In conclusion, we note that at the same particle energy averaged over the period of the HF field, the value of $\tilde{V}/V_0$ is larger by a factor $\sqrt{M_i/M_e}$ in the case of electrons that for singly-charged ions. Therefore the influence of the HF potential on the trapping of the electrons may become manifest at relatively small values of the electric field intensity, which are characteristic of plasma experiments.

The authors are grateful to V.G. Ustyuzhaninov for performing the computer calculations.

[1] A.A. Ware, Phys. Rev. Lett. 25, 15 (1970).
[2] A.A. Galeev, Zh. Eksp. Teor. Fiz. 59, 1378 (1970) [Sov. Phys.-JETP 32, 752 (1971)].
[3] P.H. Rutherford, L.M. Kovrizhnikh, M.N. Rosenbluth, and F.L. Hinton, Phys. Rev. Lett. 25, 1090 (1970).
[4] M. Dobrowolny and O.P. Pogutse, Phys. Rev. Lett. 25, 1608 (1970).
[5] R.A. Demirkhanov, T.I. Gutkin, and S.N. Lozovskii, Zh. Eksp. Teor. Fiz. 55, 2195 (1968) [Sov. Phys.-JETP 28, 1164 (1969)].
[6] N.A. Bobyrev and O.I. Fedyanin, Zh. Tekh. Fiz. 33, 1187 (1963) [Sov. Phys.-Tech. Phys. 8, 887 (1964)].
[7] A.V. Gaponov and M.A. Miller, Zh. Eksp. Teor. Fiz. 34, 242 (1958) [Sov. Phys.-JETP 7, 168 (1958)].
[8] R.A. Demirkhanov, D.G. Baratov, N.I. Malykh, V.G. Merezhkin, M.A. Stotland, Yu. Ten, and Sh.V. Khil', ibid. 60, 569 (1971) [33, 309 (1971)].

## INFLUENCE OF LONGITUDINAL STREAMS OF CHARGED PARTICLES ON THE DIFFUSION OF PLASMA IN A STELLARATOR

I.A. Kossyi
P.N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 21 June 1971
ZhETF Pis. Red. 14, No. 3, 188 - 191 (5 August 1971)

The rates of decay of plasma injected by an external source, observed in experiments with the double-entry stellarator of the Physics Institute of the USSR Academy of Sciences L-1 [1], have not yet been reconciled with calculations performed within the framework of any theoretical model [1, 2].

Undertaking the next attempt to explain the mechanism of plasma loss in closed traps, we turn in the present article to a phenomenon observed in the L-1 [3, 4], namely the existence of an average velocity of the ion component ($u_{z_i}$) along the minor axis of the toroidal chamber (the Z axis). A qualitative analysis and a rigorous theoretical analysis carried out in [4] and [5] enable us to state that the longitudinal ion streams should of necessity arise in closed traps in the regime of weak-collision plasma with a radial electric field $E_r$. The cause of the directional streams is the recoil momentum acquired by the "untrapped" ions as a result of the increased velocity of the drift of the "trapped" ions, which have at $E_r \neq 0$ an average axial velocity $\bar{v}_Z \simeq V_E/\Theta$ ($V_E = cE_r/H_Z$). The measurement procedure used in [3] and [4] has made it possible to determine the average directional velocity only for the ionic component. However, the plasma as a whole takes part in the rotation about the principal axis of the torus. Dragging of the electrons along the Z axis should be caused by the ion-electron interaction.

The axial velocity acquired by the electronic component can be estimated from the relation

$$\bar{u}_{Z_e} = \frac{\nu_{ei}}{\nu_{ei} + \nu_{en}} \bar{u}_{Z_i} \quad (1)$$

where $\nu_{ei}$ and $\nu_{en}$ are the electron-ion and electron-neutral collision frequencies, respectively. Under the experimental conditions in the L-1, $\nu_{ei} >> \nu_{en}$ and consequently $\bar{u}_{Z_e} \simeq \bar{u}_{Z_i}$.

To clarify the significance of the presence of the longitudinal electron motion from the point of view of transverse plasma transport, we turn to [5 - 7]. These investigations constitute a development of the theory of diffusion by pair collisions with allowance for the toroidality of the chamber (the so-called "neoclassics") and differs from the preceding investigations in that they have studied, for the first time, effects connected with the existence of longitudinal electric fields $E_Z$ in axially-symmetrical closed traps. It has been shown that in longitudinal electric fields the plasma (due to the drift of the "trapped" particles) acquires an average radial velocity $u_r$. In a magnetic trap of the Tokamak type, the velocity $u_r$ is directed from the periphery of the chamber towards the Z axis, and the diffusion process recalls in this case the pinching of a plasma column.

