Electron cooling and new possibilities in elementary particle physics

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Usp. Fiz. Nauk **124**, 561–595 (April 1978)

This review is devoted to a new method in experimental physics—electron cooling, which opens the possibility of storing intense and highly monochromatic beams of heavy particles and carrying out a wide range of experiments with high luminosity and resolution. The method is based on the cooling of beams by an accompanying electron flux as the result of Coulomb collisions of the particles. In the first part of the review the theoretical basis of the method is briefly considered. The apparatus NAP-M is described with its electron cooling, and the results of successful experiments on cooling a proton beam are presented. In the second part the new possibilities opened by the use of electron cooling are discussed: storage of intense beams of antiprotons and achievement of proton-antiproton colliding beams, performance of experiments at the ultimate in low energies (with participation of antiparticles), storage of polarized antiprotons and other particles, production of antiatoms, storage of antideuterons, and experiments with ion beams.

PACS numbers: 29.25.Fb, 29.20.Dh

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INTRODUCTION

In carrying out almost any experiments with use of beams of charged particles, it is of fundamental importance to be able to compress the beams, to decrease their size and the momentum spread of the particles (in magnitude and direction), in other words, to be able to "cool" the flux of fast charged particles, lowering their effective temperature in the accompanying system.

However, this cannot be achieved by use of any specified external electromagnetic fields, i.e., fields which do not depend on the motion of the individual particles of the beam. The principle which applies in this case—a special case of Liouville's theorem—is that the density of the particles of a beam in six-dimensional phase space (the space of generalized coordinates and conjugate momenta) is a quantity which is constant and determined by the initial conditions. By means of focusing and acceleration in any combination one can only change the shape of the phase space occupied by the beam particles but cannot change its magnitude or increase the phase density. Aberrations of any kind can, of course, greatly distort the shape of the volume and make it so complex that the effective phase density decreases. However, to *increase* the density it is essential to introduce forces of a dissipative nature.

Logically the simplest procedure is to use for this purpose dissipative forces analogous to ordinary friction and directed against the total velocity of each particle. If the external energy source in this case (the accelerating system of the accelerator or storage ring) adds energy to all particles of the beam, exactly compensating the energy loss of the equilibrium particle, the deviations of the particles from the equilibrium motion, for a correct choice of the storage-ring structure, will decrease with the passage of time, i.e., the betatron and synchrotron oscillations will be damped.

The characteristic damping time in this case is the ratio of the particle energy to the rate of energy loss and is equal to the time of complete stopping of a particle for an energy loss which does not depend on the particle energy. Damping of the deviations of the particle energy from the equilibrium value is due to the dependence of the rate of energy loss on the particle energy. In the simplest case these deviations are damped if the rate of energy loss increases with increasing particle energy; in the opposite case the deviations from the equilibrium energy will increase with time. In more complex cases, for example, in the presence of acceler-

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[1] Dr. Budker died July 4, 1977.

0038-5670/78/040277-20$01.10

ator-related coupling between the degrees of freedom of a particle, the damping decrements in individual degrees of freedom can change. However, the sum of the damping decrements of the phase volumes in all three independent degrees of freedom of the particles, i.e., the increment of increase of the phase density, does not depend here on the focusing structure of the storage ring and is determined by the sum of the ratio of twice the rate of energy loss to the particle energy and the partial derivative of this rate with respect to energy.

The beam will be compressed to dimensions determined by the equality of the frictional power (rate of energy loss) and the power of the diffusion processes.

The best known and most effectively used example of this type is the use of radiation damping (the forces of the reaction of radiation) for cooling electron and positron beams, which is of crucial importance for storage of large positron currents and for achievement of experiments with colliding electron-electron beams and, in particular, electron-positron beams. Such experiments, begun in 1967 with experiments at Novosibirsk, now provide a significant part of all fundamental information on elementary-particle physics.

In radiation cooling the diffusion effect which is in principle present and which at high energies is dominant is the quantization of the energy radiated by charged particles, which leads to an increase of the energy spread and a buildup of the transverse oscillations. Radiative friction turns out to be important only for the lightest charged particles—electrons and positrons—and only at a sufficiently high energy. For all other particles it is necessary to seek other methods of cooling.

For this purpose it is possible to use energy loss by ionization, placing in the storage ring or accelerator a target of the required thickness. For nonrelativistic energies the friction thus introduced turns out to be substantially reduced as the result of the large negative derivative of the rate of energy loss with respect to energy. And for all energies an unpleasant aspect of this method is the rapid diffusion due to multiple scattering of the particles by the nuclei and electrons of the target. The steady-state phase volume of the beam cannot be made particularly small even when the target is installed at an azimuth with a beam size specially reduced as the result of choice of the focusing structure of the storage ring (at a sharp minimum of the β-functions) and with use of the lightest possible materials.

For protons and antiprotons at high energies the situation is considerably less favorable because of the increase in the relative role of nuclear interactions of these particles, as a result of which the lifetime becomes less than the cooling time.

The most reasonable field of application of ionization cooling is the cooling of high-energy muons, which have no nuclear interaction. Cooled beams of muons (in cyclic installations) can be used, for example, to generate very narrowly directed and intense fluxes of neutrinos of all four types, either allowing the muons to decay directly at the cooling energy, or accelerating the muons in linear accelerators or short-pulse cyclic accelerators, thereby increasing the neutrino energy. Of particular interest is the construction of apparatus with colliding muon beams at ultrahigh energies, utilizing intense cooled muon beams of the necessary energy, guide magnets with very high fields (to increase the number of collisions during the muon lifetime), and special compression of the beams at the point of collision.

For protons, antiprotons, and ions a qualitatively new method of cooling beams of charged particles has turned out to be very effective, a method which does not involve energy loss of the equilibrium (central) particles of the beam. This method—electron cooling—was proposed by one of the authors at the beginning of the 1960s and was published in 1966.[1] At the present time at our Institute in Novosibirsk the method has been studied in detail theoretically[2–7] and experimentally.[8–29] The present review is devoted to a discussion of the physical and technical problems of electron cooling and of a wide range of applications of the technique which are apparent at this time. The review is based mainly on the work of G. I. Budker, Ya. S. Derbenev, N. S. Dikanskiĭ, I. N. Meshkov, V. V. Parkhomchuk, D. V. Pestrikov, R. A. Salimov, A. N. Skrinskiĭ, and B. N. Sukhina.

In its simplest form the idea of the method is as follows. In one of the straight sections of a storage ring in which a beam of heavy particles, for example, protons, is circulating, an intense beam of electrons with the same average velocity and a small momentum spread is passed parallel to the proton beam. Then at a common region of the trajectory in the rest system of the beams the "hot" proton gas is within the "cold" electron gas and is cooled as the result of Coulomb collisions. The cooling time corresponds to the relaxation time of the proton-gas temperature (taking into account the relativistic time dilation and the duty cycle of each proton in the electron beam). As a result the phase space of the proton beam decreases in all degrees of freedom and the beam is compressed.

This compression continues in principle until the proton temperature in the center-of-mass system becomes equal to the electron temperature. Hence it follows that the steady-state angular spread θ_p in the proton beam is less than the electron angular spread by a factor $\sqrt{M/m}$:

$$\theta_p = \sqrt{\frac{m}{M}}\,\theta_e.$$

Since the value of θ_e can be made of the order of 10^{-3}, the steady-state angular spread for protons or antiprotons can be reduced to 10^{-5}.

A completely different method which also may turn out to be applicable to compression of beams of heavy particles is the method of stochastic cooling.[30–40] The idea is that a very fast negative-feedback system is introduced in the storage ring, which quenches the local (azimuthal) fluctuations in the location of the center of gravity of the beam; the remaining degrees of freedom of the beam, which as a rule consists of a very large number of particles (10^7–10^{14}) must be cooled as the result of transfer of the momentum spread of the particles into oscillations of the center of gravity of the beam resulting from the spread in energy and, correspondingly in frequency of revolution. The efficiency of cooling falls off with increase of the number of particles, but at the same time it falls off comparatively weakly with increase of the energy and with increase of the phase space of the beam. The limit for cooling depends on the level to which it is possible to reduce the noise in the negative-feedback system; obtaining very low noise in such a wideband electronic system with high gain is not a simple problem. At CERN, encouraging initial experimental results have been obtained in the ISR proton storage ring and at the present time detailed experiments are planned. If they are successful this method will become an important supplement to the electron-cooling method.

1. GENERAL DESCRIPTION OF ELECTRON COOLING

The characteristic features of the electron-cooling process and the problems which arise in putting it into practice depend strongly on the energy region at which the cooling is carried out.

a) At comparatively low energies corresponding to electron energies up to 2–3 MeV (proton or antiproton energy up to 4–6 GeV), the most natural arrangement is use of direct electrostatic acceleration of the electrons to the necessary energy and with subsequent inflection into the cooling region and collection on a collector after extraction. In this case, while at very low energies (electron energies up to several keV) the problem of the power drawn from the high-voltage source and dissipated in the collector is practically nonexistent, on the other hand for electron energies of hundreds of keV and above this problem becomes one of the principal technical problems. A natural solution for this energy region is the use of energy recovery, i.e., slowing the electrons down to the lowest possible energy before they hit the collector, which is connected to the accelerating voltage source U_0 through a rectifier with a small positive bias voltage U_c. The voltage U_c must be sufficient for collection of the entire cooling electron current J_e on the collector (sufficient to overcome space-charge limitation). The product UJ_e in practice is what determines the power drawn from the supply and dissipated in the collector. The voltage U_c can be reduced to a level of the order of a kilovolt and correspondingly the ratio of the power dissipation to the reactive power U_0J_e can be reduced to a level of 1% or even lower.

The current requirement from the main accelerating-voltage source is determined by the loss of electrons due to scattering in the residual gas, by the ionization in the accelerating and decelerating sections (and without special measures being taken also in the cooling section), by the defects in the electron optics, and by the loss at the collector. This requirement can be reduced to a level of 10^{-4}. Such a low load on the main power source is very convenient, since the requirements on voltage stability and absence of fluctuations for the source are extremely high.

In cooling a bunched beam of heavy particles, in order to reduce the average electron current it is possible to switch off the electron gun during the entire time when there are no particles being cooled in the cooling section, with a corresponding advantage in average electron current. It is only necessary to ensure that the modulation of the electron current does not lead to modulation of the electron energy and an increase of the electron temperature.

b) An important problem is to assure transport of the intense electron beam over large distances (long cooling regions) while retaining a low effective electron temperature. Compensation of the transverse repulsion of the electrons requires introduction of focusing which is adequately distributed and of short focal length. In principle it is possible to introduce external fields of various configurations. However, any axial focusing can prevent the appearance of additional transverse velocities only for a given value of electron current; on change of the current it is necessary to readjust the focusing. Moreover, external axial focusing in a straight cooling section cannot be uniform over the length—the use of quadrupole lenses is unavoidable. The alternating sign of the focusing obtained leads to appearance of additional angles in the electron beam. But the use of ions accumulated in the beam for automatic space-charge compensation of the electron beam can lead to appearance of various types of plasma instabilities.

