Scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the Academy of Sciences of the USSR (24–25 December 1980)

Usp. Fiz. Nauk 134, 553–556 (July 1981)

PACS numbers: 01.10.Fv

A joint scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the USSR Academy of Sciences was held on 24 and 25 December 1980 at the P. N. Lebedev Physics Institute of the USSR Academy of Sciences. The following papers were delivered:

24 December

(Session dedicated to the 100th anniversary of the birth of Academician N. D. Papaleksi)

1. *V. V. Migulin*, N. D. Papaleksi (on the 100th anniversary of his birth).
2. *V. K. Abalakin and Yu. L. Kokurin*, Lunar Lidar.
3. *L. A. Kulevskiĭ*, A parametric infrared radiation generator.
4. *A. E. Salomonovich*, N. D. Papaleksi and Soviet Radio Astronomy.

25 December

5. *G. I. Dimov*, Production of strong beams of negative ions and accelerated hydrogen atoms.
6. *V. A. Kuz'min*, Neutron oscillations (from a visit to CERN).

The papers read at the session of 24 December 1980, which was dedicated to the 100th anniversary of Academician N. D. Papaleksi, appear in the "From the History of Physics" section of this issue; a brief summary of G. I. Dimov's paper is published below.

G. I. Dimov. *Production of strong beams of negative ions and accelerated hydrogen atoms.* During recent decades, a charge-transfer method of modifying the motion of accelerated-particle fluxes based on deliberate variation of the charge state of the particles (particle-energy multiplication in electrostatic accelerators, injection of protons into ring accelerators, extraction of particles from cyclotrons, separation of high-energy beams; accumulation, confinement, heating, and diagnosis of high-temperature plasma) has been used in charged-particle accelerators and in thermonuclear-fusion research.[1] The charge-transfer technique introduces fundamentally new possibilities in these areas of science and engineering, owing to the fact that transfer of particle charges removes the limitations on their motion that are established by the classical Poincare and Liouville theorems.

To bring about charge-transfer processes in proton accelerators and thermonuclear systems, it is necessary to have beams of negative ions and accelerated hydrogen-isotope atoms of appropriate intensity.

One of the principal methods of producing negative-ion beams—a charge-transfer process consisting of double charge reversal of relatively low-energy positive ions to negative ions—began its development in 1956. In 1961, beams of these ions were being produced with intensities no greater than 200 μA.

Using a specially developed multiaperture heavy-current positive-ion source, we increased significantly the intensities of negative-ion beams produced by the charge-transfer method. This ion source[2,3] differed from other sources known at the time in the method used to produce the plasma and in its use of a multiple-slit system for extraction of positive ions from the plasma. The multiple-slit system made it possible to obtain beams of protons with currents up to 3 A at an energy of 13 keV (beam emission diameter 2.2 cm). The 87-$\mu\text{A}\cdot\text{V}^{-3/2}$ maximum perveance obtained in the proton beam corresponded to an increase of the proton current by two orders of magnitude over the current of the conventional single-aperture ion source. The very low content of impurities in the ion beam (the proton content in the beam ranges up to 95%, and there are no more than 1% of heavy elements), the low emission temperature of the plasma (0.25 eV), the good homogeneity of the plasma at the emission surface, and grid stabilization of this surface ensured relatively high beam quality at high intensity.

A beam of H^- ions was obtained by charge transfer between the protons and hydrogen in a charge-transfer tube mounted directly behind the slit extraction system. Good compensation of the space charge of the ions was obtained. By 1968, we had produced beams of H^- ions with currents up to 15 mA,[4] which is 3 times the absolute results that had been obtained in negative-ion production in other laboratories. By 1973, with the first use of the vapor-jet sodium target in sources for charge-transfer conversion of positive to negative ions, well-formed beams of H^- ions with a 76-mA current, of D^- ions with 104 mA, and of He^- ions with currents up to 12.5 mA had been produced.[5] Simultaneously, the current of the H^- ion beam was brought up to 54 mA by charge transfer on hydrogen.[3] These experiments served as a basis for development of a charge-transfer H^--ion source for van de Graaf accelerators, which was used for charge-transfer injection of H^- ions into a storage ring. In 1973, a 200-μsec pulsed beam of H^- ions with an energy of 1 MeV and current of 20 mA was obtained from the charge-transfer injector.[6]