The analysis in [5 - 7] shows that the radial velocity $u_r$ acquired by the plasma is a result of the occurrence of friction force between the "trapped" and "untrapped" particles, whenever the latter have a certain average longitudinal velocity $u_{Z_i}$. Formally, from the point of view of the form of the mathematical expression obtained for the transverse flux [5], and by the very physical nature of the phenomenon, it is immaterial what causes the establishment of the average axial velocities. In the case analyzed in [5 - 7], the longitudinal motion is the result of the existence of the electric field $E_Z$. On the other hand, if $E_Z = 0$, but nonetheless, owing to some mechanism (in particular, the one noted in [4, 5]), the "untrapped" particles are accelerated along the toroidal chamber and phenomena analogous to those predicted in [5 - 7] should occur in the plasma. The radial velocity acquired by the charged particles because of the appearance of the axial motion can be determined from the relation

$$\bar{u}_{r_i} = a \frac{m_i \nu_i \bar{u}_{Z_i} c}{e H_Z \Theta} (r/R)^{1/2} \quad (2)$$

($\alpha$ is a numerical coefficient, equal to 2.1 for electrons). The sign of the velocity $\bar{u}_{r_i}$ (determined by the direction of $u_{Z_i}$, $\Theta$, and $H_Z$) may in the general case not coincide with the sign predicted for the Tokamak.

From the point of view of the experiment on the L-1, greatest interest attaches to an analysis of the behavior of the electrons, the drift velocities of which govern the lifetime of the plasma in the trap. The negative potential acquired by the plasma contained in the L-1 [1] is evidence that the ion diffusion velocity exceeds the electron diffusion velocity. The mechanism whereby the ions are lost is apparently connected with the drift into the "loss cone," which is produced in velocity space [4]. The axial motion motion of the electronic component, observed in the L-1 stellarator, should lead, according to (2), to the appearance of the transverse velocity $\bar{u}_{r_e}$. It is easy to show that under the mechanism considered in [4, 5] for the acceleration of the charged particles along Z, the transverse displacement of the electrons should be in the direction from the axis of the toroidal chamber towards the periphery, increasing thereby the plasma loss rate.

The role of the processes connected with the longitudinal electron flux can be estimated by introducing the coefficient $\kappa$, which, starting from the results of [5], can be expressed in the form

$$\kappa = \frac{\tau_0}{\tau(\bar{u}_{Z_e})} = \frac{\omega_{c_e} \Theta \bar{u}_{Z_e}}{v_{T_e}^2 \dfrac{\partial \ln n_e T_e^{-0.38}}{\partial r}} \qquad (3)$$

Here $\tau_0$ is the plasma lifetime calculated in the absence of longitudinal electron motion, and $\tau(\bar{u}_{Z_e})$ is the lifetime corresponding to the transverse velocity $\bar{u}_{r_e}$ determined from relation (2). $\omega_{c_e}$ is the cyclotron electron frequency. Under the experimental conditions characteristic of the L-1, $\kappa > 1$. ($\kappa \simeq 10$ for $H_Z \simeq 10$ kOe).

Substituting in (2) the expression for the Coulomb collision frequencies and recognizing that $\tau(\bar{u}_{Z_e}) \simeq 0.5\ (a/u_{r_e})$ (where a is the transverse dimension of the plasma) we obtain that (for a = 3 cm and a/R ≃ 1/20):

$$\tau(\bar{u}_{Z_e}) = 10^{12} \frac{T_e^{3/2} H_Z \Theta}{n_e \bar{u}_{Z_e}} \qquad (4)$$

For $T_e \simeq 2$ eV, $H_Z = 3$ kOe, $\Theta = 1/30$, $n_e = 2 \times 10^{10}$ cm$^{-3}$, and $u_{Z_e} = 5 \times 10^6$ cm/sec we get from (4) $\tau(\bar{u}_{Z_e}) \simeq 3$ msec, which is close to the experimentally measured value $\tau_{exp} \simeq 1 - 2$ msec.

The author is deeply grateful to M.S. Rabinovich, L.M. Kovrizhnykh, I.S. Shpigel', M.S. Berezhetskii, S.E. Grebenshchikov, and I.S. Sbitnikova for interest in the work, discussions, and useful remarks.

[1] M.S. Bereshetskii, S.A. Grebenshchikov, I.A. Kossyi, Yu.I. Nechaev, M.S. Rabinovich, I.S. Sbitnikova, and I.S. Shpigel', Paper CN-24/D-5 at the Third International Conference on Plasma Physics and Controlled Fusion, Novosibirsk, 1968.

[2] M.S. Berezhetskii, S.E. Grebenshchikov, L.M. Kovrizhnykh, I.A. Kossyi, I.S. Sbitnikova, and I.S. Shpigel', Paper at Third European Conference on Controlled Fusion and Plasma Physics, Utrecht, 1969.

