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New Apparatus and Methods of Measurement

THE CURRENT STATE OF THE PHYSICS AND TECHNOLOGY OF OBTAINING POLARIZED PARTICLE BEAMS

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Methods are discussed for obtaining and accelerating polarized ions of hydrogen, deuterium, helium-3, and lithium. A review is given of the physical and technological solutions of the problem of ionization of polarized atoms, of the production of polarized ions by the method of charge exchange through a metastable state, and also of the means of avoiding depolarization of particles in acceleration to high energies. The possibility is analyzed of accelerating polarized ions of deuterium in a synchrotron. The possibility of storing polarized ions in electron beams is set forth in detail. Data on working installations are presented. The review includes articles published up to March, 1971.

CONTENTS

1. INTRODUCTION

EXPERIMENTS with polarized particles occupy a special place in elementary-particle physics and nuclear physics, since they provide the most direct means of studying the spin dependence of nuclear forces. In the general case the presence of spin components of nuclear forces results in the characteristics of the observed processes turning out to be different for different particle spin orientations before and after the collision. The ideal polarization experiment can be performed with a polarized beam and a polarized target, with the condition that the polarization states of the beam particles and the target are varied in a controlled way with all remaining experimental conditions held constant.

Until recently the only method of obtaining polarized particle beams was utilization of scattering and nuclear reactions[1]. In 1954 I. I. Gurevich (see ref. 2) suggested the acceleration of ions polarized beforehand in the source. Development of a polarized ion source was initiated at the I. V. Kurchatov Atomic Energy Institute (see ref. 3) and independently at other laboratories throughout the world[4a]. In 1960 100-keV polarized deuterium ions were obtained for the first time at Basel[5].

A polarized proton beam is characterized by the reduced intensity[6] I_r, which is equal to

$$I_r = IP^2,$$

where I is the beam intensity and P is the degree of polarization of the beam. During the last ten years the reduced intensity of existing polarized ion sources has grown roughly exponentially, increasing by a factor of ten every three years (Fig. 1). The history of development of the technology of obtaining polarized ions is contained in the proceedings of the international conferences at Basel[7] (1960), Karlsruhe[8] (1965), Madison[9] (1970), and Brookhaven[10], and also in a number of review articles[11-14,15a,16a]. In the present article we present new data on the production and acceleration of initially polarized particles, and also recently advanced proposals. The technology of polarized targets and the use of unpolarized targets to obtain

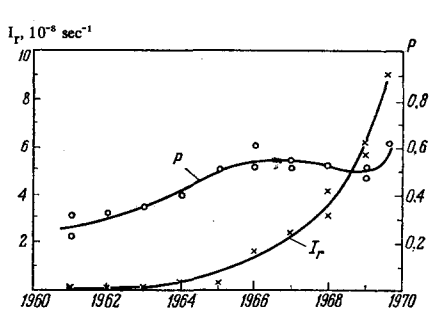

FIG. 1. Rise of reduced intensity of the polarized beam I_r and the polarization P during operation of the polarized ion source in the proton linear accelerator at the Rutherford Laboratory.

secondary polarized particles are not discussed.

a) Spin state of a particle. For particles with spin $I = 1/2$ there are two alternative orientations of the spin vector with respect to an external magnetic field: in the direction of the field ($m_I = 1/2$) and opposite to the field ($m_I = -1/2$). A beam of particles is called completely polarized if the spins of all particles are oriented only in one direction: in the direction of the field or opposite to the field. If particles with both orientations are present in the beam, the beam is called partically polarized, and the degree of polarization of such a beam is

$$P = N(1/2) - N(-1/2),$$

where $N(1/2)$ is the fraction of particles in the beam whose spins are oriented in the direction of the field, and $N(-1/2)$ is the fraction of particles with spins of the opposite orientation. In the general case the polarization state of the beam is completely characterized by the polarization vector $\mathbf{P}$ with components

$$P_i = \langle \sigma_i \rangle,$$

where σ_i are the Pauli matrices and the averaging $\langle \ldots \rangle$ is carried out over the particles in the beam. Finally, the description of the polarization state of a beam of particles with spin $I = 1/2$ is given by the density matrix[17]

$$\rho(1/2) = 1/2\,(1 + \mathbf{P}\sigma) = 1/2 \begin{pmatrix} 1+P_3 & P_1 - iP_2 \\ P_1 + iP_2 & 1-P_3 \end{pmatrix}.$$

If the quantization axis is chosen along the polarization vector $\mathbf{P}$, the density matrix is diagonalized and the only nonzero component is

$$P_3 = P, \quad P_1 = P_2 = 0.$$

The diagonal elements of the density matrix

$$\rho(1/2) = 1/2 \begin{pmatrix} 1+P_3 & 0 \\ 0 & 1-P_3 \end{pmatrix} = \begin{pmatrix} N(1/2) & 0 \\ 0 & N(-1/2) \end{pmatrix}$$

characterize the populations of the corresponding spin states of the beam.