It is much more reasonable to use a longitudinal magnetic field, uniform except for the places of inflection and extraction, accompanying the electron beam from the cathode to its exit from the cooling region; the action of the longitudinal field on the protons must be taken into account, of course, in the focusing structure and corrections of the storage ring. Here the transverse electron velocities arising as the result of the action of space charge of the electron beam are smaller, the larger is the longitudinal magnetic field, and it is comparatively easy to make them less than the temperature velocities. Here the longitudinal field $H_\parallel$ must satisfy the condition

$$H_\parallel > \frac{\pi e n_e r_0}{\beta\gamma^2\theta_e},$$

where e is the electronic charge, n_e is the electron-beam density, r_0 is the radius of its cross section, β equals the ratio of the particle velocity to the velocity of light, and $\gamma = (1-\beta^2)^{-1/2}$.

If the accompanying magnetic field is sufficiently large, the transverse velocities of the electrons are determined mainly by the cathode temperature and the imperfections in the beam optics; we note that the transverse velocities in the moving system are preserved in electrostatic acceleration.

In regard to the spread of longitudinal velocities of the electrons in the moving system, the contribution of the initial electron temperature (of the order of the cathode temperature T_c) drops sharply on acceleration by a potential, since the conserved quantity is the energy spread[23]:

$$T_\parallel \approx \frac{T_c^2}{2\gamma^2\beta^2 mc^2} \rightarrow T_c \frac{T_c}{4E_{\mathrm{kin}}}\bigg|_{\beta\ll 1}. \tag{1.1}$$

The transverse velocities of the electrons make a contribution of the same order to their longitudinal temperature. If the transverse temperature turns out to be for any reason higher than the cathode temperature, its contribution to the longitudinal temperature increases correspondingly. For not too low energies, other sources of longitudinal velocity spread become dominant: fluctuations of the accelerating voltage, coherent instabilities in the intense electron beam, and for very long cooling sections—collisions of the electrons with each other with transfer of a part of the transverse momenta to longitudinal momenta (the manifestation of a tendency to equalization of the longitudinal and transverse temperatures).

A separate question is the appearance in the case of large electron currents of a quite substantial potential difference inside the beam and accordingly a dependence of the electron energy on the distance from the center of the beam. This circumstance affects the cooling efficiency and may require, for example, compensation of the electron charge by light positive ions.

c) For proton energies of the order 4–6 GeV and above (electron energy 2–3 MeV and above) the use of the arrangement described above to produce the electron beam already becomes unreasonable and it is necessary to go over to a closed orbit in which an electron beam with the necessary value of instantaneous current and density is injected from an external source. The magnetic-field configuration must provide the possibility of cyclic motion of the electrons and sufficiently strong transverse focusing. At low energies it is perhaps reasonable to use again for focusing an accompanying longitudinal magnetic field, making it closed and toroidal. An intense cyclic beam will rather rapidly be heated, primarily as the result of coherent instabilities. To avoid an excessive increase of temperature at electron energies of about 10 MeV and below, the only available method is to replace the beam by a new batch of cold electrons. Here the average power consumed by the system will be reduced in proportion to the ratio of the electron revolution time in the toroid to the heating time of the electron beam.

At still higher energies it becomes possible to use radiative cooling of the electrons. It is possible to choose the electron-storage-ring structure such that at least the "single-particle" electron temperature will be sufficiently low.

If the proton beam being cooled has been bunched into short bunches, then of course it will be reasonable to use electron bunches of the same length, with the electron bunching coefficient reducing the average circulating electron current for a constant cooling effect.

With a circulating electron beam the ratios between the frequencies of orbital motion of the protons and of the cooling electrons apparently become important and it may be possible to achieve resonance enhancement of the cooling.

Another method of introducing average friction at high energies is the periodic brief lowering of the energy of the particles being cooled and turning on of electron cooling at a comparatively low energy. The phase volume of the beam is preserved on reduction of the energy, and its emittance and size are increased; nevertheless the cooling time (for a fixed cooling current or current density) drops rapidly and the frictional force can be made much more effective.

2. KINETICS OF ELECTRON COOLING (THE CASE OF SINGLE TRAVERSAL BY THE ELECTRON BEAM)

Let us consider in more detail the simplest case in which each electron traverses the cooling region only once; this case is at the present time, apparently, also the most important—just this arrangement is proposed for use in storage of antiprotons and other first-echelon experiments. In addition, this case has been theoretically investigated the most completely and has been achieved and studied experimentally.

a) To start with we consider the nonrelativistic motion of a proton in a stationary electron gas with a given temperature T_e (generally speaking, different for the longitudinal and transverse degrees of freedom) and density n_e' (which is equal to n_e/γ, where n_e is the density of the electron beam in the laboratory system).

The effect of collisions with the electrons on the motion of the protons can be approximately broken down into two parts. One part gives the frictional force, and the second part leads to diffusion.

We shall estimate the magnitude of the frictional force, neglecting the influence of the accompanying longitudinal magnetic field, the interaction of the electrons with each other, and the finiteness of the time of traversal of the interaction region by the proton. In addition we shall assume at first that all electrons are at rest. The frictional force is equal to the magnitude of the proton energy loss per unit length. Transfer of proton energy to electrons in our simple case is due to their acceleration perpendicular to the direction of motion of the proton. In motion of protons in matter this slowing down is referred to as ionization loss. Using the known formula for ionization loss, we find that on a proton moving in the moving system with a velocity $\mathbf{v}_p$ through an electron gas of density n_e' there is acting a frictional force directed opposite to $\mathbf{v}_p$ and equal in magnitude to

$$|\mathbf{F}_{\text{fr}}| = \frac{4\pi e^4 n_e' L_C}{m v_p^2}; \tag{2.1}$$

here $L_C \doteq \ln(\theta_{\max}/\theta_{\min})$ is the so-called Coulomb logarithm, which appears in integration over the impact parameters of the proton collisions with electrons. Here $\theta_{\max} = 2m/M$ is the maximum possible deflection angle of a proton in one collision and $\theta_{\min} = e^2/M v_p^2 \rho_{\max}$ corresponds to the impact parameter $\rho_{\max}$ beyond which the Coulomb nature of the proton-electron interaction is destroyed. The maximal impact parameter can be determined by the transverse size of the electron beam, Debye screening, and so forth. However, in all practical cases L_C varies only from 5 to 20.

If we neglect the dependence of L_C on the proton velocity, the frictional force as a function of the relative velocity will have the form of Coulomb's law in velocity space.[41,42] The case considered here of stationary electrons corresponds to the case of a point charge at the origin of coordinates. If the electrons are distributed in velocity space with a density $f(\mathbf{v}_e)$ (with a normalization $\int f(\mathbf{v}_e, \mathbf{r}) d^3 v_e = n'_e(\mathbf{r})$), the total frictional force can be represented in the form

$$\mathbf{F}_{\mathrm{fr}}(\mathbf{v}_p, r) = -\frac{4\pi e^4 L_C}{m} \int \frac{f(\mathbf{v}_e, \mathbf{r})}{(\mathbf{v}_p - \mathbf{v}_e)^2} \frac{\mathbf{v}_p - \mathbf{v}_e}{|\mathbf{v}_p - \mathbf{v}_e|} d^3 v_e, \tag{2.2}$$

where it has been taken into account that the electron density and the velocity distribution function depend on the coordinates $\mathbf{r}$.

It can immediately be seen by means of this electrostatic analog, for example, that if in the electron beam the electrons have in the moving system a Maxwellian distribution in velocities with a velocity temperature v_e^T identical in all directions, then the frictional force is proportional to the proton velocity $\mathbf{v}_p$ for $v_p < v_e^T$ and falls off in proportion to v_p^{-2} for $v_p > v_e^T$ (Fig. 1).

b) Let us now find the damping decrement of the proton oscillations due to this frictional force. The decrement of one-dimensional oscillations is equal to the ratio of the dissipative energy-loss power averaged over the period of these oscillations to the energy of the oscillations. It is simplest to find δ_z—the decrement of oscillations perpendicular to the plane of the proton orbit in the storage ring or, in accelerator terminology, axial betatron z oscillations.

For the region of small proton velocities $v_p < v_e^T$ (in the moving system), in which the frictional force is proportional to v_p, the power of the frictional force averaged over the period is

$$\overline{F_z v_{pz}} = \overline{\frac{\partial F_z}{\partial v_{pz}} v_{pz}^2} = \frac{\partial F_z}{\partial v_{pz}} \frac{v_0^2}{2},$$

where v_0 is the amplitude of the velocity of z oscillations. The energy of these oscillations is $M v_0^2/2$. If we take into account in addition that the protons spend only part of their time inside the electron flux (the fraction of the orbit occupied by the cooling section we shall designate by η) and that the time of cooling in the laboratory system is greater by a factor γ than in the moving system, we obtain

$$\delta_z = -\frac{1}{\gamma M} \overline{\frac{\partial F_z}{\partial v_{pz}}} \approx 20 r_e r_p c L_C n_e \eta \gamma^{-2} \left(\frac{v_e^T}{c}\right)^{-3} \text{ for } v_p \ll v_e^T. \tag{2.3}$$

The decrement can be expressed in terms of the angles θ_e in the electron flux ($\theta_e = \gamma^{-1} v_e^T / \beta c$):

$$\delta_z = 20 r_e r_p c L_C n_e \eta \gamma^{-5} \beta^{-3} \theta_e^{-3} \quad \text{for} \quad \theta_p \ll \theta_e. \tag{2.4}$$

Calculation of δ_z for large one-dimensional oscillations of protons for which the amplitude of the oscillations of velocity is $v_0 \gg v_e^T$ (correspondingly, $\theta_p \gg \theta_e$) gives a similar formula but with θ_p replacing θ_e:

$$\delta_z = 20 r_e r_p c L_C n_e \eta \gamma^{-5} \beta^{-3} \theta_p^{-3} \quad \text{for} \quad \theta_p \gg \theta_e. \tag{2.5}$$

Calculation of the decrements in the remaining degrees of freedom (in the case $v_{p0} \ll v_e^T$) can be carried out similarly. Here it is only necessary to take into account the possible dependence of the electron distribution function on the transverse coordinates. For example, if the average velocity of the electrons depends on the radial coordinate, the decrement of the radial betatron oscillations varies in comparison with the decrement of z oscillations. This occurs as the result of the fact that the proton in its radial betatron oscillations enters regions where the electron velocity differs from the equilibrium value and in this case the proton energy will also undergo oscillations. Correspondingly the radial position of the equilibrium orbit of the proton turns out to be modulated in a resonance manner with the radial betatron-oscillation frequency, and an additional power appears which increases or decreases the betatron-oscillation amplitude. The damping decrement of the energy oscillations (or deviations) of the proton also varies in this case. However, it can be shown that the sum of the decrements over all three degrees of freedom, i.e., the damping decrement of the complete six-dimensional phase space occupied by the protons, is determined only by the electron density along the equilibrium phase trajectory of the protons and does not depend on the variability of the distribution function over the transverse coordinates or on possible accelerator couplings between the different forms of proton oscillation. In the simple case $v_p < v_e^T$ the sum of the decrements is equal to

$$\sum \delta = 60 r_e r_p c L_C n_e \eta \gamma^{-2} \left(\frac{v_e^T}{c}\right)^3 \quad \text{for} \quad v_p < v_e^T. \tag{2.6}$$

c) For distributions of electrons in velocity, relative to the equilibrium orbit of the protons, which differ strongly from a symmetric Maxwellian distribution, the action on the protons may turn out to be qualitatively quite different. This can be seen particularly clearly in the case of the so-called monochromatic instability.