[3] M.S. Berezhetskii, S.E. Grebenshchikov, I.A. Kossyi, and I.S. Shpigel', Paper at Fourth European Conference on Controlled Fusion and Plasma Physics, Rome, 1970.

[4] M.S. Berezhetskii, S.E. Grebenshchikov, I.A. Kossyi, I.S. Sbitnikova, and I.S. Shpigel', Paper CN-28/160 at Fourth International Conference on Plasma Physics and Controlled Fusion, USA, 1971.

[5] L.M. Kovrizhnykh, Paper CN-28/161 at Fourth International Conference on Plasma Physics and Controlled Fusion, USA, 1971.

[6] P. Rotherford, L. Kovrizhnikh, and M. Rosenbluth, Paper at Fourth European Conference on Controlled Fusion and Plasma Physics, Rome, 1970.

[7] A.A. Galeev, Diffusion-electrical Phenomena in a Plasma Contained in a Tokamak, Preprint, Nuclear Physics Institute, 25 - 70, Novosibirsk, 1970.

[8] A.A. Galeev and R.Z. Sagdeev, Zh. Eksp. Teor. Fiz. 53, 359 (1967) [Sov. Phys.-JETP 26, 1115 (1968)].
[9] L.M. Kovrizhnykh, ibid. 56, 877 (1969) [29, 475 (1969)].

# NEW TYPE OF BARYON RESONANCES

O.D. Dal'karov, B.O. Kerbikov, V.B. Mandel'tsveig, and I.S. Shapiro
Submitted 25 June 1971
ZhETF Pis. Red. 14, No. 3, 191 - 194 (5 August 1971)

In [1 - 4] there were considered nonrelativistic (quasinuclear) bound states of the nucleon-antinucleon system, i.e., boson resonances with masses close to two nucleons (from 1300 to 1860 MeV). It was found that the spectrum of these bosons includes 17 particles with isospins $I \leq 1$, spins $J \leq 3$, and widths $\Gamma$ from 60 to 150 MeV.

In the present paper we report results of an analysis of quasinuclear bound states of a system of three particles - two nucleons and one antinucleon ($2N\bar{N}$). Such systems have a baryon number B = 1 and should appear as baryon resonances with masses in the region 2 - 3 GeV. A distinguishing feature of these baryon resonances is that the decay channel $N^* \to N + X$ (X is one of the light bosons $\pi$, $\eta$, or $\rho$) should not be dominating for these resonances. Therefore the quasinuclear baryon resonances can hardly appear in $\pi N$ scattering. The most probable should be decays into a nucleon and several (4 - 5) pions (more accurately, into a nucleon plus the annihilation products of the $N\bar{N}$ pair in definite states).

For a theoretical investigation of the quasinuclear states of the $2N\bar{N}$ system, we use in the present paper a potential approach: we take as the interaction Hamiltonian the sum of the pair potentials

$$H = V(r_{NN}) + \bar{V}(r_{N\bar{N}}) + \bar{V}(r_{N'\bar{N}}) \qquad (1)$$

Here V and $\bar{V}$ are the Bryan-Scott (BS) [5] and Bryan-Phillips (BP) [6] potentials for the NN and $N\bar{N}$ interactions. These potentials, which are modifications of the OBEP, describe satisfactorily the experimental data on the NN and $N\bar{N}$ scattering, and can be transformed into each other by G-conjugation. The BP potential was used in the cited papers on the NN quasinuclear bound states.

Two primary questions arise in connection with the $2N\bar{N}$ systems: a) does the Hamiltonian (1) yield nonrelativistic bound states, and b) of what order of magnitude are the widths of such states? The first question is connected with the fact that even in the $N\bar{N}$ system the binding energy is on the average much larger than for ordinary nuclei. It might therefore turn out that the binding energy per particle in the $2N\bar{N}$ system is larger than the mass of the nucleon and consequently there exists no nonrelativistic approach to the theory of such systems. The question of the widths is not trivial for the following reason: at first glance it seems that the annihilation width of the $2N\bar{N}$ system should be 1.5 - 2 times larger than the width of the NN two-particle state. Since the latter itself reaches 150 MeV, the expected width of the quasinuclear baryons turns out to be on the order of 300 MeV. But then a relatively small (by a factor 1.5) increase of the particle density in the annihilation region may turn out to be critical for the existence of the resonance.

The energy spectrum and the wave functions of the $2N\bar{N}$ system were investigated by us with the aid of the multidimensional harmonic method [7]. The wave function was constructed in a multidimensional harmonic basis with allowance for the generalized Pauli principle. According to this principle, the wave function of the $2N\bar{N}$ system should be antisymmetrical against permutation of the coordinates, spins, isospins, and baryon charges of any two particles. Thus, the wave function is represented in the form of the series