CERTAIN RESULTS OBTAINED IN RESEARCH ON CONTROLLED THERMONUCLEAR REACTIONS IN THE U.S.S.R.

(Incomplete text of a talk planned for delivery by I. V. Kurchatov at Saclay in March 1960 during a visit to France of a delegation headed by N. S. Khrushchev)

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TODAY, in the first part of this lecture, I should like to discuss plasma investigations which have been carried out in the last half year, on an apparatus called Ogra, by a group of scientists at the Institute of Atomic Energy, Academy of Sciences U.S.S.R. under the direction of I. N. Golovin.

Ogra (Fig. 1) is a magnetic-mirror system which consists of a straight tube in a constant longitudinal magnetic field which increases sharply at the ends of the tube — the magnetic mirrors.

The magnetic field is produced by a coil made up of separate sections so that different field configurations can be obtained. The distance between mirror centers can be varied up to 12 m; the maximum field which can be produced in the mirrors is 8000 oe while the maximum field at the center is 5000 oe. The tube, which is made from stainless steel, is 1.4 m in diameter and is evacuated to a pressure of 10^{-6} mm Hg by four mercury diffusion pumps. Further pumping is achieved by means of four ion-sorption pumps and by direct evaporation of titanium at the surface of the chamber by means of two evaporators located 2 m beyond the mirror centers. The chamber is provided with a heater made from stainless steel. When the tube is baked for 72 hours at 420° C and all the pumping devices mentioned above are used a vacuum of 2×10^{-8} mm Hg can be achieved after the chamber walls are allowed to cool.

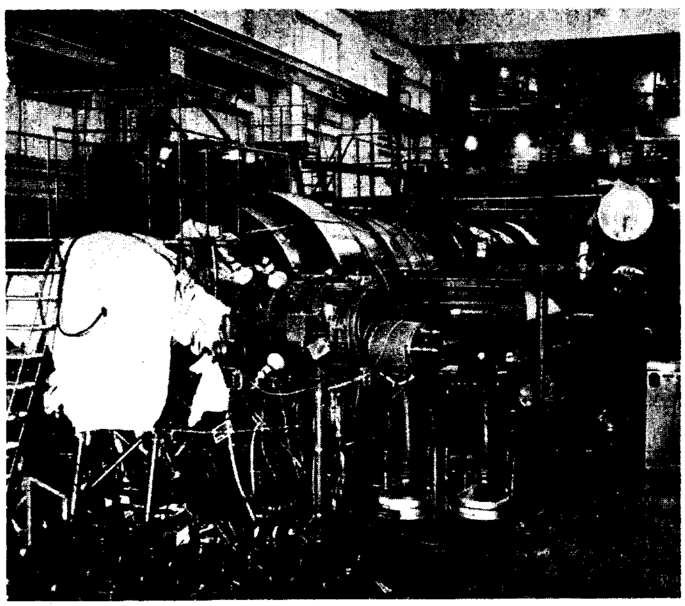

FIG. 1. General view of Ogra.

Molecular hydrogen ions H_2^+ are usually injected into the Ogra chamber; these are obtained from a source (Fig. 2) located at a distance of 8 meters from the mirror system. After H_1^+, H_3^+, heavy ions, and neutral atoms are removed, the H_2^+ beam passes through a magnetic channel in the mirror system. All control functions are carried out from a central control panel which is located on a balcony of the room which contains the Ogra system (Fig. 3). Particles are captured in the mirror system by virtue of the reduction in trajectory radius due to breakup of the molecular ions into atomic ions upon collision with molecules of the residual gas and previously captured fast ions.

The axial dimension of the mirror system must be large enough to guarantee dissociation of an appreciable fraction of the molecular ions before they are lost by striking the walls of the magnetic channel. For this purpose it is necessary to produce an azimuthal drift in the trajectories of the magnetic ions inside the mirror system.

At the beginning of the past year the appropriate conditions were obtained which provide the required azimuthal drift in Ogra. The results of this work were reported by I. N. Golovin in London at the end of April 1959 at a conference of the British Institution of Electrical Engineers.

At that time the mean free path of molecular ions before loss at the walls of the magnetic channel $\mathscr{L}$ had still not been determined.