Let us consider the case in which electrons with an extremely small velocity spread in the cooling section are moving at some average angle directed, say, along the vertical to the equilibrium proton trajectory. Let this angle be such that the general transverse velocity $\bar{v}_e$ is much greater than the spread in the electron velocities Δv_e, but not greater than the permissible transverse velocities of the protons (i.e., the corresponding oscillation amplitudes of the protons are less than the working aperture of the accelerator). In this case, if the protons execute small vertical oscillations the work done by the frictional force will be positive in the part of the oscillation period in which the protons are moving in the direction of the general electron velocity and negative for motion in the opposite direction. Here positive work will be performed for a relative proton-electron velocity smaller than $\bar{v}_e$, and negative work for a value larger than $\bar{v}_e$, and therefore the total work over a period will be positive for $|v_e - v_p| \gg \Delta v_e$ the frictional force falls off with increase of the relative velocity). Consequently the amplitude of the vertical oscillations of the protons will increase—these oscillations will become unstable under the influence of the electron beam. The oscillations will increase until the oscillation amplitude of the proton's transverse velocity is equal to $\bar{v}_e$.

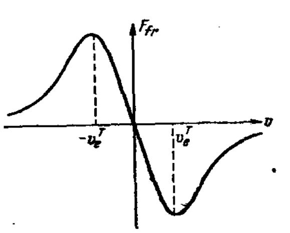

FIG. 1.

We note that this phenomenon, which on the face of it is only harmful, can be used to accelerate the damping of large proton oscillation amplitudes (at least if these oscillations are strictly one-dimensional). The fact is that the rate of damping of proton oscillations to the new equilibrium motion described above can be much greater than the rate of damping of protons with this amplitude for an electron beam moving parallel to the equilibrium orbit of the protons. Then, by decreasing the general angle of the electrons as rapidly as possible in order that only protons will have time to be damped to the (varying) equilibrium amplitude, we can much more rapidly damp the initially large oscillations of the protons. This procedure may turn out to be useful, for example, in the storage of antiprotons.

d) In discussing the friction experienced by protons moving in the accompanying electron flux, we limited ourselves to the simplest situations. There may be a substantial influence, in particular, of the fact that the interaction of the protons with the electrons is occurring in a longitudinal magnetic field. For real situations the size of the Larmor circle corresponding to thermal transverse velocities of the electrons turns out to be of the order of tens of microns or even smaller, which is several orders of magnitude less than the transverse size of the electron beams. Therefore there is a substantial region of impact parameters (corresponding Coulomb logarithm of about 3–5) for which the electrons turn out to be "magnetized" and cannot shift perpendicular to the magnetic field direction. Accordingly, part of the transverse frictional force due to these collisions does not fall off linearly with decrease of the proton velocity when the latter becomes less than the spread in the transverse electron velocities, but continues to rise rapidly until the proton velocity is equal to the characteristic longitudinal electron velocities. On acceleration of the electrons by a potential the spread in their longitudinal velocities drops rapidly (see Eq. (1.1)) and therefore the effective transverse frictional force may turn out to be much greater than that calculated from the initial formulas (2.1) and (2.2). The average longitudinal force also increases, although when a proton moves strictly along a line of force of the magnetic field the contribution of this region of impact parameters to the longitudinal frictional force decreases rapidly, since in this case the magnetization of the electrons prevents transfer of energy from the proton to the electrons.

In a detailed calculation of the frictional force it is necessary to take into account also the finiteness of the interaction time, which is limited to the time of flight of the proton over the cooling region, and the influence of the interaction between electrons, which leads to effects such as non-steady-state Debye screening, and many other factors.

e) In addition to friction, the protons moving in the electron flux experience random thrusts which lead to a diffusion growth of the squared deviation of the proton momentum $(\Delta\mathbf{p})^2$ from the initial value $\mathbf{p}=M\mathbf{v}_p$. In calculation of the average rate of increase we can neglect the variation of the electron motion and consider this diffusion process as the multiple scattering of protons moving with velocity $\mathbf{v}_p$ relative to randomly located Coulomb centers with a density n_e'. Here, if the electrons are at rest, we have

$$\frac{d\,\overline{(\Delta p)^2}}{dt}=\frac{8\pi e^4 n_e' L_C}{v_p}.$$

The total diffusion action of the electron beam is found by averaging over the distribution function $f(\mathbf{v}_e)$:

$$\frac{d\,\overline{(\Delta p)^2}}{dt}=8\pi e^4 n_e' L_C\int\frac{f(\mathbf{v}_e)}{|\mathbf{v}_p-\mathbf{v}_e|}\,d^3v_e.$$

Going over to the increase of the proton kinetic energy $E=p^2/2M$, we obtain

$$\frac{dE}{dt}=\frac{4\pi e^4 n_e' L_C}{M}\int\frac{f(\mathbf{v}_e)}{|\mathbf{v}_p-\mathbf{v}_e|}\,d^3v_e. \tag{2.7}$$

This diffusion process places a limit on the minimum velocity spread to which the proton beam is cooled. This limit corresponds to equality in absolute value of the average friction power $\overline{\mathbf{F}_{fr}\mathbf{v}_p}$ and the average rate of the diffusion increase of the energy (2.3). For the region $v_p \ll v_e^T$, and it is just this case that in simple situations corresponds to the limiting cooling, we obtain

$$\frac{4\pi e^4 n_e' L_C}{M}\left\langle\frac{1}{v_e}\right\rangle=\frac{4\pi e^4 n_e' L_C}{m}\frac{(v_p^2)_{\text{equ}}}{(v_e^T)^2}\left\langle\frac{1}{v_e}\right\rangle,$$

from which it follows that

$$(v_p)_{\text{equ}}=\sqrt{\frac{m}{M}}\,v_e^T. \tag{2.8}$$

That is, in this simplest case the equilibrium state corresponds to thermodynamic equilibrium, in which the temperatures or average kinetic energies of the protons and electrons are equal.

Of course, multiple Coulomb scattering by the electrons of the cooling beam is not the only diffusion process which prevents cooling of the proton beam. A strong influence can be exerted by multiple scattering in the residual gas, irregular fluctuations of the electron-beam density, noise in the high-frequency system (for the case of a bunched proton beam), pulsations of the magnetic field, and other diffusion-type perturbations.[2,3]

f) A completely different effect of the interaction with the cooling electron beam, which is important only for positive particles being cooled—protons and ions—is the capture of electrons into bound states (recombination)—a process leading to formation of fast neutral atoms of hydrogen or of ions with a charge reduced by unity.

The principal form of recombination for the low electron flux densities utilized at present is radiative recombination, with emission of a photon of the corresponding energy. Here mainly the lower levels of the hydrogen atom or ion are populated; this is true at least if we neglect the influence of the accompanying magnetic field. The fast neutral hydrogen atoms formed after recombination, retaining the angular spread which exists in the proton beam, leave the storage ring. The probability of their breaking up in the magnetic field which guides the protons will be low in this case if the proton energy is not too high.

The lifetime of a proton against radiative recombination at relative velocities small compared to atomic velocities in the lower levels (and just this relation is cha acteristic of the cooled beam) is proportional to the electron velocity determined by temperature v_e^T and falls off rapidly with increase of the ionic charge:

$$\tau_{\text{rec}} \approx \frac{\gamma^2 v_e^T}{20\alpha r_e^2 c^2 Z_i^2 \eta n_e \ln (Z_i \alpha c / v_e^T)}. \tag{2.9}$$

The lifetime against recombination τ_{rec} for the proton beam is usually several orders of magnitude greater than the damping time of small oscillations, but in the case of heavy ions the excess becomes insignificant—the cooling time is proportional to the mass of the ion. Therefore we can succeed in cooling a beam of heavy ions but it is impossible to maintain it in a cold state for an extended period. Use of a special procedure—proton cooling—completely removes this difficulty (see above).

At very high electron and proton densities the main role in recombination may be played by ternary collisions. Mainly upper levels will be populated in this case. The further fate of such neutrals will be more complicated and depends strongly on the specific conditions.

In addition to recombination, which is the most fundamental limitation on the lifetime of positive ions in electron cooling, particles, whatever their charge may be, are knocked out of the beam as the result of interaction with the residual-gas atoms.

Without cooling, the main process determining losses is multiple Coulomb scattering by the nuclei of the residual-gas atoms, which leads to a gradual increase in the betatron-oscillation amplitudes to the maximum permissible value. With effective cooling this diffusion process is suppressed, and single Coulomb scattering by the nuclei remains (the lifetime against this process is several times greater than in the previous case), as well as the nuclear interaction of the beam particles with the nuclei.

g) New effects arise on cooling of *intense* beams of heavy particles. Here even the well known high-current effects must be analyzed anew in the presence of electron cooling.

Thus, with unusually small currents the Coulomb repulsion can be felt between the particles of the beam—the equilibrium size and energy spread of the cooled beam can be extremely small. Weakening of the focusing as the result of transverse repulsion can shift the betatron-oscillation frequency to dangerous "machine" resonances, and further compression as the result of cooling turns out to be impossible. Compensation of this shift of betatron frequency by retuning the focusing structure of the storage ring turns out, as is usually the case in a space-charge problem, to be of little effect, as a result of the strong nonuniformity of the shift for particles with different betatron-oscillation amplitudes.

Longitudinal repulsion of the beam particles is particularly dangerous if the frequency of revolution in the storage ring (with a constant magnetic field) falls off with increasing energy (the negative-mass effect). This occurs when, in accelerator terminology, the equilibrium energy of the storage ring becomes greater than the critical energy. Then a spontaneous breakup of the beam into bunches occurs; the threshold for this instability depends on the spread in the frequencies of revolution and in a cooled beam can be very low.

This instability, and also the transverse and longitudinal instabilities due to electromagnetic interaction of the beam with the surrounding structures, for sufficiently low proton currents can be effectively suppressed by the existence of friction—the electron cooling. For instability of the beam it is required that the decrements of small oscillations be greater than the increments of all instabilities.

However, the presence of an intense electron beam strongly interacting with a circulating beam leads to qualitatively new effects, and the problem of coherent stability requires special discussion, which has already been begun.[4–5] Coherent interaction of an intense beam of heavy particles with a cooling electron flux can lead both to accelerated damping of coherent beam oscillations, which can be effectively used in combatting "extraneous" instabilities of the proton beam, and also to new instabilities.

h) Another effect which appears in an intense proton beam, especially one with maximal cooling, is the scattering of protons by other protons of the same beam—the internal-scattering effect. If the frequency of revolution of the protons in the storage ring (for a fixed magnetic field) increases with increase of their energy—this situation is similar to the case of straight-line motion of a proton beam with the same characteristics—internal scattering will lead only to equalization of the temperatures over all degrees of freedom, which in the laboratory system will lead to appearance of a longitudinal spread of the momenta larger by a factor γ than the transverse spread.

