SOVIET PHYSICS JETP VOLUME 34, NUMBER 2 FEBRUARY, 1972

INVESTIGATION OF PLASMA NEUTRON RADIATION FROM THE TOKAMAK T-3A INSTALLATION

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Submitted March 26, 1971

Zh. Eksp. Teor. Fiz. 61, 575–581 (August, 1971)

Prolonged, easily reproducible neutron radiation is recorded in the Tokamak T-3A installation at a deuteron temperature exceeding 300 eV and a plasma concentration $(4-6)\times 10^{13}$ cm^{-3}. The deuteron temperature determined on the basis of the absolute neutron-radiation intensity is identical to that obtained by analyzing the charge-exchange-atom beam from the plasma. The results of the experiments and of control tests indicate that the observed neutron radiation is of thermonuclear nature; this is in accord with the assumption of a Coulomb heating mechanism for most of the plasma ions in the Tokamak T-3A.

INTRODUCTION

In Tokamak installations the ion temperature increases with increasing plasma concentration[1]. In the T-3A installation (major radius $R = 100$ cm, minor radius $a = 20$ cm), at near-limiting conditions, the deuteron temperature reaches 400 eV, and then the intensity of the neutron radiation is strong enough to be registered[2]. The number of neutrons produced as a result of thermonuclear reactions per unit volume of the plasma is given by the well-known formula

$$G_{dd} = 6.4\cdot 10^{-10}\frac{n^2}{T_i^{2/3}}\exp\left\{-\frac{4.25\cdot 10^3}{T_i^{1/3}}\right\} \tag{1}$$

where n is the deuteron concentration and T_i is the deuteron temperature in degrees K. The strong dependence of the neutron yield on the temperature can be used (if the neutrons are of thermonuclear origin) to determine the ion temperature by measuring the absolute value of the neutron flux.

The determination of T_i on the basis of neutron measurements is of interest for the following reasons. The main method of measuring the ion temperature in Tokamaks is usually an energy analysis of the flux of charge-exchange atoms from the plasma[3]. Use is made here of the fact that the spectrum of the charge-exchange atoms in the energy range from 100 eV to 3 keV practically coincides with the spectrum of the plasma ions. A typical plot of the energy distribution of the atoms, obtained by the indicated method on the T-3A installation, is shown in Fig. 1. In the interpretation of this curve it must be recognized that the registered flux of atoms is a superposition of fluxes produced in different zones of the plasma column. The slope of the linear section of the spectrum in the high-energy region characterizes the temperature of the ions in the internal hot zones. The inflection of the curve in the low-energy region, on the other hand, is connected with the radial distribution of the ion temperature and is due to the influence of the peripheral cold zones of the plasma.

The flux of the charge-exchange atoms I_0, emitted by the internal hot region of the plasma, can be measured with the aid of an atomic analyzer in absolute units[4]. Its magnitude is determined by the concentration of the plasma ions n, the concentration of

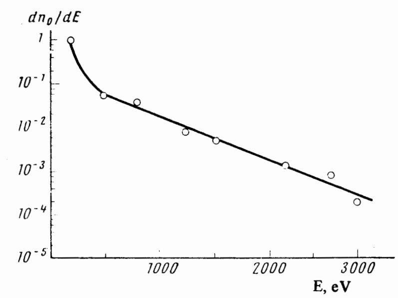

FIG. 1. Energy spectrum of neutral charge-exchange atoms, T_i = 390 eV.

the atoms n_a, the cross section for resonant charge exchange, and the radius a_T of the cylinder bounding the hot region of the plasma.

The value of n_a was measured on the T-3A Tokamak by registering the absolute intensity of the Balmer lines[5]. It turned out that n_a in the hot region of the plasma does not exceed $\sim 2\times 10^8$ cm^{-3}. Comparison of the experimentally measured value $I_0 \sim 10^{15}$ cm^{-2} sec^{-1} with the indicated value of n_a at $n = 6\times 10^{13}$ cm^{-3} yields $a_T \sim 10$ cm. This fact indicates that the slope of the linear section of the spectrum dn_0/dE characterizes the temperature of the bulk of the ions of the internal regions of the plasma in the T-3A.

In principle, another interpretation of the curve of Fig. 1 is possible. It can be assumed that there are two ion groups in the plasma, with temperatures T_1 and T_2 ($T_1 < T_2$). The measured energy distribution of the atoms is thus a sum of two Maxwellian distributions with temperatures T_1 and T_2.