It had been shown by D. A. Panov that if $\mathscr{L}$ were much less than 1000 meters, it would be necessary to abandon the method of breaking up molecular ions on the residual gas. If $\mathscr{L}$ is much less than 1000 meters the current of injected ions needed to achieve a plasma of the required density would be difficult to realize experimentally.

The collision of a H_2^+ ion with a gas molecule is characterized by two highly probable processes (in addition to others):

$$H_2^+ \to H_1^+ + H_1^0 \text{ and } H_2^+ + e^- \to H_2^0$$

with the production of a fast neutral hydrogen atom H_1^0 or a neutral hydrogen molecule H_2^0.

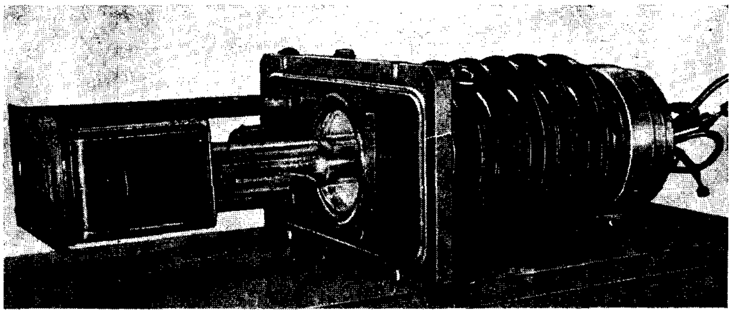

FIG. 2. Ion source.

The value of $\mathscr{L}$ in Ogra has been determined by several methods. In December of 1959, G. F. Bogdanov, D. A. Panov, and N. N. Semashko measured this quantity from the time decay of the flux of fast neutral particles at the side wall of the chamber after the injected molecular-ion current is shut off. This technique could be used because all the experiments were carried out at very low pressures, in which case the reduction in molecular-ion current is due chiefly to loss at the magnetic channel. The flux of fast neutral atoms was measured by means of a circular band of special electrodes similar to those which have been used by M. S. Ioffe at the Institute for Atomic Energy in work on the ion magnetron.

In Fig. 4 we show an oscillogram of the time decay of the flux of neutral particles after the current of injected H_2^+ ions (100 kev) is switched off.

The intensity of the longitudinal magnetic field along the axis of Ogra in these experiments is shown in Fig. 5. Two regions OA and AB, can be clearly distinguished on the oscillogram. In the second region the decay rate is appreciably smaller than in the first. The region OA is to be associated with the decay of molecular ions. The region AB is not to be associated with molecular ions, but with the fast hydrogen atoms produced by neutralization of the protons captured in the magnetic-mirror system. These protons are neutralized by collisions with gas molecules.

We shall consider these regions in greater detail below.

An analysis of the "OA" regions in the oscillogram results shows that the decay rate for the flux of neutral particles is essentially independent of pressure in the range 5×10^{-8} to 10^{-6} mm Hg; it is also independent of the kind of gas which is used (these experiments have been carried out with helium and argon). The decay curve can be approximated by the exponential relation