For particles with spin $I = 1$ the polarization state of the beam is given not only by the polarization vector P_i but also by the polarization tensor P_{ij}. Here

$$P_i = \langle S_i \rangle, \quad P_{ij} = 3/2\,[\langle S_i S_j \rangle + \langle S_j S_i \rangle] - 2\delta_{ij},$$

and S_i are the spin operators for particles with spin 1.[18] The polarization parameters P_i, P_{ij} are related to the populations of the three spin states $N(1)$, $N(0)$, and $N(-1)$ as follows:

$$\left.\begin{gathered} P_3 = N(1) - N(-1), \quad P_1 = P_2 = 0, \\ -2P_{11} = -2P_{22} = P_{33} = 1 - 3N(0) = 3\,[N(1) + N(-1)] - 2, \\ P_{12} = P_{13} = P_{23} = 0. \end{gathered}\right\} \quad (1)$$

The density matrix for particles with spin 1 in the diagonal representation has the form

$$\rho(1) = \begin{pmatrix} N(1) & 0 & 0 \\ 0 & N(0) & 0 \\ 0 & 0 & N(-1) \end{pmatrix} = \begin{pmatrix} 1/3 + 1/2 P_3 + 1/6 P_{33} & 0 & 0 \\ 0 & 1/3 - 1/3 P_{33} & 0 \\ 0 & 0 & 1/3 - 1/2 P_3 + 1/6 P_{33} \end{pmatrix}.$$

For particles with spin $I = 3/2$, for example, for ^{7}Li nuclei, the polarization parameters are defined as follows[19]:

$$P_3 = 1/3\,\{3\,[N(3/2) - N(-3/2)] + [N(1/2) - N(-1/2)]\},$$

$$P_{33} = [N(3/2) + N(-3/2)] - [N(1/2) + N(-1/2)],$$

$$P_{333} = 1/3\,\{[N(3/2) - N(-3/2)] - 3\,[N(1/2) - N(-1/2)]\}.$$

b) Principles of polarized ion production. Polarized ions can be obtained by various methods. Two of these methods have received the greatest development for protons and deuterons. These are the atomic beam method, which is usually called the classical method, and the method of charge exchange through a metastable state, which is known in the literature as the Lamb method. The classical method reduces to the spatial separation of an atomic beam according to the spin states of the atom in a nonuniform magnetic field and to the subsequent ionization of the atoms lying in one of these states. The Lamb method is based on the properties of the $2S_{1/2}$ state of the hydrogen atom in electric and magnetic fields. Other methods cited in the literature for obtaining polarized atoms have not yet been realized in the form of working apparatus.

2. THE ATOMIC BEAM METHOD

In a polarized ion source based on the classical method (Fig. 2), the following processes occur: 1) dissociation of hydrogen molecules, 2) formation of a free beam of atoms with thermal velocities, 3) spatial separation of atoms according to hyperfine-structure states, 4) change of the population of the states in a radiofrequency field (often, but not always), 5) ionization of the atoms, and 6) injection of the polarized ions into an accelerator.

a) Dissociation of hydrogen molecules. Atomic hydrogen is obtained in a high-frequency electrodeless discharge excited in a glass bulb with a gas pressure of 0.1–1 Torr with a frequency of 20–150 MHz. A discharge plasma is formed by the magnetic component of the high-frequency field[20] or by the electric field along a U-shaped tube[21]. The power required from the supply is 100–1500 W. A Wood's discharge in a constant electric field, as an alternative to the electrodeless discharge, is unsuitable in that the atoms recombine rapidly on the metallic electrode surfaces, which must be placed at a distance from the working volume of the discharge. In an electrodeless discharge recombination of atoms to molecules occurs at the walls. Pyrex glass, from which the discharge tube is usually made, has a low surface-recombination coefficient. Careful cleaning of the glass and deposition of coatings increase the degree of dissociation, and addition of 5–10% of water vapor to the hydrogen permits a 95% degree of dissociation to be achieved.

Volume recombination is kinematically possible only

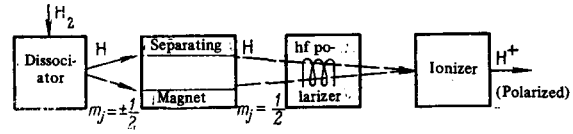

FIG. 2. Arrangement of a polarized ion source utilizing the atomic beam method.

in ternary collisions of atoms and becomes appreciable for gas pressures greater than 1 Torr[22]. For pressures above several Torr the degree of dissociation drops, and the increased temperature of the gas makes it difficult to deflect the atoms in the nonuniform magnetic field. The experiments of Clausnitzer[23a] with a low-voltage arc discharge at gas pressures up to 0.5 atm turned out to be unsuccessful. The degree of dissociation was no more than 5%. Because of the short lifetime and unstable operation, this design of dissociator has been widely used. The discharge tube of the dissociator is cooled by air or liquid. Successful trials of a liquid nitrogen cooling system, carried out recently[24], open the possibility of increasing the intensity of polarized ions by 5–6 times. Ad'yasevich et al.[25] also have reported an increase in the flux of atoms.

b) Formation of a free atomic beam. It is well known[26] that an atomic beam can be formed by effusion of atoms through an aperture into a vacuum. If the thickness of the wall in which the aperture is made is negligible and if the Maxwellian velocity distribution of the particles does not change as they leave the reservoir, the flux of particles dQ through an aperture of area A at an angle θ to the axis in a solid angle $d\omega$

$$dQ = (d\omega/4\pi)\, n\bar{v} A \cos\theta,$$

where n is the number of particles per unit volume and $\bar{v} = (8kT/\pi m)^{1/2}$ is the mean velocity. The total flux is

$$Q = n\bar{v}A/4.$$

As will be shown below, the typical capture solid angle of the separating magnet is $\sim 10^{-3}$ sr. Production of an atomic beam of intensity 10^{16} atoms/sec at the separating magnet exit requires a gas flux through the dissociator of about 1 cm^3/sec under standard conditions.

