The length of the optical path amounts to about 2m. In the equilibrium position of the moving system both photocells are illuminated symmetrically and by the same amount of light. The task of the amplifier is to create an "error signal", which is proportional to the asymmetry of the photocell illumination.

Deviation of the moving system of the balance, due to loading the scale by the deposited mass of the chemical element to be measured, causes an asymmetry of illumination.

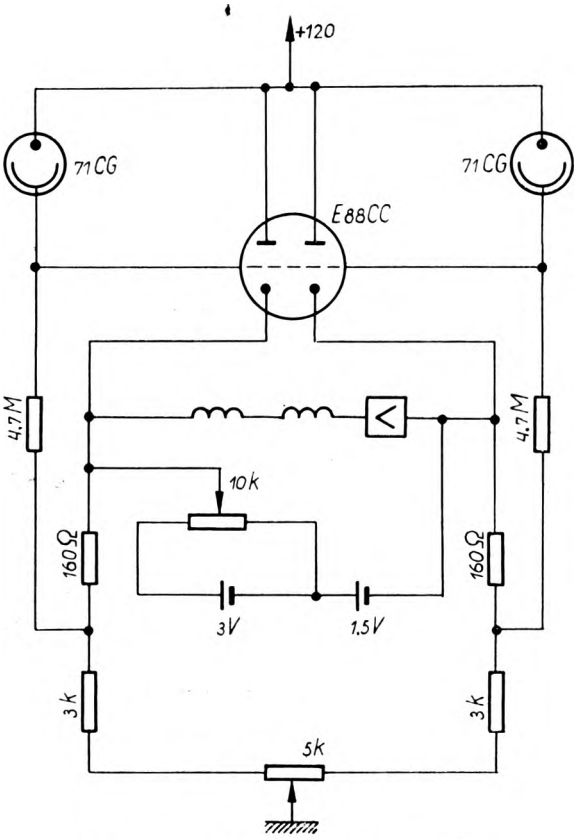

Fig. 5. Microbalance amplifier diagram

"The error signal" sufficiently amplified is directed to the electrodynamical unit of the balance where it is transformed into a force operating on the movable system.

The negative feed-back assumes a compensation of the scale movement, so that the weighing process is static. The change in mass is read out as a change in voltage U_k on the magnetoelectric meter. The value of the mass deposited on the scale is estimated by multiplying the number of millivolts by the balance factor C ($C = 2.57 \cdot 10^{-7}$ g/mV for the range 1000 mV of the photocompensator WF 112).

e) Testing of the beam profile is performed by exploiting the possibility of shifting the microbalance. It is shifted out of beam range with the aid of the Wilson pass. To ensure a horizontal shift the balance is supported by steel rails, fixed to the housing of the apparatus. There is a possibility of a shift up to 160 mm.

f) As a result of overload or shocks the movable system of the microbalance may fall down. A possi-

bility of relocating the system exactly at the same place is assured.

g) To keep down the oscillations of the movable system a mica target immersed in the silicon oil is fastened to the balance arm with the help of an elastic wire (not shown in Fig. 5).

h) The sizes of the balance are $120 \times 120 \times 270\,\text{mm}^3$. The length of the quartz arm is 300 mm and its diameter — 5 mm. The magnitude of the cylindric ferrite magnet located at the other end of the quartz arm is $\Phi = 4$ mm, its height being equal to 4 mm.

The balance calibration was carried out with the aid of thin, uniform copper wire coils reeled on a suitably shaped iron wire of Φ 3 mm. The diameter of the copper wire is 0.05 mm, the mass of the single coil is $1.8 \cdot 10^{-4}$g.

The iron wire with the copper coils playing part of the weights is positioned vertically above the microbalance scale. With the help of an electromagnet fed by 6V a.c. the wire is set into vibration, resulting in the drop of single coils on the scale of the microbalance. An increase in the voltage value is proportional to the number of dropping coils. It has been stated, that the calibration factor C does not change its value during the measurements though some alterations are to be expected at greater loads.

It has been proved that the materials used do not gas under vacuum condition.

The electric circuits of the microbalance enables the measurements within the following six ranges of load up to: 2 G, 0.2 G, 0.02 G, 0.002 G, 0.0002 G, 0.00002 G. The dependance of the indium mass increase on the scale upon the time for fixed temperature is linear, which is illustrated in Fig. 6, while Fig. 7 presents the mass increase as a function of temperature.