$$J = I_0 e^{-t/\tau_1}$$

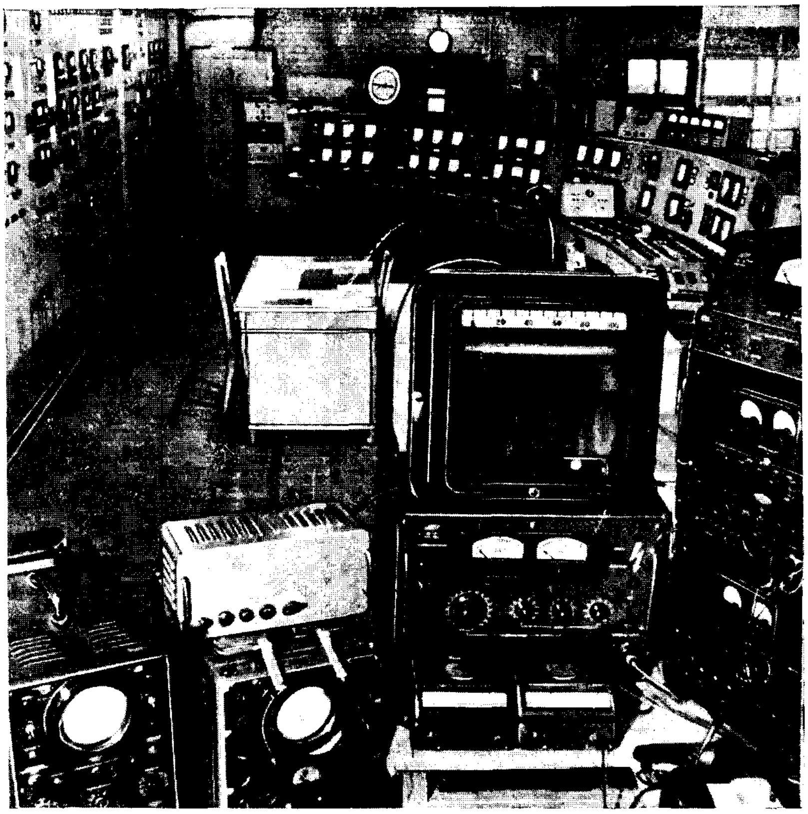

FIG. 3. Control console.

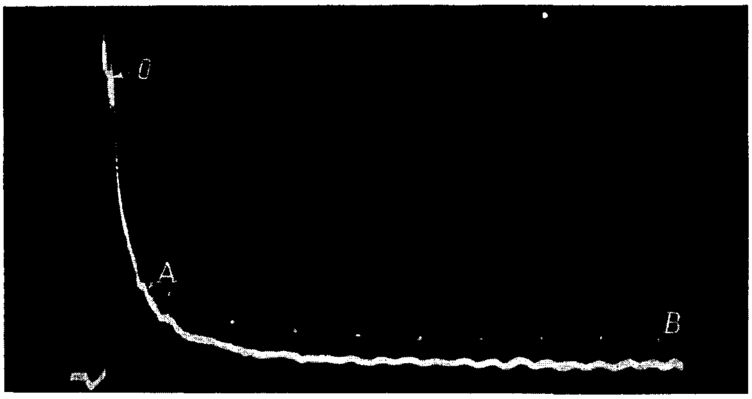

FIG. 4. Oscillogram showing the time decay of the flux of neutral atoms.

with a characteristic decay time τ_1 of 260 — 270 microseconds. The velocity of a molecular ion with an energy of 100 kev is 3×10^8 cm/sec so that the effective value of $\mathscr{L}$ is 800 meters. This value is adequate for breakup of ions on the residual gas.

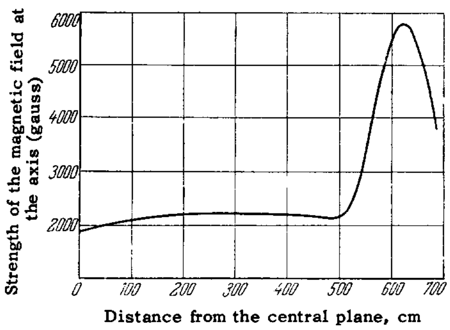

FIG. 5. The strength of the magnetic field along the axis of Ogra.

It is likely that $\mathscr{L}$ can be increased somewhat by improving the design of the magnetic channel through which the ions are introduced into the Ogra system.

It should be noted that the values of $\mathscr{L}$ determined by other methods are approximately the same as that given above.*

We now consider the region AB. As is apparent from the diagram (Fig. 6), in which we show the data obtained from a large number of oscillograms, the decay in the flux of neutral atoms can be represented by an exponential with a characteristic decay time τ_2.

In contrast with the region OA, here the lifetime is affected appreciably by the gas pressure p, varying from a value of 3.5 milliseconds at $p = 3 \times 10^{-8}$ mm Hg to a fraction of a millisecond at $p > 1 \times 10^{-6}$ mm Hg; the time τ_2 also depends on the kind of gas which is used. In the diagram (Fig. 7) we show the pressure dependence of τ_2 in helium and argon. It is apparent that this relation can be represented by straight lines which do not pass through the origin.

It is interesting to note that this same kind of dependence has been obtained by M. S. Ioffe for the lifetime of particles in an ion magnetron; this work was reported by him at the Upsala Conference on Gas Discharges in August of 1959.