An effusion aperture in the form of a channel produces a more sharply directed flux with the same intensity along the axis. For effusive outflow of atoms, the mean free path λ should be greater than the channel length. According to the measurements of Keller et al.[21a] the mean free path, if small-angle scattering of hydrogen atoms is taken into account, is related to the gas pressure p by the equation $\lambda p = 3.1 \times 10^{-3}$ Torr-cm.

Wide use[20,25,27,28] has been made of multicapillary collimators for atomic beams (multicollimators), which were first used at the Rutherford Laboratory[20]. This type of collimator consists of a bundle of closely packed capillaries about 0.2 mm in diameter occuping a circular aperture 0.6–1.0 cm in diameter. Ad'yasevich et al.[25] have tried capillaries 0.04 mm in diameter. Usually the capillary length is about ten times its diameter. Gordon and Ponomarev[29] have given a method for calculating the optimum dimensions of multicollimators with consideration of recombination of atoms inside the channel. Means of preparation of multicollimators have been described in refs. 27–30. Typical flow rates of gas through multicollimators are $\sim 5 \times 10^{-2}$ liter-Torr/sec, and therefore they are used when there is a limitation on pumping, for example, in a polarized ion source operating at a high voltage.

A dissociator with multicollimators operates at a gas pressure of 0.5 Torr or below. At pressures above 0.5 Torr, a gas cloud is formed at the exit of the multicollimators which scatters the gas flow and results in destruction of the directional effect and attenuation of the flux. The highest value of atomic flux at the separating magnet exit obtained by means of multicollimators is $(5-10) \times 10^{15}$ atoms/sec.

Somewhat higher intensity is given by a miniature de Laval nozzle. According to the theory[31] a de Laval nozzle can form a collimated ultrasonic flux of atoms with a low velocity spread. An atomic beam source produced at Saclay[32] has given a flux of atoms at the exit of a six-pole magnet of 5×10^{16} atoms/sec. The advantages of the miniature de Laval nozzle, which increase with increasing pressure in the dissociator, have not yet been realized. One of the reasons for this is the inadequate speed of pumping the gas leaving the nozzle. Only future experiments, in particular those with cryogenic vacuum pumps, will provide final data on the properties of the miniature de Laval nozzle.

c) Hydrogen and deuterium atoms in a magnetic field. In the ground state of the hydrogen atom the total angular momentum **F** is formed by the spin angular momentum of the electron **j** and the spin angular momentum of the nucleus **I**. The eigenvalues of the total angular momentum F are 1 (triplet) and 0 (singlet). Interaction of the magnetic moments of the electron and proton in the hydrogen atom produces a hyperfine splitting ΔW between the levels F = 1 and F = 0,

$$\Delta W = h \cdot 1420.4\ \text{MHz} = 5.8 \cdot 10^{-6}\ \text{eV}.$$

In an external magnetic field the level F = 1 breaks up into three sublevels with $m_F = 1, 0, -1$ (Fig. 3) (the Zeeman effect). In strong magnetic fields the interaction energy between the external field and the magnetic moment of the electron exceeds the hyperfine splitting energy, and the state of the atom is characterized by the magnetic quantum number of the electron m_j and the magnetic quantum number of the proton m_I. The effective magnetic moment of the hydrogen atom $\mu_{eff} = -\partial W/\partial B$ in the hyperfine-structure states is shown in Fig. 4 as a function of magnetic field.

The Zeeman effect in the deuterium atom is shown in Fig. 5. The spin of deuterium is I = 1, and therefore each state m_j in a strong field has three components with $m_I = -1, 0, 1$. The effective magnetic moment of the deuterium atom is shown in Fig. 6. The

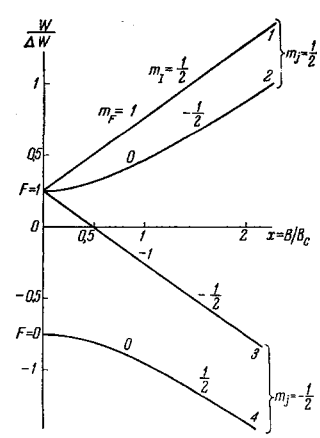

FIG. 3. Energy level diagram of the hydrogen atom in a magnetic field.

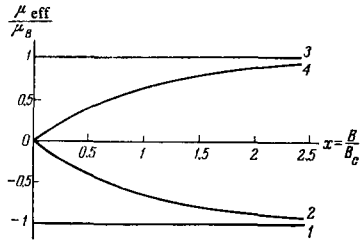

FIG. 4. Effective magnetic moment of the hydrogen atom as a function of magnetic field.

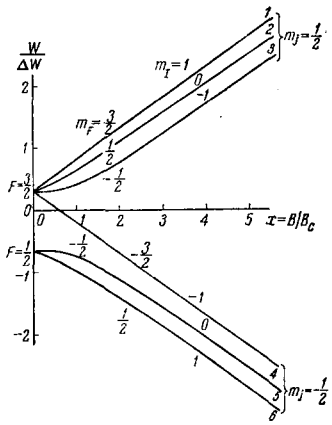

FIG. 5. Energy level diagram of the deuterium atom in a magnetic field.

