SOVIET PHYSICS JETP VOLUME 21, NUMBER 3 SEPTEMBER, 1965

EXPERIMENTS ON ION HEATING IN A MAGNETIC MIRROR TRAP BY AN ALTERNATING ELECTRIC FIELD

Yu. V. GOTT and E. E. YUSHMANOV

Submitted to JETP editor September 22, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 804-813 (March, 1965)

A new experimental method was used for internal injection of a hot plasma into a magnetic mirror trap. Using the geometry of an "ion magnetron," an oscillating voltage of the ion cyclotron frequency was applied between the plasma column and the grounded chamber, filling the trap with a hydrogen plasma of $\sim 10^{11}$ cm^{-3} density and ~5-keV mean ion energy while maintaining a vacuum of $\sim 5 \times 10^{-7}$ mm Hg. The electrons remained relatively cold. The plasma generated during a pulse decayed in about 150 μsec, mainly as a result of flute instability. Ion heating was also observed at nonresonant frequencies. It is suggested that the ion acceleration mechanism is of stochastic character.

1. INTRODUCTION

We present here preliminary results obtained in an investigation of plasma heating by a modification of the so-called "ion magnetron" method.[1-3] In magnetron injection a cold plasma beam is sent along the axis of the magnetic mirror machine. A 20—30 μsec pulsed potential difference of 10—40 kV is applied between this column and the grounded walls, leaving the trap filled with a plasma of ~1-keV ions. This effect has not yet been fully accounted for; according to the adiabatic theory, an ion in a magnetic field should not acquire appreciable energy from electric pulses with leading edges whose duration considerably exceeds the Larmor period. The ion heating that is actually observed suggests that during a pulse the radial electric field undergoes high-frequency modulation as a result of various instabilities. This is accompanied by a stochastic acceleration of the ions, which "select" their resonant harmonic in the randomly fluctuating electric field.

It was to be expected that ion heating would be enhanced by artificially generating in the plasma an alternating electric field having an intense resonant harmonic. For this purpose M. S. Ioffe suggested that a packet of harmonic oscillations with the ion cyclotron frequency could be used as the accelerating pulse. This method obviously appears to be an "electrostatic" variety of the cyclotron method of plasma heating. We know from the theory that classical cyclotron acceleration of ions in a dense plasma is impossible because of polarization.[4] However, if plasma fluctuations (or a magnetic field inhomogeneity) produce a random phase drift of ion revolution relative to the alternating field, acceleration will occur. In this case we can consider intuitively (but not rigorously) that individual ions experience the external field as more or less prolonged segments of regular oscillations interchanged at random. Each such train will slightly increase or decrease the ion energy; this leads ultimately to a stochastically increased total energy of the entire ensemble.

EXPERIMENTAL APPARATUS

Alternating-voltage injection was investigated with the PR-2 apparatus[1,2] represented by a block diagram in Fig. 1. The central diameter of the trap is 50 cm and the mirror separation is 120 cm. The magnetic field at the center is 8 kOe and the mirror ratio is 1.6. The main evacuation was performed with the aid of flashed titanium. The operating pressure (neglecting the liberation of gas during a pulse) is usually (0.5—1)

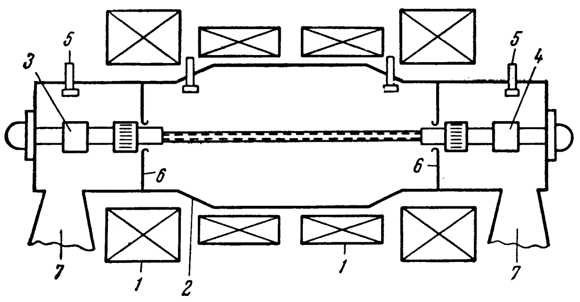

FIG. 1. Diagram of apparatus. 1 — magnetic field coils, 2 — chamber, 3 — source, 4 — collecting electrode, 5 — titanium evaporators, 6 — diaphragms, 7 — pipes to pumps.

$\times 10^{-6}$ mm Hg; the residual pressure (when the gas supply to the source is shut off) does not exceed 5×10^{-8} mm Hg.