A completely different situation arises if the proton revolution frequency in the storage ring (for a fixed magnetic field) drops with increasing energy. Two protons executing, say, radial betatron oscillations and having strictly the equilibrium energy, after scattering can change energy discontinuously (the sum of their energies, of course, is conserved); this simultaneously excites additional radial betatron oscillations and, if the energy is above the critical energy, the resulting betatron oscillations will be on the average larger than the initial ones. Therefore what occurs is not a simple equalization of the temperatures over all degrees of freedom, but so to speak a "self-heating" of a proton beam which can be limited only by the presence of friction, in our case—electron cooling.

We have only touched on the problems evident at this time in obtaining electron-cooled beams of heavy particles with high intensities. Study of these problems has just begun.

3. EXPERIMENTAL STUDY OF THE ELECTRON COOLING PROCESS

In order to achieve electron cooling for the first time and to study it experimentally, a special proton storage ring NAP-M and a system producing an electron beam with the necessary parameters in the cooling portion were developed.

a) The storage ring NAP-M was built as the prototype of an antiproton storage ring, as we visualized it in 1970,[43] and hence its designation—Nakopitel' Anti-Protonov, Model' (Antiproton Proton Storage Ring, Model). This particular circumstance explains both the general size of the storage ring and its structure with very long straight sections and use of purely edge focusing; here the edges of the plane bending magnets were directed strictly toward the center of symmetry of the storage ring—to provide focusing independent of the average radius of the proton equilibrium orbit. The general scheme of the storage ring and its general form are shown in Figs. 2 and 3, and its main parameters are given in Table I.

TABLE I.

Main Parameters of the Storage Ring NAP-M	
Energy of accelerated particles	up to 100 MeV
Injection energy	1.5 MeV
Length of perimeter	47 m
Number of magnets and straight sections	4 of each
Radius of curvature	3 m
Length of straight sections	7.1 m
Useful aperture in bending magnets	4 cm × 7 cm
Betatron oscillation frequencies:	$Q_R = 1.2$ $Q_z = 1.4$
Duration of acceleration cycle	30 sec
Accelerating high frequency voltage (first harmonic)	10 V
Stability of magnetic field during cooling	$\pm 1 \times 10^{-5}$
Average residual gas pressure (with electron beam turned on)	5×10^{-10} torr

In one of the straight sections of the storage ring was placed the apparatus with the electron beam,[12] the diagram and general appearance of which are shown in Figs. 4 and 5, and the main parameters of which are given in Table II.

TABLE II.

Main Parameters of Electron Cooling System	
Length of cooling region	1 m
Electron energy in experiments	up to 50 keV
Electron current	up to 1 A
Relative transverse velocity of electrons	$\pm 3 \times 10^{-3}$
Energy stability	$\pm 1 \times 10^{-5}$
Accompanying magnetic field	1 kG

The apparatus has three straight sections, in two of which are placed the gun and collector, while the third is the cooling region, in which the protons move together with the electron flux. For shaping and transporting the electron beam we use an accompanying longitudinal magnetic field in which the electron gun is immersed.[9] The straight sections are connected by two sections with a toroidal magnetic field which serves to inflect the electrons into the cooling region and to extract them from it. The centrifugal drift in the bends is eliminated by application of a transverse magnetic field which guides the electrons along a trajectory whose curvature coincides with that of the line of force of the longitudinal field.

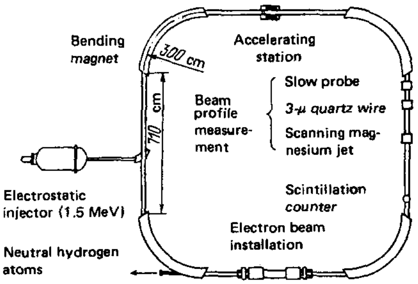

FIG. 2. Diagram of proton storage ring NAP-M.

The apparatus employs recovery of the electron energy, so that the power consumed by the high-voltage source does not exceed a few percent of the reactive beam power.[10,11]

The operating cycle of the complex as a whole is as follows. Protons of energy 1.5 MeV are injected in a single turn into the storage ring. In the course of 30 sec the field is raised to the necessary value. The high-frequency accelerating system provides a proton energy increase matched to the rise of the magnetic field. On reaching the necessary level the rise of the magnetic field and the change in the frequency of the accelerating voltage are halted, and the protons, which have been formed into a bunch of length about one quarter of the orbit perimeter, can "live" many hundreds of seconds in the storage ring, gradually leaving it as the result of scattering by the residual gas. If one wishes to work with a continuous beam, the high-frequency voltage is removed. After the acceleration the electron beam is turned on and the electron-cooling process proper begins.

b) The experimental achievement of electron cooling required solution of a number of complicated technical problems. For example, in a storage ring with a vacuum chamber length of about 50 m and an internal intense electron beam with a power of several kilowatts, an average vacuum of about 5×10^{-10} torr is maintained. The stability of the magnetic field and of the electron en-

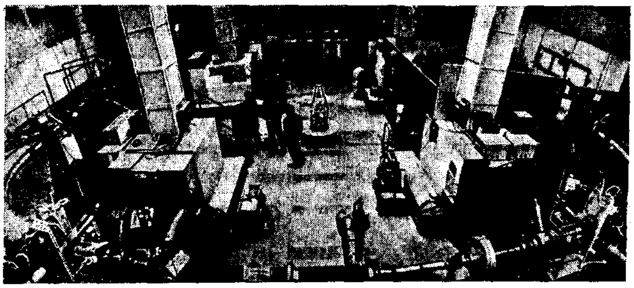

FIG. 3. The storage ring NAP-M.

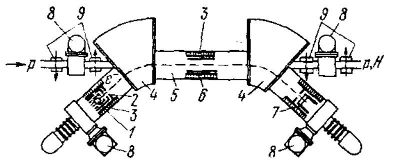

FIG. 4. Diagram of electron beam installation. 1—electron gun, 2—anodes, 3—solenoid, 4—electron beam bending regions, 5—cooling region, 6—vacuum chamber, 7—collector, 8—vacuum pumps, 9—correcting magnets.

ergy amounts to 1×10^{-5}. The entire process of acceleration and transition to the cooling regime is accomplished automatically by computer. The same computer is used for recording and immediate processing of experimental information, for providing the output in a form convenient for the experimenter on the display unit and printer, and for subsequent long term storage.

In the experiments on electron cooling we used various means of observation—pickup electrodes (integral and differential) to measure the time structure and position of the bunched beam, ferromagnetic magnetometers to measure the circulating current, destructive probes to measure the integral distribution of betatron oscillation amplitudes, and micron-size wires rapidly crossing the beam for recording protons scattered into an angular aperture to measure the proton-beam density distribution with high resolution.

Particularly useful devices were a magnesium jet and the detection of fast hydrogen atoms arising in radiative recombination.

The magnesium-jet method (Fig. 6) is based on detection of ionization electrons arising from a thin jet of magnesium vapor intersecting the proton beam. The ionization electrons are accelerated and collected on a phosphor; the luminescence of the phosphor is detected by a photomultiplier. The experiments utilized a ribbon-shaped jet with transverse dimensions 0.5×20 mm^2 (the long dimension was along the direction of proton motion) and a vapor pressure of about 10^{-6} torr. This jet results in practically no additional scattering. A horizontal jet can be shifted (scanned) along the vertical direction; the photomultiplier signal is then proportional to the density distribution of the proton beam along the vertical direction. Similarly, a vertical jet permits information to be obtained on the radial distribution of protons. A jet can be stopped at any point; in this case it is possible to trace the change in the proton-beam density as a function of time.

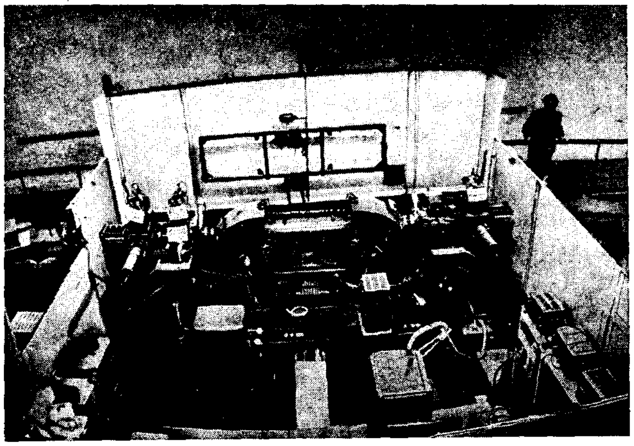

FIG. 5. General appearance of electron beam installation.

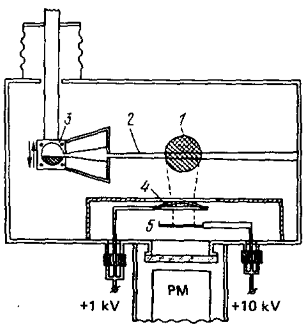

FIG. 6. Arrangement for measuring proton beam density (magnesium jet method). 1—proton beam, 2—magnesium jet, 3—container with magnesium, 4—collecting electrode, 5—luminescent screen.

By observing the flux of fast hydrogen atoms, it is possible to estimate the average relative velocity of the protons and electrons from the total flux of such atoms (see Eq. (2.9)) and to measure the equilibrium size and angular spread in the proton beam with very high resolution (Fig. 7).

c) A nontrivial effect of the electron beam on the motion of the protons appeared only when the average velocities of the protons and electrons in the cooling region were brought together with a relative accuracy better than 1×10^{-3}. In the experiments we observed the following effects:

damping of betatron oscillations;

the existence of an equilibrium size of the proton beam;

decrease of the energy spread in the proton beam and entrainment (acceleration or retardation) of the protons by the electron beam;

existence in the proton beam of an equilibrium energy spread;

increase in the lifetime of the proton beam.

These phenomena have a particularly simple nature for low proton currents (<50 μA) and electron currents

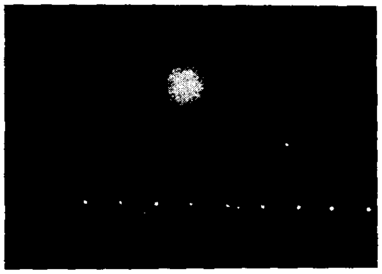

FIG. 7. Photograph of nuclear emulsion exposed to a beam of fast hydrogen atoms ($v/c=0.35$) arising in recombination of proton and electron beams in the cooling section. The emulsion was located 10 m from the interaction region. The fiducial marks are every one millimeter. The size of the image corresponds to a proton beam diameter 0.5 mm and an angular divergence 3×10^{-5} rad.