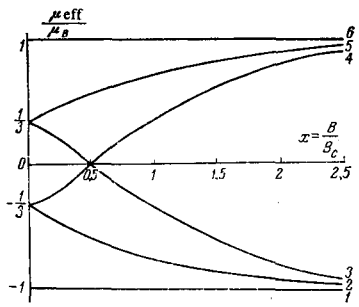

FIG. 6. Effective magnetic moment of the deuterium atom as a function of magnetic field.

external magnetic field strength is measured in units of the critical field

$$B_c = \Delta W/\mu_B (g_I - g_j^e),$$

where ΔW is the hyperfine splitting energy in zero field and g is the gyromagnetic ratio. For the electron $g_j^e = -2.0023$, for the proton $g_I^p = 3.04 \times 10^{-3}$, and for the deuteron $g_I^d = 0.47 \times 10^{-3}$. The external field B is considered strong if $x \gg 1$. For the hydrogen atom $B_c^H = 507$ G, and for the deuterium atom $B_c^D = 117$ G.

The energy of a level in a magnetic field B is given in general form by the Breit-Rabi formula (see ref. 26)

$$W_{F=I\pm1/2,\, m_F} = -[\Delta W/2(2I+1)] - \mu_B g_I m_F B \pm 0.5\Delta W[1 + (4m_F/2I+1)x + x^2]^{1/2}. \quad (2)$$

Table I gives values of the parameters occurring in Eq. (2).

The behavior of the metastable $2S_{1/2}$ state of the hydrogen or deuterium atom is described by similar energy level diagrams but with smaller splitting:

$$\Delta W_{2S_{1/2}} = \Delta W_{1S_{1/2}}/8.$$

Each of the hyperfine structure levels has a definite value of nuclear polarization. Nuclear polarization in a polarized ion source is obtained in two stages. First, states with $m_j = 1/2$ are separated from states with $m_j = -1/2$ in a strong magnetic field. The atomic states selected in a strong magnetic field are polarized only in electron spin. If the atoms are then transported adiabatically to a region of weak field, the hydrogen spin state 1 (Fig. 3) preserves its nuclear polarization ($m_I = 1/2$). The state 2 will be described after such a transition by a wave function having both an $m_I = 1/2$ component and an $m_I = -1/2$ component. The total polarization in nuclear spin will be 1/2. Application of this method to deuterium atoms gives a beam polarized in the deuterium nuclei with $P_3 = -1/3$ and $P_{33} = -1/3$.

Other methods of obtaining nuclear polarization also exist which use atoms polarized in the electron spin. One of these methods, which is described below, is the induction of radiofrequency transitions between the hyperfine-structure sublevels of an atom in a magnetic field. Direct separation[23b] of the 1 state is also possible, but for this purpose only a weak field ($x \lesssim 1$) is suitable. Because of the low intensity of the atomic beam obtained, this method has not been widely used.

d) The separating magnet. Selection of atomic states with $m_j = 1/2$ is accomplished in a strong magnetic field which contains high gradients. The atom is a magnetic dipole, acted on by a force

$$F = -\frac{\partial W}{\partial B}\frac{\partial B}{\partial r}.$$

It is customary to use long magnets whose cross section has four or six poles alternating in polarity[33] (Fig. 7). The pole contours are chosen so that the magnetic field strength has a dependence of the form

$B = B_m (r/r_m)^2$ for a six-pole magnet,
$B = B_m r/r_m$ for a four-pole magnet,

where B_m is the field strength at the pole tips and r_m

Table I

Atom	State	I	$g_I \cdot 10^{-3}$	ΔW, MHz	B_c, G
H	$1S_{1/2}$	1/2	3.04	1420.406	507.591
H	$2S_{1/2}$	1/2	3.04	177.557	63.450
D	$1S_{1/2}$	1	0.466	327.384	116.842
D	$2S_{1/2}$	1	0.466	40.924	14.605
T	$1S_{1/2}$	1/2	3.24	1516.702	542.059
T	$2S_{1/2}$	1/2	3.24	189.594	67.759
^{6}Li	$S_{1/2}$	1	0.448	228.208	81.5
^{7}Li	$S_{1/2}$	3/2	1.18	803.512	287

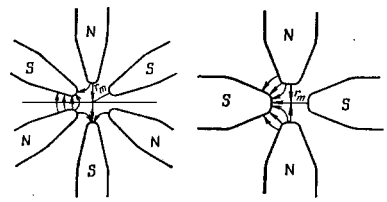

FIG. 7. Cross section of (a) six-pole and (b) four-pole magnets and shape of the magnetic field lines.

is the distance from the pole tip to the axis. The bending force is given by

$F_6 = (2B_m/r_m^2)\,\mu_{eff}\,r$ for a six-pole magnet,
$F_4 = (B_m/r_m)\,\mu_{eff}\,r/r$ for a four-pole magnet.

It is directed to the magnet axis if the energy of the state is increased with increasing B ($\mu_{eff} < 0$, $m_j = 1/2$), and away from the magnet axis if the energy of the state is decreased with increasing B ($\mu_{eff} > 0$, $m_j = -1/2$). Such a multiple magnet efficiently transmits only those atoms which are in a state with $m_j = 1/2$. The transmission efficiency reaches 95% for sufficiently great magnet length.