The plasma source [1] consists of a tungsten cathode heated by an electron beam and a tubular anode into which about 200 cm^3/hr of hydrogen is fed continuously. Plasma is generated by applying, between the cathode and anode, a 1.2—1.3-kV square pulse through a 3Ω limiting resistance. An arc discharge is ignited with a current of about 150 A. A cold plasma column of at least 10^{13}/cm density flows along the magnetic field from the anode hole. During a discharge the gas inside the anode is ionized and is possibly occluded on the anode walls. This supply is sufficient for a few hundred microseconds, after which the discharge becomes intermittent. The plasma beam passes through the central compartment of the trap and terminates at a special collecting electrode located in the last compartment; this electrode is connected to the source anode. A rf pulse is applied to the anode of the plasma source about 30 μsec after the arc discharge is ignited. The duration of the oscillation packet is 250—300 μsec. The rf and the discharge in the source are switched off simultaneously.

The self-exciting rf oscillator, with one tube, is of imperfect design, so that the generated voltage is strongly nonsinusoidal; the spectrum of the accelerating pulse thus contains strong harmonics, which are multiples of the fundamental frequency (Fig. 2). The maximum amplitude of the output voltage oscillations is of the order of 5 kV at about 0.5 megawatt pulse power. The fundamental harmonic varies from 4.8 to 7 Mc.

The apparatus used to study the plasma consisted of detectors of charge-exchange particles (using secondary electron emission), electric probes, and a spectrometer to measure the energies of the charge-exchange particles. All these instruments were located in the central cross-section plane of the trap.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Signal of charge-exchange particles. When an alternating voltage is applied to a cold plasma beam the detector of charge-transfer particles registers a strong signal, the typical form of which is shown in Fig. 3. During an injection pulse hot plasma is accumulated. The signal also continues for some time after the pulse; this "tail" indicates that the accumulated plasma exists for a time τ. All of our data will pertain to the tail, i.e., to the freely decaying plasma.

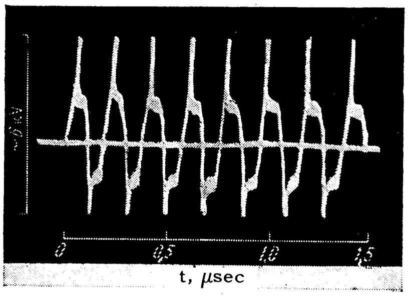

FIG. 2. Oscillator output oscillations.

When only the plasma source is switched on (without applying the rf) a certain signal of charge-exchange particles is also observed. This appears to indicate that ion acceleration then occurs in an unstable beam.[5] The signal is about 50 times smaller than that observed with the rf.

In selecting the optimum conditions for acceleration the principal criterion of efficiency was the strength of the charge-exchange particle signal, which is obviously enhanced with increasing density and energy of the hot plasma ion component (for a given vacuum). The signal strength was measured 10—20 μsec after termination of the injection pulse, i.e., at the start of plasma decay.

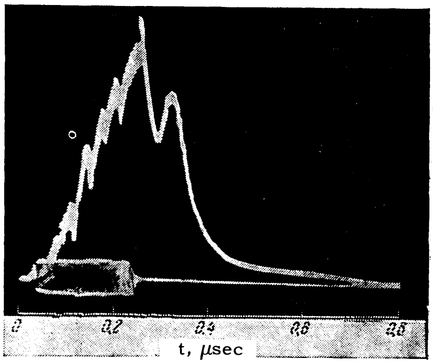

FIG. 3. Signal of charge-exchange particles; p = 10^{-6}mm Hg.

Our investigations were performed using the two extreme oscillator frequencies, 4.8 and 7 Mc. At 7 Mc in a 4.4-kOe field the resonance of H^+ atomic ions is observed (Fig. 4). At 4.8 Mc in a 6-kOe field the resonance of H_2^+ molecular ions

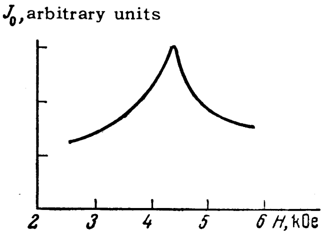

FIG. 4. Charge-exchange particle signal vs. magnetic field. f = 7 Mc.

is observed; in this case the charge-exchange particle signal is about five times greater than in the case of atomic resonance.