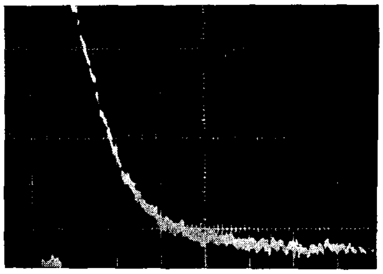

FIG. 8. Change with time of the density at the center of the proton beam after turning on the inflector. The horizontal scale is 0.1 sec/cm.

(<300 mA) and in describing the experiments we shall have in mind this case, and only mention briefly what new phenomena are observed at higher currents.

If the electron beam is not turned on, then after acceleration the transverse size of the proton beam (in other words, the proton betatron-oscillation amplitudes) gradually increases as the result of scattering by the residual gas atoms. This is clearly visible from the increase in the width and decrease in the amplitude of the signal from the secondary electrons obtained in scanning with the magnesium jet over the storage-ring chamber cross section. The size increases up to that permitted by the aperture (average diameter of the proton beam up to 1.5 cm). If after this the electron beam is turned on with a correctly chosen average velocity, the proton beam is compressed to a fraction of a millimeter, the small amplitudes being damped first, and the large ones being "collected" only gradually.

It is particularly convenient to measure the betatron-oscillation decrement and to bring out the corresponding functional dependences by stopping the magnesium jet in the center of the proton beam and observing the dependence of this density on time after special pulsing of an inflector exciting betatron oscillations in the cooled beam, which were identical for all protons (Fig. 8). Here, if the proton current is small, the measured cooling time does not depend on this current, i.e., cooling occurs completely incoherently, and the oscillation amplitude of each proton decreases independently.

For large proton currents a portion of the initial amplitude in certain regimes is damped very rapidly (in less than 10 msec), the fraction of this coherent loss of amplitude increasing with increase of the number of protons. Then the betatron oscillations apparently lose their initial in-phase relation and further damping occurs independently of the proton current. It is possible to obtain a damping time for the amplitude of small betatron oscillations of less than 0.1 sec.

The damping of the deviations of the proton velocity from the average longitudinal velocity of the electrons manifests itself clearly in the "entrainment" of the proton beam with the electron energy undergoing only a small change. For example, if the electron energy is raised discontinuously, the energy of the freely circulating protons also begins to increase and the proton beam transfers to a new equilibrium orbit of larger radius. Particularly impressive is the possibility of accelerating protons with the aid of an electron flux with the electron energy and the magnetic field of the storage ring increasing simultaneously in a coordinated manner. By this means we were able to raise the proton energy from 60 to 80 MeV in three minutes.

d) In the experiments we were successful in obtaining very small equilibrium dimensions of the proton beam. A measurement of the transverse dimensions can be made with the utmost reliability and very high resolution by measuring the flux of fast atoms formed in recombination in the cooling region, detecting them by means of a nuclear emulsion placed behind a thin foil at a distance of 10 m from the cooling section (see Fig. 7). The proton beam size calculated from the spot size on the emulsion could be reduced to 0.4 mm.

The energy spread in the freely circulating beam was measured by observing the spread in frequencies of revolution. For this purpose from a closed cooled proton beam about half of the total azimuth was knocked out and the time of disappearance of the phase grouping of the protons was measured (from the disappearance of the signal from a pickup electrode). At low currents this time reached 3 sec; when the diffusion nature of the spreading of the bunch in the presence of strong longitudinal damping is taken into account, this corresponds to an energy spread of 1×10^{-5}. This spread increases as the proton current is increased.

The overall effectiveness of electron cooling is well characterized by the ratio of the initial six-dimensional phase volume of the beam, which corresponds to a betatron-oscillation amplitude of 1 cm and an energy spread of 0.1%, to the steady-state phase volume at a betatron oscillation amplitude of 0.25 mm and an energy spread of 1×10^{-5}. This gives an increase in the phase density of $1^4\times10^{-3}/(2.5\times10^{-2})^4\times10^{-5}=2\times10^8$ times!

Effective cooling naturally excludes completely the loss of protons as the result of multiple scattering by the residual gas atoms, and the lifetime is determined only by direct, single knockout. The experimentally observed dependence of the proton current on time becomes purely exponential, and the lifetime is several times greater than without electron cooling.

e) The set of experimental dependences, especially those obtained recently,[25,28,29] shows that the electron-cooling process is substantially more complicated than simple cooling of a gas of protons in a cold electron gas. In particular, it can be seen that an important role is played by proton-electron collisions with impact parameters greater than the Larmor radius of the electrons. New effects appear also as the electron and proton currents are increased.

Thus, electron cooling has been tried successfully and has been investigated in the energy range from 1.5 MeV (the injection energy) to 85 MeV (momentum 0.4 GeV/*c*) both for a freely circulating proton beam and for a bunched beam. Table III shows the best results obtained up to the present time and the corresponding experimental conditions.

TABLE III.

Proton momentum	0.4 GeV/c
Electron energy	45 keV
Electron current	0.8 A
Electron beam diameter	2 cm
Fraction of orbit occupied by cooling section	2×10^{-2}
Effective electron temperature:	
transverse	0.2 eV
longitudinal	10^{-4} eV
Longitudinal magnetic field	1 kG
Damping time (small amplitudes)	0.1 sec
Steady-state proton-beam diameter	0.4 mm
Steady-state angular spread	$\pm4\times10^{-5}$
Steady-state energy spread	1×10^{-5}
Lifetime	10 hours

Apparently a further increase in the effectiveness of electron cooling is also possible. In any case the cooling time can be reduced several fold as the result of filling a larger fraction of the proton orbit with electrons.

4. STORAGE OF INTENSE ANTIPROTON BEAMS

The principal purpose for which we undertook development of the electron-cooling method was the storage of intense beams of antiprotons, although it was first proposed for compression of beams of heavy particles.

a) According to Liouville's theorem, without dissipative forces it is impossible to add new quantities of antiprotons into regions of phase volume of a storage ring without removing particles already present in them. The best that can be accomplished in this operation is to fill the entire phase volume of the storage ring with a density given by the antiproton generator. However, the phase density achievable today for antiproton beams obtained as beams of secondary particles in proton accelerators, without going over to very thin and accordingly very inefficient target-converters, is far from providing the needs, for example, of installations with colliding proton-antiproton beams of high luminosity. The possibility exists, it is true, of accumulation of antiprotons with no fundamental limitations by use of antihyperon beams.[44] In this arrangement a beam of, say, $\bar{\Lambda}_0$ hyperons traverses a region of the storage ring along a tangent to the trajectory and those antiprotons which in the decay

$$\bar{\Lambda}^0 \to \bar{p} + \pi^+$$

turn out to be at appropriate points of the storage-ring phase space (near the equilibrium trajectory with momentum of the proper magnitude and direction) will remain in the storage ring. However, the efficiency of this arrangement (i.e., the ratio of the number of stored antiprotons to the number of accelerated protons) turns out to be very low and in reasonable times does not provide the storage of the necessary number and necessary phase density of antiprotons.

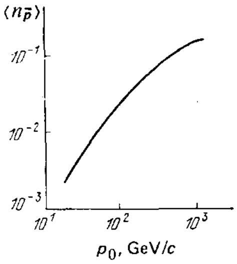

FIG. 9. Average multiplicity of antiprotons in $p+\bar{p}$ collisions as a function of the incident proton momentum p_0.

Use of electron cooling permits a solution of the problem. This was shown in the Novosibirsk colliding proton-antiproton beam project,[43] and in the proton-antiproton projects which have appeared recently for the accelerator-storage ring complex at Serpukhov (the proposal of our Institute at Novosibirsk[45]), at CERN,[46] and at the Fermi National Accelerator Laboratory in the USA.[47]

b) Let us consider in somewhat more detail the basic characteristics of the antiproton beams produced.

The ratio of the total number of produced antiprotons to the number of incident protons for proton energies considerably above threshold, which for the case of a proton target is 6.5 GeV, increases from 3×10^{-3} at 20 GeV to 0.1 at 1000 GeV (Fig. 9). In principle it is possible to use a nuclear cascade in which in each step antibaryons are extracted from the total flux with low energy (below 10–20 GeV), which prevents their nuclear absorption in the target. Here it is possible to raise the transformation coefficient of the initial proton energy into antiproton rest mass to a level somewhat higher than 10^{-3}. However, such complete transformation is at the present time an extremely awkward affair and in the first stage we will be clearly forced to limit ourselves to the cascade-free version with use of a small fraction of the energy spectrum and perhaps also only a small fraction of the transverse phase volume of the antiprotons produced.

In the cascadeless version for a "light" target the spectrum of antiprotons corresponds to the spectrum of an "elementary central event." Here antiprotons having low energies in the center of mass system of the colliding nucleons are produced with the greatest probability, which corresponds to the situation in the laboratory system that the peak of the antiproton spectrum occurs at $E_{\bar p}^{\max} \approx \sqrt{M_p c^2 E_{\text{init}}}$.

In the antiproton energy region substantially lower than $E_{\bar p}^{\max}$—and just this region is most convenient for storage of antiprotons—the spectrum falls off rather rapidly and at a kinetic energy of 1 GeV turns out to be greatly reduced (Fig. 10). Use of a target with heavy nuclei shifts the antiproton spectrum somewhat toward the low energy region.

The angles of antiproton production are determined by the momentum p and are approximately given by

$$\langle\theta^2\rangle \approx \frac{2M_p M_\pi c^2}{p^2}.$$

Correspondingly, the effective phase volume of the anti-

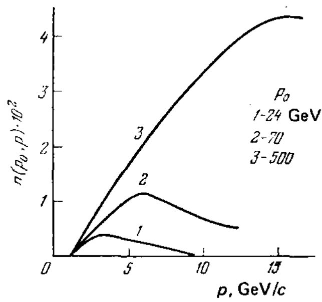

FIG. 10. Distribution of antiproton momenta in the laboratory system, expressed in units of $n(p_0,p) = (8\pi/3)M_\pi M_p(p/\sigma_{in})d^3\sigma/dp^3$ (σ_{in} is the cross section for inelastic interaction of a proton, σ is the cross section for production of an antiproton) from the experimental data[58–60] for various primary-proton momenta p_0.

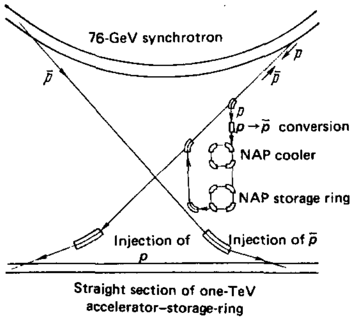

FIG. 11. Arrangement of proton-antiproton complex.

protons (one-dimensional) for a very small transverse dimension of the initial proton beam is determined by the target-converter length l_c and by the antiproton momentum:

$$\Omega_{\bar{p}} \approx \frac{\pi l_c \langle\theta^2\rangle}{2} \sim \frac{\pi l_c M_p M_\pi c^2}{p^2}.$$

In the simplest case the maximal yield of antiprotons will be obtained if the converter used is a cylinder of small radius with a length equal to the nuclear-absorption length of the primary protons l_{nuc}. However, the antiproton phase volume obtained in this case $\Omega_{\bar{p}}^0$ turns out to be too large and in practical projects it is necessary for the time being to limit oneself to the use of a small fraction of the phase volume of the produced antiprotons.