It was shown with the TM-3 installation[6] that such a situation is actually obtained in regimes with low plasma concentration. This situation can arise, for example, as a result of the action of ion-acoustic instability, the main condition for the occurrence of which is $u/c_s > 1$ and was satisfied in practice in the given experiments (here u is the translational velocity of the electrons and c_s is the speed of sound). Such an interpretation, however, seems less probable, for under conditions of high plasma concentration there should occur in the Tokamaks an intense energy exchange between the two indicated ion groups. Indeed, the free path time of an ion with energy 2 keV between

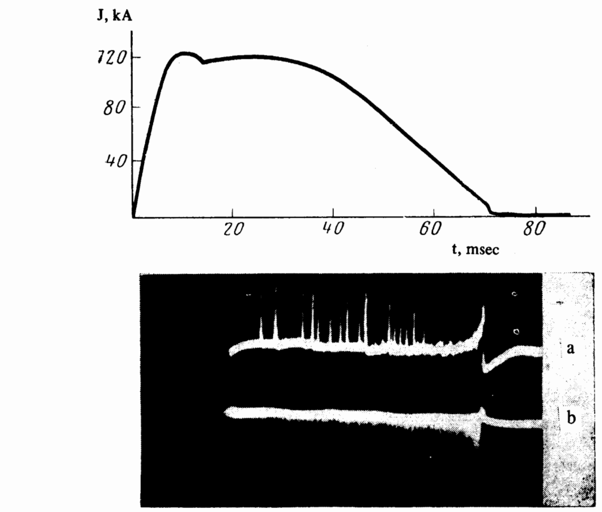

FIG. 2. Oscillogram of signals of boron (a) and scintillation (b) counters; top—oscillogram of discharge current on the same time scale.

collisions with the cold part of the plasma, at a concentration $n = 4 \times 10^{13}\ \mathrm{cm}^{-3}$, is only 1.5 msec. This is much shorter than the characteristic times of the process in the T-3A. Nonetheless, the final choice of the interpretation method can be made only by using an independent method of measuring the ion temperature.

APPARATUS FOR THE MEASUREMENT OF THE NEUTRON RADIATION

The expected neutron intensity, calculated from formula (1) at the parameters $n \sim 4 \times 10^{13}\ \mathrm{cm}^{-3}$ and $T_i = 300$ eV characteristic of the T-3A, is only $\sim 10^5$ neutrons per discharge at a plasma hot-zone volume $3 \times 10^5\ \mathrm{cm}^{-3}$ and a high-temperature plasma lifetime of 10 msec. To register the neutrons in the T-3A, we used an SNM-8a counter placed inside a paraffin moderator and located 70 cm away from the plasma column. A disturbing factor in the measurements of the neutron flux could be the fact that the plasma in the Tokamak is a source of intense hard x-radiation. To determine the influence of the x-rays on the operation of the boron counter under the T-3A conditions, a time comparison was made of the signals of the boron counter and of a scintillation counter having a high sensitivity to x-rays. Typical oscillograms of such signals are shown in Fig. 2. We see that the boron counter registers individual pulses within 20 msec in the middle stage of the discharge. The scintillation counter, on the other hand, registers the radiation only at the start and at the end of the discharge. The absence of noticeable correlation between the signals of the two counters is evidence that the radiation registered by the boron counter is not x-radiation.

To verify the same circumstance, control experiments were performed with two boron counters placed in a common paraffin block, one of which was covered with a thick boron shield. The sensitivities of the counters to x-rays were in this case the same, but the sensitivities to neutrons differed by more than 100 times. As a result, there were only two—three counts of the covered counter for 200 counts of the uncovered one. These experiments also indicate that the signal of the uncovered counter is connected not with x-rays but with neutron radiation.

To determine the absolute intensity of the neutron radiation, the efficiency of the counter was calibrated under geometrical conditions analogous to those in the experiment. Such a calibration was carried out with the aid of Po + Be and Pu + Be sources, with allowance for the absorption and scattering of the neutrons in the chamber walls, in the iron core, and in the coil material of the longitudinal magnetic field winding. As a result we obtained the connection between the counter readings and the number of neutrons produced in the volume of the plasma column.

Estimates have shown that the calibration error connected with the difference between the spectra of the calibration sources and the neutrons produced as a result of the reaction $d(d, n)He^3$ can lead in the worst case to an error of 10—15% in the measured deuteron temperature.