It must be emphasized that in the case of molecular resonance atomic ions are also accelerated because the second harmonic of the fundamental frequency is present in the oscillation spectrum. As already mentioned, the harmonics are contained in the primary rf pulse, but should also arise within the plasma in the absence of a pulse. Indeed, the plasma outside of the central column is located between the grounded ends of the trap and cannot acquire a negative potential because cold electrons are escaping. Within the plasma, therefore, the negative half of the accelerating packet should evidently be cut off; this means that harmonics of the fundamental frequency will appear. We thus actually have double molecular resonance.

The high efficiency of double resonance evidently provides no basis for a conclusion that the molecular component predominates in the composition of the plasma ions. First, as we know, for a strong discharge in the source the plasma beam should not contain many molecular ions; secondly, it can be expected that the accelerated H_2^+ ions will not be accumulated due to dissociation in a dense plasma. The strong signal of charge-exchange particles in double resonance is still unexplained; pertinent factors can include both variation of the magnetic field and variation of the accelerating voltage frequency.

We shall investigate mainly the double resonance, which is the more efficient phenomenon. All experimental data, unless otherwise specified, will pertain to the case of H = 6 kOe and f = 4.8 Mc at near-maximum oscillator power.

The impairment of the vacuum during an injection pulse is important. A vacuum gauge can obviously not register short-period pressure variations. It would therefore be wrong to use its readings as a measure of the vacuum while the trap contains a hot plasma. However, by measuring the dependence of the charge-exchange particle signal J on the initial pressure p determined by the vacuum gauge, we can evaluate the pulsed variation of the vacuum which is present as a constant component. It is assumed here that the plasma parameters and gas liberation are not strongly pressure dependent. The experimental dependence J(p) is shown in Fig. 5, where it is seen that with decreasing initial pressure the flux of charge-exchange particles approaches a constant value depending on the unregistered impairment of the vacuum. The latter is equivalent, according to its charge exchange effect, to a hydrogen pressure of $\sim 5 \times 10^{-7}$ mm. All pressures given in the present article include this error.

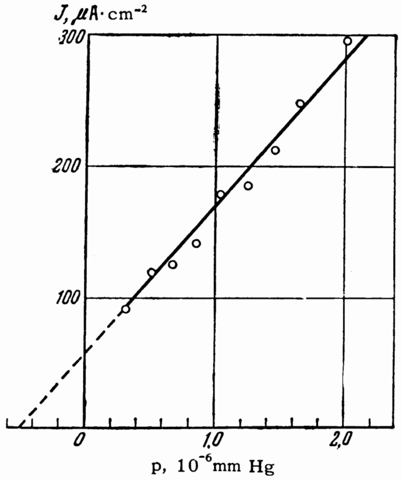

FIG. 5. Charge-exchange particle signal vs. pressure. f = 4.8 Mc; H = 6 kOe.

The shape and duration of the charge-exchange particle signal require special discussion. The oscillogram in Fig. 3 shows that about 100 μsec after injection a spike appears on the tail. This enhancement of the signal cannot result from changes of the plasma parameters, which vary considerably more slowly in the absence of external influences. The same applies to the vacuum.

Investigations using differently placed detectors of charge-exchange particles and electric probes showed that the aforementioned anomaly is of geometric origin. After the rf is switched off most of the plasma is concentrated in a blob that begins to move within the trap. When this concentration passes near the detector window an enhanced signal is observed. The blob always moves in the same direction, evidently as a result of small magnetic field asymmetry. This motion is obviously one form of magnetohydrodynamic flute instability of hot plasma in a magnetic mirror machine, which was thoroughly investigated previously at lower density and energy with the same apparatus.[1,2] In the present case the development of instability differs in a new way; the bunched plasma moves in one direction instead of exhibiting the previously observed azimuthally quasiuniform turbulent convection. The characteristic plasma decay time as a result of instability (the "anomalous time" τ_a) is about 150 μsec, as previously. In the described experiments the plasma instability was not investigated and all information concerning this is contained in the foregoing discussion.

2. Ion energy spectrum and plasma density. To measure the ion energy distribution we used the spectrometer of charge-exchange particle energies.[6] This spectrometer functions as follows. Fast charge-exchange particles pass through a very thin (~100 A) silver foil, where some of them are stripped. The energies of emerging ions are analyzed with an electrostatic analyzer. Individual particles are counted using an electron multiplier. The spectrometer was calibrated for an ion beam in the range 0.25—40 keV. The spectrometer saw only a small (±4°) solid angle; therefore the data pertain only to the ion group with small longitudinal velocities.