The ratio of the useful number of antiprotons to the number of primary protons turns out, thus, to be

$$k_{\bar{p}} = n(p_0,\ p)\frac{\Omega_{\text{sto}}}{\Omega_{\bar{p}}^0}\frac{\Delta p}{p};$$

here $\Delta p/p$ is the momentum bin captured by the antiproton storage ring, Ω_{stc} is the transverse phase volume accepted by the accelerator (in one direction), and $n(p_0,p)$ characterizes the spectrum of produced antiprotons and depends on the momenta of the primary protons p_0 and of the antiprotons utilized p (see Figs. 9 and 10).

The yield of antiprotons entering a given volume of the storage ring can be increased by several times by the following procedure. Instead of one target converter, several short targets are used, between which are placed very high-aperture lenses[48] which transmit an image of the antiproton beam from target to target. Here the phase volumes of the antiprotons from all targets are combined with each other. Scattering in the targets and in the shortfocal-length lenses can be made sufficiently small, and the final phase volume of the antiprotons turns out to be equal to the phase volume of a short single target.

The cooling time for antiprotons increases rapidly with increase of their phase volume (see Eq. (2.5)):

$$\tau_{\bar{p}} \approx \frac{0.1\,(v/c)^4\,\gamma^5}{r_e r_p L_C \eta}\,\frac{e}{J_e}\,\frac{\Omega_{\bar{p}}^{5/2}}{\sqrt{\beta_0}},$$

where J_e is the current of cooling electrons and β_0 is the value of the storage-ring β function in the cooling region (the analog of the focal length of the focusing system). Since the number of captured antiprotons increases with increase of the storage-ring phase volume only linearly, the optimum phase volume turns out to be that for which the cooling time (with a technically achievable electron current) will be equal to the period between the injection cycles provided by the proton accelerator used.

c) The first antiproton storage-ring project was developed in 1966 for the Novosibirsk proton-antiproton colliding-beam project.[43] This project already included the use of electron cooling. After its complete realization the project was supposed to provide an antiproton storage rate of about 10^6 $\bar{p}$/sec.

After the experimental demonstration of the possibilities of electron cooling, "antiproton" activity increased greatly also in other laboratories. In the last two years antiproton storage-ring projects have been developed for the proton-antiproton colliding beams for the projected accelerator—storage-ring complex at Serpukhov[45] (UNK), for performance of proton-antiproton experiments in the ISR storage ring,[46] and for conversion of the presently largest proton synchrotrons at the Fermi National Accelerator Laboratory (USA) and the European Center for Nuclear Research (CERN) to proton-antiproton colliding-beam operation.[47,49]

We have shown in Fig. 11 for illustration the scheme of antiproton storage proposed by our Institute at Novosibirsk for UNK. With the complete arrangement planned this system will permit storage of 10^8 $\bar{p}$/sec.

We should note that, even after achievement of these antiproton storage rates, a tremendous field remains for further improvements and inventiveness. At an initial proton energy of about 100 GeV and the planned intensities of proton synchrotrons it is possible in principle to obtain more than 10^{12} $\bar{p}$/sec.

5. NEW POSSIBILITIES IN ELEMENTARY-PARTICLE PHYSICS

The main purpose of the present review is to draw the attention of experimenters working in various fields of elementary-particle and nuclear physics to the new and, frequently, fundamentally new possibilities opened up by the use of electron cooling. For this purpose we shall try to touch, if only briefly, upon the most varied fields of possible applications of this method.

a. Experiments with super-thin internal targets

The first results in storage of antiprotons will already permit one to carry out a broad range of new experiments.

1) In the storage rings themselves for antiprotons with electron cooling it will be possible to perform an extensive group of experiments with super-thin internal gas and vapor targets. In the super-thin target regime[50] the energy losses of the antiprotons, the fluctuations of these losses, and the multiple scattering of the antiprotons by the atoms of the target are suppressed by electron cooling and the lifetime of the antiprotons is determined only by single interactions with the target. Scattering by the residual gas at modern vacuum levels can be made negligible. At antiproton energies of the order of 1 GeV and above, the dominant interaction is the nuclear interaction with cross sections of about 10^{-25} cm^2/nucleon; at lower energies Coulomb scattering by an angle greater than the aperture angle becomes more important (the "loss" cross section increases as $Z^2\theta_{\max}^{-2}$). To reduce the cross section for loss of antiprotons as the result of the Coulomb interaction and to reduce the influence of multiple scattering on the antiproton beam size it is reasonable to install internal targets in the parts of the storage ring which have sharp minima of the β functions.

The luminosity in such experiments is determined by the rate of storage of antiprotons $\dot N_{\bar p}$ and by the loss cross section σ_{loss}:

$$L=\frac{\dot N_{\bar p}}{\sigma_{\text{loss}}}. \tag{5.1}$$

For example, at high energies and a storage rate 10^8 $\bar p$/sec the luminosity reaches 10^{33} cm^{-2} sec^{-1}, which is sufficient for an extremely wide range of experiments. For example, the number of cases of production of the recently found $p\bar p(1939)$ resonance may reach 10^6 per second. Performance of experiments in the super-thin target regime is facilitated by the 100% duty cycle of the reactions in time and by the small target thickness, which permits detection even of very slow reaction products such as nuclear fragments. We note that from this point of view it may turn out to be useful to use the super-thin target regime even for proton beams.

2) It is particularly effective to use super-thin internal targets for precision spectrometric experiments.[50]

The use of electron cooling will permit achievement of an energy resolution of the order 10^{-4}–10^{-6} with completely satisfactory luminosity in antiproton-proton and antiproton-nucleus experiments. Similar experiments with proton beams will provide the same high resolution and luminosity, which is comparable with that which can be obtained with equal resolution in tandem accelerators and meson factories. At higher energies a proton storage ring with electron cooling and a super-thin internal target will provide a luminosity for spectrometric experiments many orders of magnitude higher than contemporary proton accelerators.

A circumstance important for spectrometric experiments is the possibility of extremely accurate measurement of the absolute energy of particles of known mass in the storage ring by measuring the voltage which accelerates the cooling electrons. The accuracy already achieved at this time is better than 10^{-5}

3) It is interesting that for a study of antiproton-neutron interactions it turns out to be possible to use a target of free neutrons (which, apparently, is particularly attractive at low energies). For this purpose it is most reasonable to use high-current pulsed deuteron accelerators with a target located adjacent to the storage-ring vacuum chamber and surrounded by a moderator. The luminosity in such an arrangement can be made clearly sufficient for the study of nuclear cross sections, especially of annihilation processes, and the main problem will be obtaining the vacuum necessary because of background conditions in the interaction region with intense neutron irradiation.

4) An interesting application of an antiproton storage ring with electron cooling and an internal target is the production of intense directed fluxes of antineutrons and antihyperons of the required energy in charge-exchange reactions of the type $\bar p p\to\bar Y Y$. At an energy of, say, 2 GeV with the luminosity estimated above it is possible to obtain up to 3×10^4 $\bar n$/sec and 10^4 $\bar\Lambda$/sec. Here detection of the neutron or hyperon or their decay products permits the subsequent antineutron and antihyperon reactions with the targets being studied to be separated from the general background of secondary reactions.

b. Acceleration of stored antiprotons

New experimental possibilities will be opened up if in a portion of the acceleration cycles of the main proton synchrotron the stored antiprotons are accelerated. With the projected rates of storage of antiprotons, using a slowly extracted accelerated antiproton beam and existing experimental systems, it is possible to carry out a detailed study of antiproton-nucleon and antiproton-nucleus collisions. The high intensity of the antiproton beam and its complete purity and extremely small phase volume will permit the necessary information to be obtained with present-day "proton" accuracy over the entire energy range from a few MeV to the limiting energy of the main accelerator.

In addition, it will be possible to obtain well collimated beams of clearly "labeled" antineutrons and antihyperons of high energy and appreciable intensity.

c. Continuously cooled colliding beams

Unique possibilities appear in the study of proton-antiproton interactions on performing experiments with continuously cooled colliding beams in the energy region <10 GeV in each beam. Simultaneous cooling of the colliding beams is possible even in a single guide field—the point is that the flux of electrons which is cooling, say, the protons is moving against the antiprotons and therefore their mutual collisions in no way perturb the antiproton beam. An experimental installation of this type can turn out to be interesting, in comparison with the super-thin target arrangement, if it is necessary to remove completely the unnecessary interactions with electrons of the target and/or to obtain the best possible monochromaticity.

In particular, it is possible to investigate ψ mesons with a resolution much better than their intrinsic width, which cannot be done even with contemporary experiments using electron-positron colliding beams. Of course, only a very small fraction of all atoms of proton-antiproton annihilation will proceed via ψ mesons, even at the peak of the curve. Therefore it is reasonable to detect leptonic decay modes

$$\bar{p}p \to \psi \to \begin{cases} e^+e^-, \\ \mu^+\mu^-. \end{cases}$$

The cross sections for these processes just at the peak of the resonance are of the order of 100 nb. In a specialized storage ring with strong focusing at the point of collision it is possible to obtain tens of thousands of such events per day.

We note that in proton-antiproton collisions it is possible to obtain directly narrow states of the ψ-meson type with less severe restrictions on quantum numbers than in the case of electron-positron colliding beams, where the quantum numbers of such a state must be equal to the photon quantum numbers. It will be particularly easy to pick out states which have appreciable probabilities of decays which are not purely hadronic. An example of this type of meson is the $\chi(2750)$, which decays into two γ rays.

d. The ultimate in low energies

Completely new possibilities appear in the study of antiproton-proton (and antiproton-nucleus) interactions at extremely low energies. Stored antiprotons can be decelerated in the synchrotron regime to an energy of the order of 1 MeV and then further cooled. Sometimes it may be more convenient to decelerate stored and continuously cooled antiprotons by means of a coordinated reduction of the storage-ring magnetic field and the energy of the cooling electrons. The minimal energy is determined by Coulomb repulsion effects in the antiproton beam at the required intensity.

1) Several possibilities exist for the transition to experiments at extremely low energies. The simplest arrangement is to release antiprotons, slow them down with an electric field to the required energies (down to the energy spread in the antiproton beam), and to direct them at a target made in the form of a gas jet. The following somewhat exotic arrangement is also possible: in one of the straight sections in a small region with a minimum of the β functions it is possible to reduce the electrostatic potential in such a manner that the antiprotons are slowed down to the required energy, pass through the target, and then are again accelerated to the storage-ring energy. Of course, the contributions of the regions of deceleration, uniform motion in the target region, and acceleration must be taken into account in the focusing structure of the storage ring. In this arrangement it is possible to use both gas jets and ion beams of the same low energy as a super-thin target for annihilation experiments with very slow antiprotons.