*The geometric path length of the molecular ions before loss to the magnetic channel should be calculated with account of the loss of ions on the residual gas. For the mode of operation described in the text this quantity is approximately 1.5×10^5 cm.

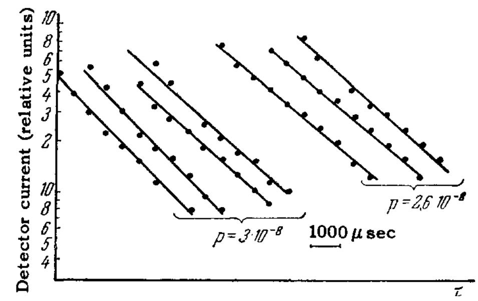

FIG. 6. The time dependence of the flux of neutral atoms on a semilogarithmic scale. For $p = 3 \times 10^{-8}$ mm Hg, $\tau_2 = 2700$ μsec; for $p = 2.6 \times 10^{-8}$ mm Hg, $\tau_2 = 3000$ μsec.

The results which have been obtained with Ogra are completely at variance with what one would expect on the basis of the elementary theory of an adiabatic magnetic-mirror system.

According to this theory, the magnetic moment of a particle $mv_\perp^2/H$ is conserved if the variation in magnetic field is small over the Larmor radius of the particle. At the low plasma density used in the experiments the loss of particles from the mirror system should, by this theory, be small. The particles should experience more than a million reflections at the mirrors before being lost, and should be trapped for many seconds. Escape of protons from the mirror system is thus attributed to a single process — charge exchange; this escape mode should be characterized by a strict linearity between $1/\tau_2$ and p.

Cross sections for proton charge exchange in argon and helium at a proton energy of 50 Kev.

Reference	Gas	
	He	Ar
Present work	$1.4 \cdot 10^{-16}$	$3.9 \cdot 10^{-16}$
K. Barnett [Phys. Rev. **103**, 896 (1956)]	–	$3.1 \cdot 10^{-16}$
G. Stedeford [Proc. Roy. Soc. **A227**, 466 (1955)]	$1.15 \cdot 10^{-16}$	–
N. V. Fedorenko (private communication)	–	$4.3 \cdot 10^{-16}$

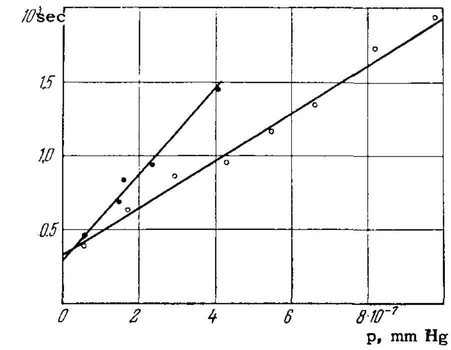

FIG. 7. The lifetime of fast atomic ions as a function of helium pressure and argon pressure; ○ helium, ● argon. The quantity $1/\tau_2^*$ is plotted along the ordinate axis.

It is reasonable to ask how we can be sure that the pattern shown on the diagram is not due to errors in the measurements, or some other mechanism not accounted for in the analysis of the experimental results. It is not very likely that this is the case. While it is true that large errors may appear in measurements of the absolute value of this quantity at low gas pressures, the cross sections for proton charge exchange in argon and helium obtained in the present experiments are very close to those which have been obtained by Fedorenko, Barnett, and Stedeford.

The diagram can be interpreted incorrectly because the composition of the gas changes along the abcissa; this effect is especially noticeable in the low-pressure region. At the first point near the origin of the diagram the pressure is due to the residual gas and all anomalies could be explained by assuming a very large cross section for proton charge exchange on these molecules.

However, this cannot be done because none of the components of the residual gas (Fig. 8) (hydrogen 46%, methane 12%, nitrogen 21%, argon 16%†) has a very high charge-exchange cross section.

Thus, it may be assumed that in Ogra there is some mechanism by which protons are lost through the mirrors, or to the walls of the chamber, which is not taken into account by the usual theory.

In the first place, one must make sure that these losses do not arise because the conditions in Ogra do not correspond to those used in the theory of adiabatic traps.