Each point of the observed energy distribution of charge-exchange particles is converted into the corresponding velocity and charge-exchange cross section, from which the energy spectrum of plasma ions is obtained. It was assumed that the neutral particle flux consisted only of fast hydrogen atoms; we shall show that this apparently introduces only a small error.

The experiments show that ions in registrable quantities are found in the entire accessible energy range. Figure 6 shows the ion energy spectrum averaged over several measurements. The very slowly descending hot-ion tail, at least 50 keV long, is noteworthy. The coldest part of the spectrum (below 0.5 keV) cannot be measured exactly, but we can expect a cutoff near 100 eV, since under the described conditions the plasma is charged as a whole to a considerable positive potential. A mean ion energy of 5 keV was calculated from the spectrum in Fig. 6.

It should be noted that the spectrum can be well approximated by the sum of two Maxwell distributions (hereafter called "cold" and "hot") with temperatures of 0.8 and 15 keV, the mean energies being one and one-half times greater, respectively. The ratio of hot to cold ion densities is 0.3.

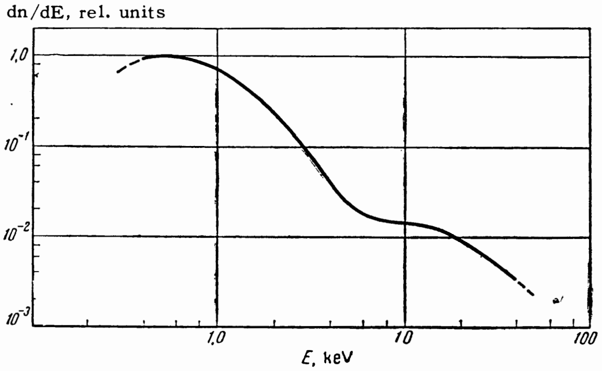

FIG. 6. Energy spectrum of plasma ions. p = 10^{-6} mm Hg; f = 4.8 Mc; H = 6 kOe.

The absolute ion density was determined from the signal of the charge-exchange particle detector. The most direct way to determine the number of fast ions in the trap is to measure the total flux of charge-exchange particles during the entire existence of the plasma. For the experimental pressure 10^{-6} mm the density of ions experiencing charge exchange is $(3-4) \times 10^{10}$ cm^{-3}, the plasma diameter being arbitrarily taken as everywhere equal to 20 cm. This result can be taken as the minimum plasma density, but is clearly greatly underestimated, because losses due to instability are several times greater than the charge-exchange effect.

More accurate results are obtained similarly by increasing the pressure until charge transfer is the principal cause of loss. The density is then $\sim 2 \times 10^{11}$ cm^{-3} in a vacuum of $\sim 10^{-5}$ mm. It must be emphasized, however, that in this case because of the poor vacuum the charge-exchange losses must also play an important part during injection by changing the plasma parameters as compared with the usual conditions ($p \lesssim 10^{-6}$ mm). Specifically, the ion energy spectrum will then be shifted to lower temperatures.

The most accurate plasma density n can evidently be obtained by using the previous ion energy distribution. We have the relation

$$J = \frac{\pi r_0^2}{2\pi a} n_0 n \langle k v \sigma \rangle, \qquad (1)$$

where J is the charge-exchange current signal (per cm^2 of the detector entrance slit), r_0 is the plasma radius, a is the distance from the chamber axis to the detector, n_0 is the neutral gas density (including gas liberation), and $\langle k v \sigma \rangle$ is the product, averaged over the entire spectrum, of the secondary electron emission coefficient, the velocity, and the charge-exchange cross section.

In the calculations k was taken as proportional to the velocity and as equal to unity at the energy 2 keV. The value of the cross section σ was taken from [7,8]. The total density for a typical case is $\sim 1.5 \times 10^{11}$ cm^{-3}, while the density of ions having energies greater than 5 keV is $\sim 3 \times 10^{10}$ cm^{-3}.