2) Investigation of the interaction of antiprotons and protons (nuclei) at extremely low energies is possible by using two storage rings with a common straight section in which continuously cooled antiprotons and protons are moving parallel to each other with quite close or even equal average velocities. In the latter case as the result of radiative recombination it is possible to form a rather significant flux of protonium atoms—electromagnetically bound states of the proton and antiproton. However, the most interesting arrangement for performing experiments at extremely low energies, which permits the antiproton-proton bound states to be studied the most completely, is as follows. Along one of the straight sections of a storage ring in which a cooled beam of antiprotons with energy of the order 1 MeV is circulating, a beam of hydrogen atoms with the same or very nearly the same average velocity and small spread is transmitted parallel to the antiprotons. The necessary beams can already be obtained at the present time by stripping accelerated negative hydrogen ions, for example, by means of a laser.

We note that in some cases it may be useful to obtain a flux of neutral hydrogen atoms by neutralization of a proton beam in a special storage ring, in particular, as the result of radiative recombination with the cooling electrons. The "used" hydrogen atoms, after traversing the region of interaction with the antiprotons, can be captured by removal of an electron into an additional storage ring with electron cooling, with subsequent transfer of the proton beam back into the first proton storage ring.

3) If in a collision of an antiproton with a hydrogen atom the kinetic energy in their center-of-mass system is less than the electron energy, the cross section for formation of protonium will be close to the geometrical cross section of the hydrogen atom. In this case an electron will be emitted and will carry away the excess energy (close to the average kinetic energy of the electron in the atom). Under these conditions, highly excited levels of protonium with principle quantum numbers of the order $\sqrt{M/2m}$ will mainly be populated, the orbital quantum numbers also being large on the average. The fraction of states with high angular momentum will be particularly great if the initial relative energy of the atom and the antiproton is close to the ionization energy of the hydrogen atom; for this purpose it is necessary to provide the appropriate difference between the average velocities of the atomic beam and the antiproton beam.

4) The lifetime of such highly excited and high-angular-momentum states of protonium against annihilation turns out to be very great; annihilation occurs effectively only from states with orbital quantum numbers no greater than 1. Transitions to these states occur as the result of emission of photons. The lifetime of such transitions turns out to be greater than 10^{-8} sec and the protonium can travel a distance of tens of centimeters, so that it is possible to separate spatially the flux of these "atoms" and the antiproton beam. All of this will permit study of the further fate of protonium under the purest and best defined conditions. For example, by recording the x-ray cascade of radiative transitions in

coincidence with annihilation quanta and mesons, it is possible to pick out annihilation from states with nonzero angular momenta, which is extremely difficult with other experimental arrangements.

Similarly it is possible to study also antiproton-deuteron bound states.

e. Antiatoms

By using stored antiprotons it is possible to obtain beams of antihydrogen atoms. For this purpose it is necessary to pass through an electron-cooled antiproton beam in one of the straight sections of the storage ring a beam of cold positrons parallel to it and with the same average velocity. As the result of radiative recombination it is possible to convert a major part of the antiprotons into antihydrogen. In fact, using the NAP-M with no special efforts 10% of the protons go over into a beam of fast atoms.

A beam of antiatoms can be used, for example, for extremely precise comparison of the properties of hydrogen and antihydrogen atoms. The most accurate data can apparently be obtained in experiments on the interference of states,[51] which in their sensitivity to possible differences in the properties of matter and antimatter are equivalent to measurements of the Lamb shift.

It is possible by the method described to obtain beams of antiatoms of very low energy, which provides the hope of accumulating neutral antihydrogen in special cyclic magnetic systems by acting on the antiatoms via the magnetic moment of the positron.

f. Polarization experiments

1) An important possibility made available by antiproton storage rings with electron cooling is the production of polarized antiproton beams. At the present time the principal method of accomplishing this must be considered to be the interaction of a stored antiproton beam with super-thin polarized targets of atomic hydrogen. On the basis of existing data it is still difficult to choose optimal conditions which permit a high degree of polarization to be obtained with the lowest possible loss of antiproton intensity.

One of the possible schemes is to utilize interaction with longitudinally-polarized protons in a section of the storage ring where longitudinal polarization of antiprotons is stable.[52—54] Here use is made of the difference in the total cross sections for interaction of antiprotons and protons with different relative helicities. Estimates for a proton beam show that for protons in the region of excitation of the Δ^{++} resonance (the optimum momentum of the proton in the storage ring is about 1.4 GeV/c) it is possible by this means to obtain a degree of polarization of the order of 50% with an intensity loss by a factor 30. For antiproton-proton interactions the spectrum of resonances is much richer and it will perhaps be possible to obtain polarized antiproton beams with an even smaller loss of intensity.

2) A completely different arrangement is the scattering of an extracted cooled antiproton beam by a polarized proton or nuclear target, and collection in some manner of the scattered antiprotons, followed by injection of them into a storage ring with electron cooling. To obtain the required degree of polarization, apparently, it is necessary to carry out several such cycles.

3) The possible rate of production of polarized antiprotons will therefore be 10–100 times lower than the number of initially stored antiprotons (per second). However, even this level is sufficient to carry out a very wide range of polarization experiments with antiprotons. Thus, in an antiproton storage ring with electron cooling with utilization of the best polarized gaseous proton and deuteron targets (thickness up to 10^{12} p/cm^2), a luminosity up to 10^{29} or even 10^{30} cm^{-2} sec^{-1} can be obtained. Moreover, polarized antiprotons can be accelerated in the main accelerator and used in experiments of the usual type. It is also a very attractive possibility to carry out polarized proton-antiproton experiments in colliding beams, which will become possible on achievement of the full rate of antiproton storage which is proposed in current projects.

4) Polarization experiments in storage rings with electron cooling are appropriate not only with antiproton beams. This method is adequate also for experiments with polarized protons and deuterons. Only to obtain polarized beams it is necessary, of course, to store directly the accelerated polarized particles. The beams of accelerated polarized protons obtained today and the existing polarized gas targets permit attainment of a luminosity of at least 10^{30} cm^{-2} sec^{-1} under very clean conditions.

We note that today systems with use of electron cooling are already in sight which can enable us to raise the intensity of accelerated polarized proton beams to the level of the existing proton beams in high energy accelerators.

g. Antideuterons

1) The use of electron cooling opens up the possibility of storage also of completely pure beams of antideuterons. The rate of storage of such beams is 10^{-4} of the rate of storage of antiprotons. This permits us to obtain—by using a super-thin deuteron target—luminosities up to 10^{29} cm^{-2} sec^{-1}, and this provides the possibility of studying in some detail the strong neutron-antineutron interactions, including also the annihilation processes. To pick out these interactions it is necessary to record the antiprotons which have essentially preserved their motion and to select events with zero total charge of the remaining final particles or to detect also the low-energy proton remaining after the breakup of the deuteron.

At low energies it may turn out to be of interest to investigate the interaction of antideuterons with complex nuclei, including the study of bound antideuteron-nucleus states.

It is not excluded that the number of stored antideuterons is sufficient for studying similar processes at extremely high energies in colliding deuteron-antideuteron beams. Identification of neutron-antineutron events is possible by means of the protons and antiprotons which remain almost unperturbed.

2) The process of storage and purification of antideuteron beams may appear as follows. A beam of negative secondary particles is injected into a storage ring; mesons, antiprotons, hyperons, antihyperons, and antideuterons will be captured with a momentum corresponding to the magnetic field and radius of the storage ring. All mesons and hyperons decay rapidly, and there will remain antiprotons and, as a small impurity, antideuterons. If the velocity of the electron beam is chosen equal to the average velocity of the antideuterons, which as a result of the greater mass of the deuterons is much less than the velocity of the antiprotons, then the antideuteron beam will be efficiently cooled; at the same time the influence of the electron beam on the antiprotons will be negligible. If after cooling the electron energy and the magnetic field of the storage ring are changed in a coordinated manner, the antideuterons will change their energy correspondingly (the entrainment effect described above), while the antiprotons, retaining their initial energy, will change their orbit radius, leave the storage ring aperture, and be lost. After carrying out the necessary number of cycles a comparatively intense and absolutely pure beam of antideuterons will be obtained.

In principle it is possible in exactly the same way to store also pure beams of antitritium nuclei and antihelium-3 nuclei; however, their intensity will be lower by another four orders of magnitude.

h. Experiments with ion beams

1) Electron cooling opens up interesting prospects for experiments with storage of ions. The principal variant of such experiments will apparently be carried out in the super-thin target mode. The advantage of this arrangement of experiments will be the possibility of precision experiments utilizing the high monochromaticity of a cooled beam and the availability for detection and analysis of all reaction products, including even slow, highly ionizing fragments. It becomes possible, in particular, to study precisely the quasimolecular states of nuclei.

The use of electron cooling is particularly important for experiments with hard-to-obtain ions, mainly heavy ions. A fact which turns out to be convenient here is that in a storage ring with electron cooling there is an ideal separation of isotopes, which makes possible operation with the very lightest isotopes under absolutely clean conditions.

The super-thin target mode described above significantly enriches the possibilities of experiments on the interaction of nuclei, especially heavy nuclei, at energies from the MeV range to the range of GeV per nucleon.

2) However, quite unusual possibilities arise in using this mode when both beams consist of stored, continuously cooled nuclei of the desired type, stripped of their electron shells. Here, in particular, even reactions with emission of nuclear γ quanta become completely background-free. In just this way it may be convenient to study Coulomb excitation processes and to investigate quantum electrodynamics in the critical and "supercritical" electric fields of superheavy compound nuclei.

If the compound nucleus formed in collision of the initial nuclei may have long-lived states (with a lifetime greater than 10^{-8} sec) it is useful to go over to the so-called transverse-beam mode. In this case two storage rings have orbits which intersect, for example, at an angle of 90°. For this purpose the centers of the storage rings can be separated by a distance comparable with their average radius. The compound nucleus will have a momentum equal to the sum of the momenta of the initial nuclei, and after a time of the order 10^{-8} sec will leave the interacting-beam region (if necessary this time can be made even smaller). This mode is of particular interest in the study of superheavy ($Z > 100$) nuclei and provides the possibility both of obtaining detailed information on all such nuclei and of finding their long-lived isotopes, which can be considered as the observation of new elements. If necessary such nuclei can be slowed down in light material and "supplied" with electron shells, and these candidates for new superheavy elements can be subjected to all the procedures of chemical control. The luminosity of such experiments will be clearly sufficient for studying processes occurring with standard nuclear cross sections.

It is not excluded that a cooled beam of "bare" heavy ions will turn out to be of interest for use as the internal target of electron or positron storage rings.

3) In working with heavy ions, a complicating circumstance is the enhancement of the rate of loss of ions as the result of radiative recombination with the cooling electrons. Indeed, the lifetime against radiative recombination and the cooling time are inversely proportional to the square of the ionic charge, but the cooling time is in addition proportional to the mass of the ion. For this reason for the heaviest ions one can succeed in having time to cool the ions but one can not maintain them cooled for an extended period (much longer than the cooling time). This situation can be improved by several times as the result of using the magnetized regime of the electron beam.[7] In fact, in this case the rate of cooling is determined by the relative velocities of the ions or by the spread in the longitudinal electron velocities, while the large transverse electron velocities have almost no effect on the cooling process. At the same time the rate of recombination is determined mainly by the maximum relative velocities, and the influence of the magnetic field should be weaker.