Developmental work on charge-transfer sources continues in other laboratories with the best results obtained thus far having come recently from the scheme that we had tested (a multiple-slit ion-extraction system with charge transfer in sodium vapor). H^-- and D^--ion beams with currents of 1.4 and 2.2 A have been obtained at the I. V. Kurchatov Institute of Atomic Energy (IAÉ) and at Livermore, respectively.[7,8]

In 1965, Ehlers developed a Penning plasma source of H^- ions with a 5-mA current in which the negative ions are formed in a gas-discharge plasma as a result of dissociation of molecules and molecular ions on collisions with electrons.[9] On going from the Penning chamber to a gas-discharge chamber in the form of a flat magnetron (planotron), we succeeded in raising the H^--ion current from the plasma source to 22 mA.[10]

It was found subsequently that proximity of the cathode to the emission orifice in the planotron made it possible to detect an increase in the H^--ion yield when cesium vapor was added to the hydrogen (from 5 to 20 mA).[11] At the same time, we obtained a high H^- secondary emission coefficient from a cesium-coated tungsten surface by bombarding it with ions in a hydrogen atmosphere.[12] This fact, the increase in the H^- yield with decreasing thickness of the plasma layer between the cathode and the emission orifice, the decrease in H^- yield with increasing density of the hydrogen, and the saturation of this yield with increasing plasma density pointed to the conclusion that strong H^--ion fluxes from a plasma depend on emission of these ions into the discharge from the surface of the cathode. Optimization of the geometry and discharge regime on the basis of this conception resulted early in 1972 in the production of H^--ion beams with a current of 200 mA.[13] Studies of the energy spectra of the H^- ions produced and various other experiments,[14,15] together with calculations of the H^--ion yield from the surface,[16,17] definitely established the following surface-plasma mechanism of formation of strong H^--ion fluxes from a hydrogen plasma with a cesium impurity.[18,19]

The electrodes are bombarded in the gas-discharge plasma by fast ions and atoms formed as a result of ionization of the gas, acceleration of ions in electric fields, dissociation of molecular ions, and charge transfer between particles. Reflection of the fast particles and their dispersal of the hydrogen sorbed on the electrodes give rise to a high-velocity flux of hydrogen particles from the electrode surfaces. As a result of electron exchange between the electrode and the outgoing particles, some of the outgoing atoms capture electrons at the electron-affinity level and cross the surface barrier in the form of free negative ions. If the plasma above the electrode is thin enough, the negative ions leaving the electrode surface can pass through the plasma layer to the extraction system without large losses. Emission of negative ions from a cathode is most favorable: the density of the bombarding ions and atoms is higher, and the negative ions leaving from the surface are accelerated in the near-cathode potential drop. Sorption of cesium lowers the electrode-surface work function. Under gas-discharge conditions, however, it is not possible to lower the work function below 1.5 eV, which is still quite far above the electron-affinity energy of the hydrogen atom. The unexpectedly high (~1) yield of H^- ions from the surface under these conditions is explained by the long-range action of the electron image forces and the high velocity (~10 eV) of most of the reflected and dispersed hydrogen particles.

By 1973, the surface-plasma method was being used to produce H^--ion beams with currents up to 300 mA at emission densities up to 3.7 A/cm^2.[14] By 1974, the H^--ion current had been increased to 0.9 A,[20] and by the end of 1979 an H^--ion beam with a current of 4 A had been produced.[21] By 1977, a surface-plasma source had been developed for accelerators—specifically, for the meson factory being built in the USSR.[22, 23] Its parameters: pulsed beam intensity up to 150 mA, pulse duration up to 300 μsec, pulse repetition frequencies up to 100 Hz, and ion energies up to 30 keV.

The surface-plasma method can be used to obtain negative ions not only of hydrogen, but also of many other elements. It is possible in principle to build quasistationary multiampere surface-plasma sources with sufficiently high gas efficiencies for thermonuclear system atom injectors. Work on the development of surface-active negative-ion sources is being advanced in various other laboratories.