The solid angle for capture of atoms in paraxial trajectories with $r_{init} = 0$ is determined by the relation

$$0.5mv^2\alpha_0^2 = W(B_m) - W(0),$$

where α_0 is the maximal angle between the velocity vector v of the atom at the magnet entrance and the magnet axis. The solid angle is

$$\Delta\Omega(r=0) = \pi[W(B_m) - W(0)]/0{,}5mv^2.$$

For an effusion source at a temperature T,

$$\overline{\Delta\Omega}(r=0) = \pi[W(B_m) - W(0)]/kT.$$

For selection of states with $m_j = 1/2$ in a strong field

$$W(B) - W(0) = \mu_B B.$$

Thus, for example, for $B_m = 6$ kG and $T = 400°K$

$$\overline{\Delta\Omega}(r=0) = \pi\mu_B B/kT = 3\cdot10^{-3}\ \text{sr} \qquad (\alpha_0 = 1.8°).$$

For paraxial trajectories with $r_{init} = \rho$

$\overline{\Delta\Omega}(\rho) = (\pi\mu_B B_m/kT)[(r_m - \rho)/(r_m + \rho)]^{1/2}$ for a four-pole magnet,

$\overline{\Delta\Omega}(\rho) = (\pi\mu_B B_m/kT)[1 - (\rho^2/r_m^2)]^{1/2}$ for a six-pole magnet.

If the magnet aperture is uniformly filled by the beam, the solid angle averaged over the aperture and over velocity is[15a]

$$\begin{aligned} \overline{\Omega} &= 1.35\mu_B B_m/kT \quad \text{for a four-pole magnet,} \\ \overline{\Omega} &= 2.09\mu_B B_m/kT \quad \text{for a six-pole magnet.} \end{aligned} \qquad (3)$$

The magnet length is chosen sufficiently large to remove from the beam the greater part of atoms with $m_j = -1/2$. An estimate of the intensity of the undesired component has been given by Dickson[11] and by Rudin[5].

A six-pole separating magnet has the properties of a lens, and therefore an image of the source of atoms is formed at its exit. However, the velocity spread of the atom results in strong chromatic aberrations.

Profiling of the magnet with a gradual decrease in the radial field gradient[34] leads to an increase in the capture solid angle[35]. Here the source of atoms must be placed sufficiently close to the entrance aperture of the separating magnet. The profiled six-pole magnet at Saclay[36] has an aperture diameter of 0.4 cm at the magnet entrance and 0.8 cm at a distance of 25 cm from the entrance, the diameter remaining constant during the remaining 25 cm. The four-pole magnet at Khar'kov has excellent optical properties. The length of this magnet is 25 cm and the aperture diameter 0.8 cm[37]. Use of Permendur pole tips for the magnet has provided a very high field, $B_m = 20$ kG.

e) Radiofrequency transitions. Transitions between the two hyperfine-splitting states of atoms in a radiofrequency field give a polarized ion source very valuable properties. These are the highest possible polarization and the possibility of operating with change of polarization. In this case, in contrast to polarized-ion-source systems with ionization of the atoms in a weak magnetic field without use of transitions, the occurrence of radiofrequency transitions doubles the vector polarization of protons and deuterons and triples the tensor polarization of deuterons.

The radiofrequency-transition technique in polarized ion sources is based on the adiabatic-traversal method of Abragam and Winter[38]. A detailed description of this method has been published by Beurtey[39a]. The essence of the method in classical language[40] reduces to the following. The magnetic moment of an atom **M** associated with angular momentum **I** ($\mathbf{M} = \gamma\mathbf{I}$) experiences in a magnetic field a torque*

$$\mathbf{T} = d\mathbf{I}/dt = [\mathbf{M}\mathbf{B}_0].$$

The vector **M** precesses about the vector $\mathbf{B}_0$ with an angular velocity of precession

$$\omega_0 = -\gamma B_0.$$

In a frame of reference S′ which rotates about the vector $\mathbf{B}_0$ with angular velocity ω_0, the vector **M′** is fixed. This means that in the frame of reference S′ the magnetic field acting is zero, $B_0 = 0$. Now let us add a rotating radiofrequency magnetic field with amplitude B_1 and frequency ω_0 directed perpendicular to the vector $\mathbf{B}_0$. Then introduce slow changes of the external field B_Z in time from an initial value $B_0 + \Delta B_0$ to a final value $B_0 - \Delta B_0$. This change occurs when the atom moves through a nonuniform magnetic field. In the rotating system of coordinates S′ the initial field B_Z' is equal to ΔB_0 and, slowly changing, goes over to the final field $(-\Delta B_0)$. The combined field $\mathbf{B}_{eff}$ in this case changes with time as shown in Fig. 8. If the rotation of the combined magnetic field occurs slowly in comparison with the period of Larmor precession, the vector **M** adiabatically follows the vector $\mathbf{B}_{eff}$. For a linear variation of the field B_Z in time, the region $B_{eff} \approx B_1$ turns out to be the most dangerous. The adiabatic condition at this point is written in the form

$$B_1^{-1}\,dB_z/dt \ll \gamma B_1.$$

In order to preserve a high value of beam polarization at the exit of the system, ΔB_0 is chosen large in com-

*$[\mathbf{M}\mathbf{B}_0] \equiv \mathbf{M} \times \mathbf{B}_0$.