The Larmor radius of 50-kev protons, with which these experiments are carried out, is 14 cm; appreciable changes in the strength of the magnetic field occur along a radius of this magnitude. At the present time, a group of mathematicians at Moscow State University, under the direction of Corr. Mem. Acad. of Sci. U.S.S.R. A. N. Tikhonov, is using electronic computers to determine whether the additional losses observed in the experiments are due to deviations from the adiabaticity conditions.

Another possible mechanism for these losses is the perturbation of the magnetic field of the mirror system

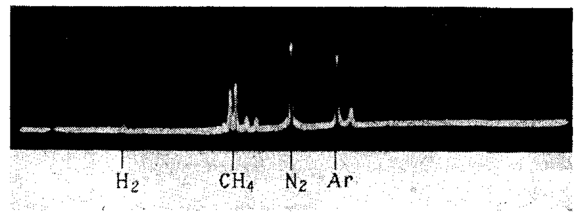

FIG. 8. The composition of the residual gas (obtained with a chronotron).

by the channel through which the molecular ions are injected into Ogra.

Losses of this kind have also been observed at our Institute by N. N. Brevnov and M. K. Romanovskii in a system called Ogrenok, which is a model of Ogra. However, special experiments must still be carried out to show the extent to which these perturbations explain quantitatively the observed effects.

A third cause for these additional losses may be certain features of plasma behavior which are as yet unknown. In order to investigate this problem we have started experiments in which faster molecular hydrogen ions are being injected into Ogra (200 kev); an investigation of the uniformity of the plasma structure in the trap is also under way.

I now turn to the second part of the report . . . . (at this point the notes left by I. V. Kurchatov end).

Editor's Note: I. V. Kurchatov planned a trip to France in March of 1960. He intended to deliver at Saclay a lecture surveying the work on controlled thermonuclear reactions in the U.S.S.R. Part of this talk, devoted to the Ogra system, is published in the present issue. Kurchatov took an active personal part in the experiments which are described.

Kurchatov wrote his report at the end of January 1960. At that time an important problem was that of determining the proton lifetime in the mirror system. The results of the first measurements of fast-ion lifetimes are discussed in the report. The possible mechanisms for the additional losses noted by I. V. Kurchatov have, to a considerable degree, been verified since that time. As predicted by Kurchatov, later measurements showed that in the experiments which have been described it is not easy to obtain accurate information concerning the pressure in the chamber. The argon and helium pressures had been measured satisfactorily at that time but the pressure of the residual gas was not known accurately. The pressure was recorded by pressure gauges located at the ends of the chamber, close to the titanium sorption surfaces. The pumping rate for argon and helium is negligible so that the pressure of these gases is essentially the same over the entire chamber. However, the pumping rates for hydrogen and air are high and there is a considerable pressure differential between the center and the ends of the chamber [this differential was measured later and found to be $(1.0 - 1.5) \times 10^{-7}$ mm Hg]. Hence the mean pressure of the residual gas in the plasma region could not have been less than 1×10^{-7} mm Hg. For this reason, in Fig. 7 the zero of the abcissa axis should be displaced to be left by $(1.0 - 1.5) \times 10^{-7}$ mm Hg with no change in the slopes of the lines. If the lines are extrapolated to the left, within the limits of the experimental errors they can now pass through the origin. Thus, in any case the additional losses are not as great as shown in Fig. 7.

On the other hand, the question of the "nonadiabatic" losses has not been resolved up to this time. A more satisfactory method

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*See also Editor's Note on this page.

†Determined with a chronotron.

of measuring losses shows that in the modes of operation discussed in the Kurchatov report the conditions which apply for the theory of adiabatic traps are not, in fact, satisfied; hence, ions which spend some time in the trap are not only lost by charge exchange, but also escape through the mirrors. This result has now been verified by a group of mathematicians under the direction of A. N. Tikhonov, and experimentally with the electron model of Ogra. Other modes of operation have been found in which non-adiabatic escape through the mirrors is reduced appreciably.

The second mechanism mentioned by Kurchatov, the effect of the channel, has not as yet been investigated in detail. It is already clear, however, that the effect of the channel is much smaller in Ogra than in Ogrenok and that the losses due to this effect are much smaller than the losses described in the report.

The third possible mechanism for supplementary loss mentioned by Kurchatov is the subject of a research program being carried out at Ogra. Work on this problem is not yet completed.

Translated by H. Lashinsky