When the spectrum is divided into cold and hot parts, we again note that the density of the first part is ~50% inaccurate at low energies. This inaccuracy is associated with insufficient statistics and with the fact that the lower limit of the spectrum is unknown. Therefore the mean energy and density of the cold group are also not determined very accurately. However, the parameters of the hot group ($E_m \approx 23$ keV and $n \approx 3 \times 10^{10}$ cm^{-3}) were determined quite reliably, because, as a result of the small value of $k\nu\sigma$, the cold region of the spectrum makes practically no contribution to the charge-exchange particle signal.

All the foregoing results were based on the assumption that the ion component of the plasma consists only of protons. If the plasma contains an appreciable number of fast H_2^+ ions, the charge-exchange particle flux will contain fast molecules. Since the described analyzer does not separate atoms from molecules, some error is thus introduced into the spectrum and the associated plasma parameters. In order to evaluate the effect of a H_2^+ admixture we calibrated the ion spectrum, mean energy, and density assuming that the charge-exchange particle flux consists entirely of fast molecules. In this case the spectrum resembles that previously obtained, but is farther extended in the high-energy direction. The mean energy is 7.5 keV at a density of about 0.9×10^{11} cm^{-3}. The possible presence of molecular ions in the plasma therefore somewhat reduces the mean energy and increases the density only slightly.

3. Influence of magnetic field and rf amplitude on injection efficiency. The resonance character of the relation between the magnetic field and the total signal of charge-exchange particles has already been discussed. However, the given data do not enable us to determine whether increased density or increased energy has the principal role. We therefore obtained "resonance curves" in different segments of the energy spectrum; the results are shown in Fig. 7.

It appears that the hotter portion of the spectrum, corresponding to energies of tens of keV, is manifested only at resonance. At the same time, the portion of the spectrum below ~15 keV undergoes an important reduction in absolute value. One might assume that at resonance some ions are transferred from the cold group to the hot tail; however, a quantitative comparison of the spectra shows that the increased density of the hot group is far from being sufficient to compensate the impoverishment of the cold portion of the energy distribution, i.e., the total density at resonance is lower than the nonresonant value. We must therefore assume that the "inversion" of the resonance peak in the cold spectral region results from greater plasma loss during injection at resonance.

Figure 8 shows the dependence of the total charge-exchange particle signal on the amplitude of the accelerating pulse, as well as other dependences in different parts of the spectrum. As the amplitude of the accelerating pulse increases, the ion density at a given energy increases at first, and then begins to decrease; the maximum

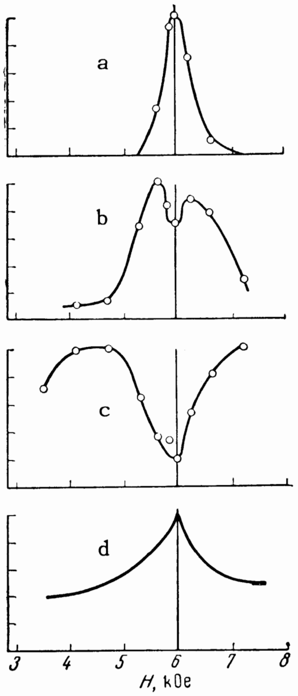

FIG. 7. Magnetic field dependence of ion density at different energies. a – 30 keV; b – 15 keV; c – 2 keV; d – total signal of charge-exchange particles (arbitrary units).

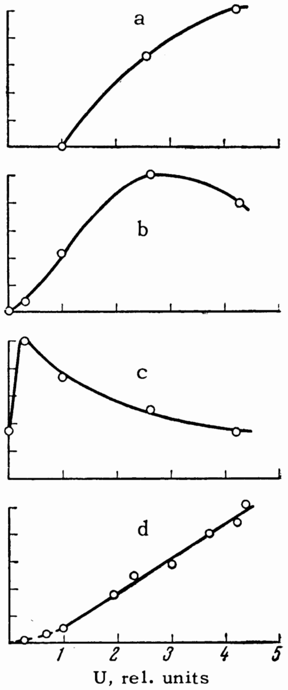

FIG. 8. Ion density at different energies vs. accelerating voltage. a – 30 keV; b – 20 keV; c – 3 keV; d – total signal of charge-exchange particles (arbitrary units).

is reached at a rf amplitude which increases with the energy. Consequently, as the accelerating pulse amplitude increases, the number of ions in the hot part of the spectrum is increased with a corresponding reduction of the cold part of the spectrum. At the same time the total density is reduced, at least for a rf amplitude above a certain value.