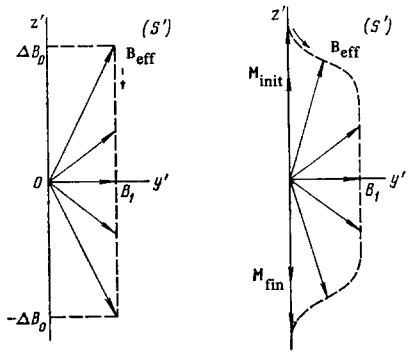

FIG. 8. Total magnetic field as a function of time in the rotating coordinate system.

parison with B_1. This condition is automatically satisfied in real systems, since the atoms slowly enter the radiofrequency resonator or coil and B_1 increases from zero at the entrance and falls to zero at the exit.

Adiabatic transitions are realized both in a weak external magnetic field and in a strong field.

1) Radiofrequency transitions in a weak field[38b]. In this case m_F is a good quantum number and levels with different m_F are equidistant. Therefore the radiofrequency field produces transitions between several levels with the same F but different m_F. For hydrogen, three levels take part in the transitions, and for deuterium—four levels. The frequency of the field corresponds to the energy difference between neighboring states in m_F. As the result of an adiabatic transition the populations of states 1 and 3 are exchanged and the populations of states 2 and 4 remain constant. Since only states 1 and 2 are populated in an atomic beam at the exit of the separating magnet, states 2 and 3 become equally populated after adiabatic transitions. If an atomic beam of this type is ionized in a strong field (see below), the degree of polarization of protons turns out to be $P_3 = -1$. Transitions in a weak field for deuterons exchange the populations of states m_F and $-m_F$. The exchange transitions $1 \longleftrightarrow 4$, $2 \longleftrightarrow 3$, $5 \longleftrightarrow 6$ occur simultaneously. The mixture of states $(1 + 2 + 3)$, obtained after the separating magnet, is converted to a mixture $(4 + 3 + 2)$. On ionization of the atomic beam in a strong field, deuterons are obtained with pure vector polarization ($P_3 = -2/3$, $P_{33} = 0$).

2) Radiofrequency transitions in a strong field. In a strong magnetic field two-level transitions are excited. In hydrogen atoms the transition $2 \longleftrightarrow 4$ is produced, after which the proton polarization is $P_3 = 1$. In deuterium atoms the transitions which occur are $2 \longleftrightarrow 5$, $2 \longleftrightarrow 6$, and $3 \longleftrightarrow 5$ or only one of them, or successively in various combinations, so that the radiofrequency sections are separated from each other by a region of weak field. The condition for an adiabatic transition for hydrogen has the form

$$\hbar^{-1} d(E_2 - E_4)/dt \approx (E_2 - E_4)\, v/l\hbar \ll \mu_B B_1^2/\hbar^2,$$

where $E_2 - E_4 = \hbar\Delta\omega_0$ is the energy difference of levels 2 and 4 at the exit and entrance of a region of radiofrequency field of length l, and v is the velocity of the atoms, or in other words,

$$2\Delta B_0 v/l \ll (\Delta W B_1^2/4B_c\hbar)/x\,(1 + x^2)^{1/2}.$$

The condition for achieving high polarization $\Delta B_0' \gg B_1'$ is written in the form

$$\Delta\omega_0 \gg B_1\Delta W/2B_c\hbar\,(1 + x^2)^{1/2}, \quad \omega_0 = \Delta W\,(1 + x^2)^{1/2}/\hbar.$$

An arbitrary polarization state is achieved by means of a system of three radiofrequency sections: two of them at the entrance and exit in a weak external field, and between them a radiofrequency section in a strong external field. Possible transitions in a combination of three radiofrequency sections are listed in Table II.

3) Working installations. Polarized in sources with radio frequency sections in a weak field have been built at Saclay[39a], the Rutherford Laboratory[41], and at other laboratories. At Saclay a constant magnetic field changes along the atomic beam from 6 to 10 G in a length of 2 cm. The resonance field at the center $B_0 = 8$ G corresponds to a proton frequency of about 7.5 MHz. Excitation of the magnetic component of the radiofrequency field with an amplitude of 0.6 G requires a power of only a few watts.

The hydrogen transition $2 \longleftrightarrow 4$ in a strong field is also used at Saclay. An atomic beam passes through a resonator excited at a frequency 2850 MHz. The magnetic field is $B_0 \approx 1000$ G, and the drop in field $\Delta B_0 = 10-20$ G in a length of 3 cm. A power of about 50 W is required to produce a microwave field of intensity $B_1 = 1$ G in the resonator.

A two-level deuterium transition requires a power of 300—400 W. If a field $B_0 \approx 100$ G is used, as has been suggested by Collins and Glavish[42], the deuteron frequency becomes equal to about 400 MHz, and the required power about 20 W. In order to produce a radiofrequency field parallel to the vector B_0, a single-wire loop is used. Kuhfeld[43] has proposed a method of successive radiofrequency transitions in an intermediate magnetic field.