For containment of cooled ions for unlimited periods, which may be of interest, say, in studying the radioactive decay of heavy nuclei stripped of their electron shells, it is possible to use *proton cooling*. For this purpose an ion storage ring is supplemented by a proton storage ring with a straight section common to the two storage rings. The average velocities of the protons and ions must be made identical. A low temperature of the protons must be maintained by electron cooling. For a given temperature and current density of the cooling particles the cooling time is proportional to $AZ^{-2}M_{\text{cool}}^{-1/2}$, where A and Z are the atomic weight and charge of the ions and M_{cool} is the mass of the cooling particles, so that the efficiency of such cooling in practice can be completely satisfactory.

It is possible to obtain cooled beams also of ions only partially stripped of their electron shells, and of negative ions, and even molecular ions. It is not excluded that such beams may be useful for certain experiments.

i. Colliding proton-antiproton beams at the ultimate in high energies

However, the most important and most exciting of the approaching applications of the electron-cooling method even today remains the use of this method to carry out experiments with colliding proton-antiproton beams at the highest possible energy.

1) One of the main problems in carrying out these experiments is obtaining high luminosity. The limiting possible luminosity is determined by the average rate of storage of antiprotons and at these energies (see Eq. (5.1)) is equal to

$$L_{\text{lim}} = \frac{\dot{N}_{\bar{p}}}{\sigma_{\text{loss}}}. \tag{5.2}$$

For the presently projected storage rates of 10^6-10^8 $\bar{p}$/sec this gives a luminosity of $10^{31}-10^{33}$ cm^{-2} sec^{-1}. Of course, realization of luminosities close to this limit imposes strict requirements on the storage ring in which the $p\bar{p}$ collisions are achieved. Let us consider the principal ones of these requirements for the case of a storage ring with a single guide field. It is just this arrangement which will be used first, since the proton-antiproton projects closest to realization at ultrahigh energy propose to use proton synchrotrons now existing or being built with conversion of them to the storage mode (SPS at CERN, and the accelerators at the Fermi National Accelerator Laboratory). To achieve the maximal luminosity in such a case it is necessary to work with short bunches of the colliding particles, in order that all interactions between them be localized in regions scanned by the detecting apparatus. The luminosity summed over all collision regions is determined by the number of particles N_p and $N_{\bar{p}}$, by the areas of the beam cross sections at the points of collision S, and by the frequency of revolution in the storage ring f:

$$L_{\Sigma} = \frac{N_p N_{\bar{p}}}{S} f. \tag{5.3}$$

With use of electron cooling, the size of the beams will be determined only by collision effects (the distortion of the particle motion by the field of the colliding beam) and it becomes reasonable to work with an equal number of colliding particles, $N_p = N_{\bar{p}} = N$. This number cannot be greater than

$$N_{\max} \approx \frac{\gamma \Delta\nu}{r_p} \Omega, \tag{5.4}$$

where Ω is the one-dimensional phase volume of the storage ring (the admittance), r_p is the classical proton radius, γ is the relativistic factor of the particles, and $\Delta\nu$ is the allowable shift of betatron-oscillation frequencies which does not yet lead to a nonlinear buildup of the oscillations. The permissible shift has a value from 0.1 to 0.001, depending on the time of damping or of existence of the beams, on the magnet system selected, and on the care in its adjustment. We note that if the acceleration of the particles is carried out in the storage ring itself, the orbits of the colliding beams must be separated at low energies to avoid their loss as the result of collision effects. Here the number of particles in each of the colliding beams in a storage ring with a single guide field cannot be greater than $N_{\max}$.

Accordingly, the maximal possible luminosity of the storage ring will be

$$L_{\max} = \frac{\gamma^2 (\Delta\nu)^2 f}{r_p^2} \frac{\Omega}{\beta_0}, \tag{5.5}$$

where β_0 is the value of the β function of the storage ring (the analog of the focal length) at the collision point.

The phase volume Ω for the largest proton synchrotrons mentioned above is of the order of 10^{-4} cm-rad, the collision frequency is $f_2 = 5\times10^4$ Hz, and $\Delta\nu$ can hardly be made better than 10^{-2}. For complete utilization of the possible average rates of storage of antiprotons and, accordingly, for obtaining the indicated luminosities ($10^{31}-10^{33}$) cm^{-2} sec^{-1} it is necessary to go over to extremely strong focusing at the collision point with values of β_0 less than 1 m. Here the length of the proton (antiproton) bunches must also be less than 1 m.

The problem of obtaining bunches of such short length and long life is far from simple and requires for its solution careful suppression of noise in the magnetic field and the accelerating voltage, good feedback systems to suppress possible coherent oscillations of the bunches, and apparently a transition to short wavelengths when high values of the accelerating voltage are used.

If the rate obtained for storage of antiprotons assures a luminosity (see Eq. (5.2)) higher than that which can be obtained in a stroage ring with a single guide field (see Eq. (5.5)), it becomes useful to go over to a storage ring with two independent guide fields (as in the case of proton-proton colliding beams). The limiting luminosity of such a two-track storage ring of this type can be increased substantially by filling the entire perimeter of the storage rings with bunches, with these bunches being made to collide only in the special sections which have small values of the β functions and which are scanned by the detecting apparatus.

2) In the first years after the first proton-antiproton colliding-beam project was reported (the project VAPP-NAP at Novosibirsk),[43] proton-antiproton experiments at the highest possible energies have been considered by many only as an extremely elaborated addition to proton-proton experiments at the same energies. Of course, even then it was clear that this addition is very important. In fact, obtaining sufficiently complete information even concerning the general properties of the strong interaction requires the most complete possible set of initial states. Therefore it is necessary to have both proton-proton and proton-antiproton experiments,

and preferably also deuteron-antideuteron experiments. Of course, even this set is not complete and with time it will be necessary to have colliding meson-nucleon and meson-meson beams. It can be shown that the luminosity of arrangements already forseeable today for such experiments is sufficient for studying hadron interactions occurring with a cross section of the order of the total cross section.

There have been discussed also two classes of experiments which are specific just for proton-antiproton colliding beams—first, the study of hadron annihilation and, second, investigation of two-particle charge-exchange reactions, i.e., reactions with conservation of baryon charge of each of the colliding particles. The annihilation cross section evidently drops off only as the reciprocal of the colliding-beam energy and even at an energy of 2×1000 GeV will be of the order of 10^{-30} cm^2. Therefore the principal problem will be the identification of annihilation processes from the great bulk of events comprising the total cross section. At the same time the cross section for processes of the type

$$\bar{p}p \to \bar{\Lambda}\Lambda$$

drops off (in the region known at this time) as E^{-4} and only with a luminosity of the order of 10^{32} cm^{-2} sec^{-1} will it be possible to obtain information on these processes at energies above 100 GeV.

3) In recent years the attitude toward proton-antiproton colliding beams has changed greatly. The quark model is acquiring more and more dynamical content and more and more "public opinion" is inclined to consider hadrons as consisting of quarks interacting as point particles. Accordingly, processes with very large momentum transfers will occur through the interaction of quarks, the components of the colliding hadrons. Here proton-proton collisions give quark-quark reactions, while proton-antiproton collisions give quark-antiquark reactions. In this sense one can say that in experiments in colliding proton-antiproton beams it is possible to obtain the same fundamental information as in colliding electron-positron beams of the same luminosity and with an energy of the order of a third of the energy of the baryons. Similarly, proton-proton colliding beams are equivalent to electron-electron collisions. Of course, for strongly interacting particles such as protons and antiprotons we cannot say that they consist only of quarks of one "polarity." However, according to contemporary neutrino data[55] the content of antiquarks in a proton is about 5% (this is also the estimate of the content of quarks in the antiproton). Therefore quark-antiquark interactions are dominant in proton-antiproton collisions, and quark-quark interactions provide only a small admixture. For proton-proton collisions the ratio will be the reverse. In addition, the average energy of quark-antiquark reactions in proton-proton collisions will be substantially lower than in proton-antiproton collisions.

By studying, say, the lepton-pair-production reactions

$$\bar{p}p \to X + \begin{cases} e^+e^-, \\ \mu^+\mu^-, \end{cases}$$

which occur both as the result of the electromagnetic interaction and as the result of the weak interaction of quarks, the factors cited will permit obtaining information of fundamental importance on these interactions at the highest possible energies. In particular, if there actually are neutral intermediate bosons of the weak interaction Z^0, they can be observed in these reactions if the combined energy of the proton and antiproton exceeds the rest mass of the proton by a factor of 3–6. According to current estimates, this requires a proton-antiproton colliding-beam energy in the region of $2\times(150-500)$ GeV. In the same energy range it is also possible to observe, if they exist, charged bosons of the weak interaction, $W^\pm$.

The search for heavy leptons is also possible in similar experiments.

We note in addition that it is also possible to study reactions in which a quark-antiquark pair annihilates into a neutrino-antineutrino pair. The occurrence of such a reaction can be recorded by the "disappearance" of a significant fraction of the initial energy of the proton-antiproton pair (of the order of a third), this loss occurring almost symmetrically with respect to the initial particles.

An even more detailed investigation will be possible when experiments with polarized proton-antiproton colliding beams become possible, as well as proton-proton and deuteron colliding beams. At the limiting high energies considered it is particularly important[56,57] that there is the possibility of experimenting with particles which are longitudinally polarized (at the point of collision).[52,61] Electron cooling permits solution of the problem of obtaining polarized antiproton and proton beams of the necessary intensity.

The quark treatment of the interactions of protons and antiprotons reveals high promise for experiments in colliding proton-antiproton beams. However, it is not excluded that the real physics of the interaction of matter and antimatter at ultrahigh energies will turn out to be even more interesting and completely unexpected.

CONCLUSION

In the present review we have attempted to show what interesting prospects are opened up by the application of electron cooling. Together with other methods for cooling beams of heavy particles, this method provides the possibility of performing qualitatively new experiments in diverse fields of elementary-particle physics and nuclear physics.

We wish to thank our colleagues in the development of the electron-cooling method: Ya. S. Derbenev, N. S. Dikanskiĭ, I. N. Meshkov, V. V. Parkhomchuk, D. V. Pestrikov, R. A. Salimov, B. N. Sukhina, V. I. Kudelainen, and others. We are also grateful to V. N. Baĭer, V. E. Balakin, L. M. Barkov, S. T. Belyaev, A. I. Vaĭnshteĭn, T. A. Vsevolozhskaya, V. G. Zelevinskiĭ, A. S. Patashinskiĭ, S. G. Popov, I. Ya. Protopopov, D. D. Ryutov, V. A. Sidorov, G. I. Sil'vestrov, I. B. Khriplovich, and other members of the Nuclear Physics Institute for helpful discussions.

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Translated by Clark S. Robinson