3. EXPERIMENTAL CONDITIONS AND RESULTS

All the measurements of the neutron flux from the plasma described in the present article were carried out at a longitudinal magnetic field intensity 38 kOe, a discharge current 120 kA corresponding to a current density in the plasma $j = 200\ \mathrm{A/cm}^2$, and a duration of the process 70 msec. If it is assumed that the Coulomb mechanism of ion heating is predominant at a plasma concentration above $1 \times 10^{13}\ \mathrm{cm}^{-3}$, then the intensity of the neutron radiation should increase with increasing concentration up to $1 \times 10^{14}\ \mathrm{cm}^{-3}$, while the energy contribution per particle, given by the current density, remains sufficiently large.

However, this series of experiments was performed at a concentration lower than $1 \times 10^{14}\ \mathrm{cm}^{-3}$. This was because of the peculiar instability that develops in Tokamaks under conditions of high plasma concentration[7] and becomes manifest in the form of a sharp dip on the voltage oscillogram, accompanied by a change in the position of the plasma column, in its inductance, and in other parameters. It was not our purpose to study this instability. We note only that the concentration n_{cr} at which such an instability sets in increases with increasing longitudinal current and with increasing transverse magnetic field but prevents the plasma column from moving along the major radius of the torus. In our experiments we succeeded in obtaining a stable plasma column with a concentration up to $6 \times 10^{13}\ \mathrm{cm}^{-3}$ at the center of the plasma column, as measured with the aid of multi-chord microwave sounding.

To determine the character of the registered neutron radiation, it was necessary to determine the form of the azimuthal distribution of the intensity of the neutron radiation along the toroidal chamber of the installation. Such an experiment, in particular, can reveal whether the deuterium-saturated diaphragm is a source of the registered neutrons when acted upon by the fast plasma deuterons. With the aid of two counters, one of which served as a monitor while the other was moved along the toroid, it was demonstrated that the neutrons are emitted practically isotropically and that there is no noticeable increase of the neutron flux on approaching the diaphragm.

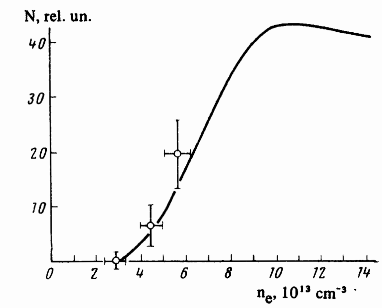

FIG. 3. Dependence of the intensity of the neutron radiation on the plasma concentration. Solid curve—result of calculation at j = 200 A/cm^2 and a time of energy containment in the plasma $\tau_e = \tau_i = 10$ msec.

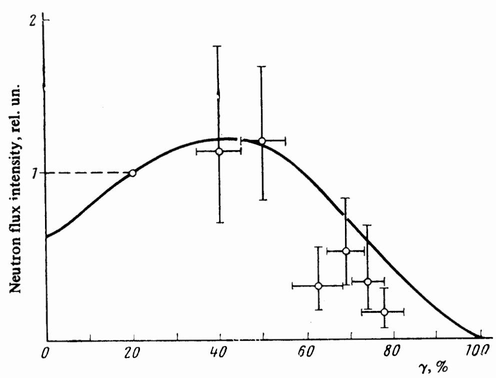

FIG. 4. Intensity of neutron radiation for different amounts of hydrogen added to the deuterium plasma; γ—relative concentration of hydrogen. Solid curve—result of calculations assuming the ions are heated as a result of paired collisions.

A reliably measured and reproducible neutron intensity (up to 30 counts per discharge) was reached only at the limiting plasma concentration of the stable plasma column. As soon as the column became unstable with further increase of the concentration, the neutron flux decreased sharply to below the sensitivity limit of the apparatus. This limited the range in which the dependence of the neutron yield on the concentration was investigated. Nonetheless, we succeeded in establishing that when the concentration decreases by 20% from the maximum value, the neutron yield decreases to approximately one-third, and with further decrease of the concentration it becomes too low to be registered. As expected on the basis of preliminary calculations, the absolute intensity of the neutron radiation exceeded 10^5 neutrons per discharge and amounted to 10^6 neutrons per discharge at the maximum concentration.

Figure 3 shows the dependence of the neutron yield on the plasma concentration together with the calculated data. The calculation was carried out assuming Coulomb energy transfer from the electrons to the ions and assuming that the quantities τ_e and τ_i, which characterize the degree of thermal insulation of the electronic and ionic components, are independent of the plasma concentration.