f) Ionization of the atomic beam. The first designs

Table II

	Weak field	Strong field, transitions between two levels	Weak field	P_3	P_{33}
Deuterium	+	—	—	−2/3	0
	+	2 ⟷ 5	—	−2/3	0
	+	2 ⟷ 5	+	2/3	0
	—	3 ⟷ 5	—	1/3	−1
	—	2 ⟷ 6	—	1/3	1
	+	2 ⟷ 6	—	−1/3	1
	+	2 ⟷ 6	+	1/3	−1
	—	2 ⟷ 6	+	−1/3	−1
	—	3 ⟷ 5	+	−1/3	1
Hydrogen	+	—	—	−1	
	—	2 ⟷ 4	—	1	

of ionizers for polarized ion sources utilized the classical technique of ionizing atomic and molecular beams by electron impact. Electrons emitted from a hot cathode were accelerated to several hundred electron volts and directed at an atomic beam. The positive ions formed were extracted by an electrode at a potential below that of the region of ionization. This type of ionizer works in a weak magnetic field of intensity up to roughly 20 G. If the atomic beam, after leaving the separating magnet, passes directly into the region of ionization in such a way that the transition from strong field to weak field occurs adiabatically, the protons obtained in such an ionizer have a polarization P = 0.5. An important deficiency of the first designs of ionizers was the high emittance of the ion beam and, as the result of this, the inefficient use of the ions produced. Further development has led to increase of the ion current and decrease of the emittance of the polarized ion beam. The use of radiofrequency sections in polarized ion sources has permitted the ionization to be carried out in a strong magnetic field. The electron beam in such an ionizer moves parallel to the atomic beam along the magnetic field. Extraction of the ions is carried out in the same direction.

One of the parameters of a polarized-ion-source ionizer is the ionization efficiency η, which is equal to the ratio of the ion beam intensity I^+ to the intensity of the flux of atoms I^0 fed to the ionizer:

$$\eta = I^+/I_0;$$

here

$$I^+ = (j_e/e)\,\sigma\rho V$$

is determined by the electron current density j_e (in A/cm^2), the density of atoms in the beam ρ, the cross section σ for ionization, and the volume of the ionization region V.

The intensity of atoms

$$I_0 = \rho\bar{v}S$$

depends on the average velocity of the atoms $\bar{v}$ and the cross-sectional area of the atomic beam S. Thus,

$$\eta = j_e\sigma V/e\bar{v}S = j_e\sigma L_{\text{eff}}/e\bar{v}.$$

The quantity $L_{\text{eff}} = V/S$ is called the effective interaction length.

The ionization cross section of hydrogen atoms is characterized by a maximal value[44] $\sigma_{\max} = 7 \times 10^{-17}$ cm^2 at an electron energy eU = 70 eV and a falloff at higher energies, described for U > 100 V by the relation[45]

$$\sigma(U) = (3.15 \cdot 10^{-15}/U)\,\lg(U/0.325).$$

In order to avoid the effect of space charge it is desirable to use high-energy electron beams. In this case the electron current rises more rapidly ($\sim U^{3/2}$) than the cross section $\sigma(U)$ falls. However, at high values of U an increase in the energy spread of the ion beam occurs. In ionizers of the type described the probability of depolarization of the ions is extremely small. A decrease in polarization arises from unpolarized ions produced in ionization of residual gases containing hydrogen, such as, for example, hydrocarbons and water vapor. Entry of molecular hydrogen into the ionizer is not so dangerous, because of the low cross section for dissociative ionization and the possibility of separating protons from molecular ions by means of a magnetic field.

1) Ionizers with weak magnetic fields. Ionizers with a weak magnetic field are simple in design. Most of the ionizers described in the literature utilize plane-parallel geometry with crossed electron and atomic beams.[11,12,15a] According to Clausnitzer et al.[46] the maximal density of an electron beam accelerated by a grid electrode to an energy eU is

$$j_e^{\max} = (32/9)\,\varepsilon_0\,(2e/m)^{1/2}\,U^{3/2}/D^2,$$

where D is the distance between the grid and the anode. For an atomic beam of cross section b × D and an ionizer length l the maximal ion current is

$$I^+_{\max} \sim bl/D.$$

A ribbon-shaped beam (D small) turns out to be most advantageous, Under typical conditions for j_e = 0.2 A/cm^2, eU = 200 eV, S = 1 cm^2, and V = 1 cm^3, the ionization efficiency is $\eta = 2 \times 10^{-4}$. The experimentally measured value of η is close to this estimate.

An ionizer with cylindrical geometry has been built at the Rutherford Laboratory[41]. Electrons are emitted from several filaments placed parallel to the atomic beam. This type of ionizer is more efficient than the plane ionizer[20] used previously. In Clausnitzer's design[23a] the filaments are arranged cylindrically and ion extraction is accomplished radially.

In the Erlangen analyzer[47] (Fig. 9), which consists of two cathodes K and two grids G, extraction of ions along the line of divergence of the grids is accomplished by means of reduction of the potential by the electron space charge (in the figure HS designates a heat shield, and GS the grid support). The essence of this effect reduces to the fact that the value of the minimal potential on the line of divergence of the ionizer grids changes in such a way that a potential gradient arises which attracts the ions to the exit. The ionization efficiency for a length of 9 cm is $\eta = 2 \times 10^{-3}$.

A system developed at the Lebedev Institute in Moscow[48] (Fig. 10) has a cylindrical geometry (the designations are: IR—ion reflector, EE—extracting electrode). Hydrogen atoms pass along a mesh cylindrical anode A and are ionized by electrons emitted from a coaxial cathode K. The electrons complete oscillatory motions before hitting the anode. Therefore a comparatively small current in the external circuit

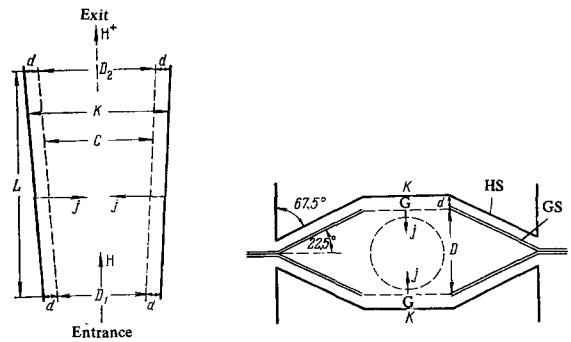

FIG. 9. Arrangement of ionizer developed at Erlangen, West Germany.