The surface-plasma method permits generation of strong hydrogen-atom beams with energies of the order of 100 eV: negative ions formed on the surface of the gas-discharge-chamber cathode are accelerated in the cathodic potential drop and, on passage through a moderately thick plasma and gas layer, are converted to a fast-atom flux. In 1979, this scheme was used to produce a beam of hydrogen atoms with a current of 2.7 A, an energy of 200 eV, and an energy scatter of ±15%.[24]

In 1973–1976, a number of laboratories developed several types of atomic-hydrogen injectors with currents in the tens of amperes and energies in the tens of keV for thermonuclear installations.[25–28] These injectors are plasma sources of positive ions with large emission areas and multiple-aperture extraction systems, in which, immediately after extraction and acceleration, the ions are recharged to atoms on interacting with the hydrogen leaving the sources. At the present time, the currents and energies of the atomic beams from such injectors are approaching 80 A and 120 keV, respectively.

At Novosibirsk, we are working on the development of similar atomic injectors with high (95%) content of atomic ions in the primary beam. In 1980, a beam of hydrogen atoms with an energy of 25 keV and a current of 35 A was produced here. The DINA-1, DINA-2, and DINA-3 diagnostic atomic injectors with energies up to

25 keV and currents up to 3.5 A were developed in 1974–1979; they are distinguished by low scatter of energy and angle. The local parameters of ions in high-temperature tokamak plasmas were first measured on the T-4 unit of the I. P. Kurchatov IAÉ with the aid of DINA-1 injector. The DINA-3 injector had been installed on the T-10 tokamak.

The yield of hydrogen atoms from positive ions on charge transfer drops off rapidly with energy, amounting to ~20% at 100 keV per nucleon. At energies above 50–100 keV/nucleon, it is more advantageous to produce hydrogen atoms by conversion from accelerated negative ions. We have proposed and tested experimentally a plasma target in which H^- and D^- ions are converted to atoms with energies up to 1 MeV and higher with a conversion coefficient of 84%.[32–34] The state of development of surface-plasma and charge-transfer H^- and D^--ion sources is encouraging for the development of powerful high-energy hydrogen-atom injectors for thermonuclear installations in the very future.

[1] G. I. Dimov and V. G. Dudnik, Fiz. plazmy **4**, 692 (1978) [Sov. J. Plasma Phys. **4**, 388 (1978)].

[2] G. I. Dimov, Yu. G. Kononenko, O. Ya. Savchenko, and V. G. Shamovskiĭ, Zh. Tekh. Fiz. **38**, 997 (1968) [Sov. Phys. Tech. **13**, 754 (1969)].

[3] G. I. Dimov and G. V. Roslyakov, Prib. Tekh. Éksp. No. 1, 29 (1974).

[4] G. I. Dimov and O. Ya. Savchenko, Zh. Tekh. Fiz. **38**, 2002 (1968) [Sov. Phys. Tech. Phys. **13**, 1609 (1969)].

[5] G. I. Dimov and G. V. Roslyakov, Prib. Tekh. Éksp. No. 3, 31 (1974).

[6] G. I. Dimov and G. V. Roslyakov, Prib. Tekh. Éksp. No. 2, 33 (1974).

[7] N. N. Semashko, V. V. Kusnetsov, and A. I. Krylov, In: Proc. of Symposium on Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven. BNL-50727, 1977, p. 170.

[8] E. B. Hooper, Jr. and P. Poulsen, Preprint LLL UCRL-84962, Livermore, 1980.

[9] K. W. Ehlers, Nucl. Instrum. and Meth. **52**, 309 (1965).

[10] Yu. I. Bel'chenko, G. I. Dimov, and V. G. Dudnikov, Zh. Éksp. Teor. Fiz. **43**, 1720 (1976) [Sov. Phys. JETP **70**, 896 (1976)].

[11] V. G. Dudnikov, Author's Certificate, Intl. Cl. HOI 3/40, No. 41152, Byull. izobreteniĭ No. 2 (1974).