Figure 4 shows the experimental values of the neutron intensity following the addition of different amounts of hydrogen to the deuterium plasma. The ratio γ of the proton and deuteron concentrations in the plasma was determined by measuring the ratio of the fluxes of the hydrogen and deuterium atoms from the plasma with the aid of an atomic-particle analyzer. The value of γ was estimated simultaneously by measuring the comparative intensities of the $H\alpha$ and $D\alpha$ spectral lines. It was impossible to perform the experiments on pure deuterium, since the hydrogen absorbed by the walls in the preceding experiments was released during the discharge and entered the plasma. The minimum value of γ was in practice 20%.

4. DISCUSSION OF EXPERIMENTAL RESULTS

Thus, we registered in this series of experiments regularly-reproducible neutron radiation lasting for the duration of the entire middle phase of the discharge (20—40 msec). The radiation was observed only in a macroscopically stable column and only under those regimes where the plasma concentration and the ion temperatures approached the maximum values. The isotropy of the neutron emission on moving along the toroid indicated that there were no local neutron sources in the plasma.

It must be recognized that in principle the registered neutrons could result from bombardment of the liner walls by fast deuterium atoms produced in the plasma as a result of charge exchange of the hot deuterons. A simple calculation shows, however, that the amount of deuterium encountered by the fast deuteron on its path in the plasma is more than 1000 times larger than the number of deuterium atoms along the deceleration length in the wall material. It was assumed for such estimates that the number of deuterium atoms saturating the walls is 10^{22} cm^{-3} and the deuteron energy is 10 keV. The lifetime of such deuterons in the plasma is not less than 10^{-2} sec, since an estimate of the upper limit of the concentration of the neutral deuterium atoms in the column yields a value $n_a \lesssim 2 \times 10^8$ cm^{-3} [5].

The experiments demonstrated that the neutron-radiation intensity increases with increasing plasma concentration up to the instant when the plasma column becomes unstable, in good agreement with the assumed Coulomb heating of the bulk of the ions in the T-3A plasma and of the thermonuclear character of the neutron flux (Fig. 3).

Turning to Fig. 4, it should be noted that the intensity of the neutron radiation increases with decreasing deuteron concentration in the plasma, in the range of γ from 20 to 50%. Such a situation is typical of the Coulomb mechanism of deuteron heating in a deuteron-proton mixture, in view of the dependence of the energy transfer on the ion mass.

Thus, the entire considered aggregate of experimental data and the results of their comparison with the calculated relations do not contradict the assumed Coulomb mechanism of deuteron heating and thermonuclear character of the observed neutron radiation. According to calculations by Kogan[8], in the case of Maxwellian distribution of deuterons with temperature 0.4 keV, approximately 70% of the thermonuclear reactions produce deuterons having energies up to 3 keV. The energy spectrum measured by us in this region is actually close to Maxwellian (Fig. 1). We can there-

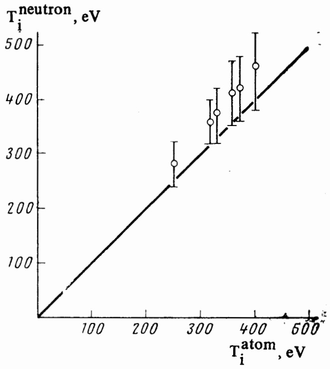

FIG. 5. Comparison of ion temperatures in the central region of the plasma column, determined from the spectrum of the charge-exchange atoms (T_i^{atom}) and from the intensity of the neutron radiation ($T_i^{neutron}$). Solid line—equal-temperature line.

fore use measurements of the absolute value of the neutron flux to determine the values of the ion temperature in the hot region of the plasma column.

Figure 5 shows the result of a comparison of the ion temperature in the center of the plasma column as determined by measuring the energy spectrum of the atoms and as calculated in accordance with formula (1) on the basis of measurements of the absolute intensity of the neutron flux. It is seen from the figure that the data obtained by both methods are in sufficiently good agreement. A small systematic difference between the values of the temperatures is most likely connected with the assumptions made concerning the character of the radial distribution of the ion temperature during the calculation of this temperature from the neutron-radiation intensity. It was assumed in this case that the deuteron temperature decreases parabolically with the radius, and is equal to zero at a distance 12 cm from the discharge axis. Such an assumption agrees with the measured distribution of the electron temperature in the T-3A installation[5] and does not contradict the data on the ion-temperature distribution in the T-5 installation[9].

Thus, a comparison of the results of two methods of measuring the ion temperature confirms the fact that the linear part of the energy spectrum of the neutron atoms (Fig. 1) represents the true value of the temperature of the bulk of the ions in the interior regions of the plasma.

In conclusion, the authors are deeply grateful to the crew of the T-3A installation and to A. V. Glukhov for help in measuring the spectrum of the neutral atoms.

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Translated by J. G. Adashko
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