With increasing amplitude of the accelerating pulse we thus observe the same effect as in the transition from a nonresonant to a resonant magnetic field. The number of fast ions is greatly increased, although the total density is reduced by a factor of two to three. The total signal of charge-exchange particles is strengthened, because of higher registration efficiency ($\sim k\nu\sigma$) for hot ions than for cold ions. The reduced density is apparently associated with higher ion loss during the injecting pulse.

CONCLUSION

The following comments are based on the results. By using magnetron injection with an alternating accelerating voltage, we can under the described conditions fill a trap with hydrogen plasma of density $(1-2)\times 10^{11}$ cm^{-3} having a mean ion energy of 5 keV. The electron temperature then does not appear to exceed a few tens of electron volts. The ion energy spectrum is approximately represented by the superposition of two Maxwell distributions, a cold distribution at the temperature ~ 0.8 keV and density $\sim 1\cdot 10^{11}$ cm^{-3}, and a hot distribution at 15 keV and $\sim 3\times 10^{10}$ cm^{-3}. The conditions for producing a plasma with these parameters are a sufficiently high density of the initial beam (not less than 10^{13} cm^{-3}) and rf voltage of the order of a few kilovolts at the resonance frequency. The vacuum conditions must be well maintained after injection.

The ion heating mechanism is presumably of stochastic character. This hypothesis is supported by the fact that intense heating also occurs at frequencies when the resonance condition is unfulfilled throughout the entire volume of the trap. Indeed, stochastic acceleration of a single ion requires only a large number of random energy changes occurring during the interactions of an ion with an unordered sequence of rf oscillation packets (see the Introduction). These variations will also occur when the packet is formed by nonresonant oscillations. However, the individual energy changes will then be of smaller magnitude than at resonance, and the acceleration will be slower.

We can thus account for the observed difference between the resonant and nonresonant ion energy spectra, which consists in the fact that both the hot and relatively cold ion groups are present at resonance, whereas in the absence of resonance there is no hot group. It can be assumed that the cold group results from general stochastic acceleration in a nonresonant alternating field (we recall that the principal rf harmonic is not resonant for protons), but that oscillations with a resonant frequency generate a hot ''tail'' of the energy distribution. The acceleration of ions in the hot group can reasonably be assumed to be stochastic also, because pure cyclotron acceleration would make their energy much greater. There is no conflict here between experiment and a theory that denies the possibility of pure cyclotron acceleration. In any event, it is seen that fulfillment of the resonance condition plays a very important part.

The purpose of the experimental work was only to investigate the possibilities of the described injection method, and not to serve as a comprehensive study; therefore the interpretation of the results provides essentially only a working hypothesis. The efficiency of the given method for producing denser plasmas is an important practical question that remains unanswered.

In conclusion the authors wish to thank M. S. Ioffe for suggesting the problem and for useful discussions, A. A. Smirnov for invaluable experimental assistance, and Yu. T. Baĭborodov for constructing the rf oscillator.

---

[1] Ioffe, Sobolev, Tel'kovskiĭ, and Yushmanov, JETP 39, 1602 (1960) and 40, 40 (1961), Soviet Phys. JETP 12, 1117 (1961) and 13, 27 (1961).

[2] M. S. Ioffe and E. E. Yushmanov, Yadernyĭ sintez (Nuclear Fusion), Supplement, Part 1, 177 (1962).

[3] Baĭborodov, Ioffe, Petrov, and Sobolev, Atomnaya Énergiya 14, 443 (1963).

[4] L. I. Rudakov and R. Z. Sagdeev, Fizika plasmy i problema upravlyaemykh termoyadernykh reaktsiĭ (Plasma Physics and the Problem of Controlled Thermonuclear Reactions), AN SSSR, 1958), Vol. 3, p. 153.

[5] M. V. Nezlin and A. M. Solntsev, JETP 45, 840 (1963), Soviet Phys. JETP 18, 840 (1964).

[6] Yu. V. Gott and V. G. Tel'kovskiĭ, ZhTF 34, 2112 (1964).

[7] Fite, Brackmann, and Snow, Phys. Rev. **112**, 1161 (1958).

[8] Afrosimov, Il'in, and Fedorenko, JETP 34, 1398 (1958), Soviet Phys. JETP 7, 968 (1958).

Translated by I. Emin
115