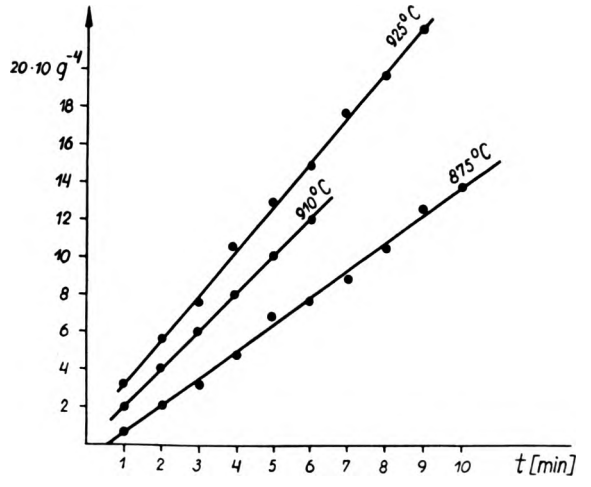

Fig. 6. The graph of the mass of the indium atoms deposited on the scale of the balance versus time t

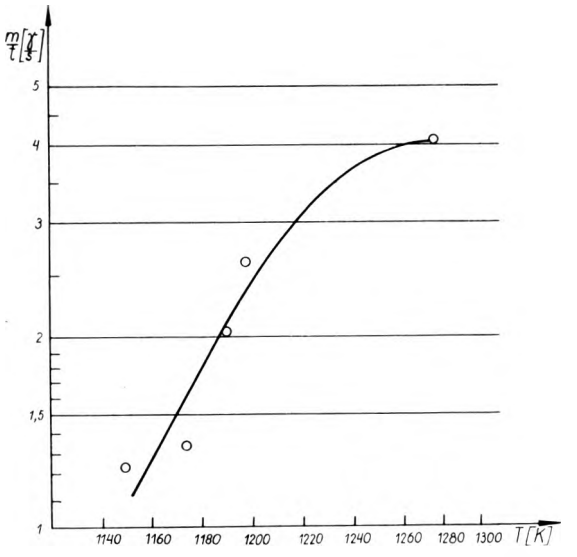

Fig. 7. The graph of the mass of the indium atoms deposited on the scale of the balance versus temperature $\gamma = 10^{-6}$g

The consistancy of the measurement results in time is very good as it was checked over several months. The value of the calibration factor remained unchanged.

With the help of this equipment measurements of the oscillator power for the resonance transition ${}^4P_{1/2} - {}^4S_{1/2}$ ($\lambda = 3067.72$ Å) in the bizmuth arc spectrum are performed. For this purpose a furnace unit has been developed by adding a dissociator to the molibdenum container in order to obtain a source of

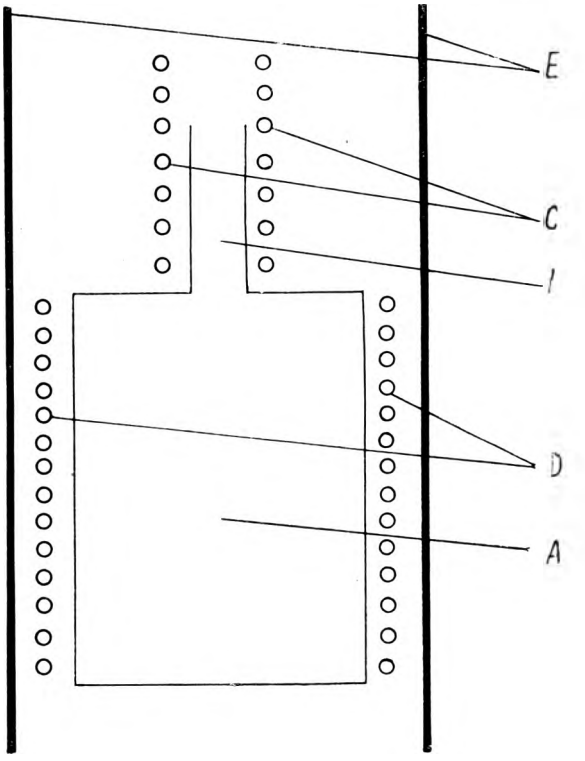

Fig. 8. The source of the bismuth atomic beam
A — crucible, B — dissociation channel, C — crucible heating spire, D — channel heating spire, E — tantal screen

atoms because — in the temperature range 600-700 °C, which is an optimum for the container — about 40 percent of the bismuth vapour consists of two-atom molecules. The pipe of the dissociator, also made of molybdenum (size: Φ 1mm, wall thickness 0.3 mm), is heated up to the temperature of 1250 °C.

The source of the bismuth atoms, which guarantees the dissociation of the molecules Bi_2 into single atoms, was designed on the base of works [18] and [19].

A simplified scheme of the source is presented in Fig. 8.

The atom beam apparatus described above is actually used to measure probabilities of electron transition in atoms. It is clear, however, that the atom beam apparatus may offer much wider applications while the magnetoelectric microbalance may be exploited independently to measure the atom densities also in other arrangements.

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