[12] E. D. Bender, G. I. Dimov, and M. E. Kishinevskiĭ, in: Trudy I Vsesoyuznogo seminara po vtorichnoĭ ion-ionnoĭ emissii (Proceedings of First All-Union Seminar on Secondary Ion–Ion Emission), p. 119, Khar'kov, 1975; VINITI File No. 2783-75 (1975).

[13] G. I. Dimov, Report at II Symposium on Ion Sources and Formation of Ion Beams, Berkeley, 1974.

[14] Yu. I. Bel'chenko, G. I. Dimov, V. G. Dudnikov, and A. A. Ivanov, Dokl. Akad. Nauk SSSR **213**, 1283 (1973) [Sov. Phys. Dokl. **18**, 814 (1974)].

[15] Yu. I. Bel'chenko, G. I. Dimov, and V. G. Dudnikov, Zh. Tekh. Fiz. **43**, 1720 (1973) [Sov. Phys. Tech. Phys. **18**, 1083 (1974)].

[16] M. E. Kishinevskiĭ, *ibid.* **45**, 1281 (1975) [**20**, 799 (1975)].

[17] M. E. Kishinevskiĭ, *ibid.* **48**, 773 (1978) [**23**, 456 (1978)].

[18] Yu. I. Bel'chenko, G. I. Dimov, and V. G. Dudnikov, *ibid.* **45**, 68 (1975) [**20**, 40 (1975)].

[19] Yu. I. Bel'chenko, G. I. Dimov, V. G. Dudnikov, collection cited in [7], p. 79.

[20] Yu. I. Bel'chenko, G. I. Dimov, and V. G. Dudnikov, Nucl. Fusion 14, 113 (1974).

[21] Yu. I. Bel'chenko and V. G. Dudnikov, Preprint 80-34, Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences, Novosibirsk (1980).

[22] V. G. Dudnikov, in: Trudy IV Vsesoyuznogo soveshchaniya po uskoritelyam zaryazhennykh chastits (Proceedings of IV All-Union Conference on Charged-Particle Accelerators), Moscow, 1974, Nauka, Moscow, 1975, Vol. 1, p. 327.

[23] G. I. Dimov, G. Ye. Derevyankin, and V. G. Dudnikov, IEEE Trans. Nucl. Sci. **NS-24**, 1545 (1977).

[24] V. G. Dudnikov and G. I. Fiksel', Fiz. plazmy **6**, No. 6 (1980) [*sic*].

[25] K. W. Ehlers, W. K. Baker, K. H. Berkner, W. S. Cooper, W. B. Kunkel, R. V. Pyle, and J. W. Stearns, J. Vac. Sci. and Technol. **10**, 922 (1973).

[26] N. N. Semashko, N. V. Pleshivtsev, V. V. Kusnetsov, B. P. Maximenko, and N. P. Malakhov, in: Proc. of II Symposium on Ion Sources and Formation of Ion Beams. Berkeley, California, LBL-3399, 1974, Rept. VI-11.

[27] W. L. Stirling, R. C. Davis, O. B. Morgan, D. E. Schechter, L. D. Stewart, and R. E. Wright, *ibid.* Rept. VI-10.

[28] M. Furmelli and F. P. G. Valckx, Nucl. Instrum. and Meth. **135**, 203 (1976).

[29] G. I. Dimov, G. V. Roslyakov, and V. Ya. Savkin, Prib. Tekh. Éksp. No. 4, 29 (1977).

[30] G. V. Roslyakov and V. Ya. Savkin, *ibid.* No. 1, 148 (1978).

[31] V. I. Davydenko, I. I. Morozov, and G. V. Roslyakov, Preprint 80-118, Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences, Novosibirsk (1980).

[32] G. I. Dimov and G. V. Roslyakov, Nucl. Fusion **15**, 551 (1975).

[33] G. I. Dimov, A. A. Ivanov, and G. V. Roslyakov, Fiz. Plazmy 6, 933 (1980) [Sov. J. Plasma Phys. **6**, 513 (1980)].

[34] A. A. Ivanov and G. V. Roslyakov, Zh. Tekh. Fiz. **50**, 2300 (1980) [Sov. Phys. Tech. Phys. **25**, 1346 (1980)].

Translated by R. W. Bowers