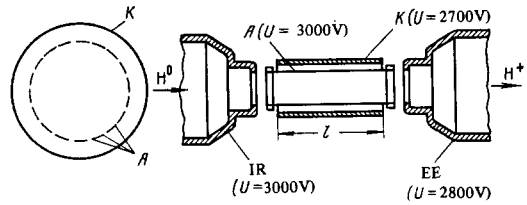

FIG. 10. Arrangement of ionizer developed at the Lebedev Institute in Moscow.

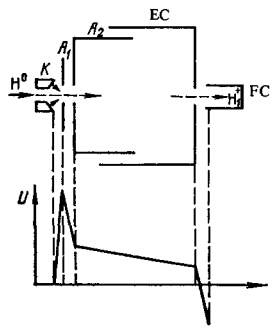

FIG. 11. Arrangement of ionizer developed at the Physico-technical Institute, Academy of Sciences, Ukrainian SSR, at Khar'kov.

is required to achieve a space-charge-limited ion current. The ionization efficiency is $\eta = 2 \times 10^{-3}$ for an anode length 2.4 cm.

The ionizer developed at Khar'kov[49] (Fig. 11) utilizes neutralization of a narrow electron beam by positive ions which arise in ionization of a passing atomic beam (the designations in the figure are A_1—first anode, A_2—second anode, FC—Faraday cup). A ring-shaped oxide cathode K forms a conically converging electron beam. The electrons are first extracted by a potential of 3 kV and then slowed down to an energy of 600 eV. The potential of the electron collector EC is 500 V, and therefore the ions are extracted through an opening in the collector from the entire length of ionization. The ionization efficiency is $\eta = 1.6 \times 10^{-3}$ for an ionization length of 6 cm. An ionizer of this type is used in Czechoslovakia[50b].

2) Ionizers with strong magnetic fields. An ionizer with a strong magnetic field is placed after the radio-frequency section in which quantum transitions are induced between the components of the hyperfine splitting of the ground state of the atom. Therefore the path traveled by the atoms from the separating magnet to the ionizer increases by several tens of centimeters, and the density of atoms in the ionization region decreases in comparison with the density of atoms in the region of an ionizer with a weak magnetic field which is located directly after the separating magnet.

The electron current density in a strong axial magnetic field can be increased up to the point where reflection of electrons back to the cathode occurs, i.e., until a virtual cathode is formed. The maximal electron current inside a cylinder at potential U, if the cross section of the cylinder is uniformly filled, is

$$I_e^{\max} = 32.4 \cdot 10^{-6} U^{3/2} \mathrm{A}.$$

The first version of an ionizer with a strong magnetic field, developed at Auckland[51] with an electron-injection current of 25—40 mA, produced an ion current of 0.5 μA with a beam emittance of 2 cm-rad-$eV^{1/2}$. The atomic beam was ionized inside a cylinder of length 16 cm and diameter 1.6 cm. The electron energy was 100—250 eV. The ionization efficiency, although it amounted to only 1×10^{-3}, was substantially greater than in the ionizer with a weak magnetic field built at the same laboratory[27].

A second version[52] used a ring-shaped electron beam for which the maximal current was determined by the expression

$$I_e^{\max} = 29{,}4 \cdot 10^{-6} (r/\Delta r)\, U^{3/2} \mathrm{A}, \qquad (4)$$

where r is the radius of the cylinder and Δr is the radial width of the electron beam. The use of radial modulation[52] does not permit the beam width Δr to be made smaller than the value

$$\Delta r_{\min} = mE/eB^2, \quad E = U/\Delta r_{\min}.$$

Thus, for example, for U = 400 V and B = 1000 G, $\Delta r_{\min} \approx 1$ mm. Achievement of limiting electron currents is also prevented by nonuniformities in the magnetic field and by thermal deformations of the cathode.

In the ionizer shown schematically in Fig. 12, U = 400 V, r = 0.5 cm, $r/\Delta r = 2.5—5$, $l = 15$ cm. (The electrode potentials relative to the filament are: $U_{E_1} = 300—500$ V, $U_{E_2} = 550$ V, $U_{E_3} = 400$ V, $U_{E_4} = 0$, $U_{E_5} = -1—3$ kV, $U_{E_0} = -5$ kV). The electrons undergo multiple reflections. The space-charge-limited current under these conditions (4) is $I_e^{\max} = 940$ mA. Obviously there are still unused possibilities here. The ion current is 1.5 μA, and about 60% of the ions fall in a phase space 5.6 cm-rad-$eV^{1/2}$. The measured ionization efficiency is $\eta = 3.3 \times 10^{-3}$.

In Saclay an ionizer is used which is similar to the first version developed at Auckland. The ion current is about 5 μA[39b]. Similar ionizer designs are used in Zurich[53a,d], Erlangen[54], and Minnesota[55].

In the Rutherford Laboratory[41,56] and at Dubna[16b] ionizers using a Penning discharge have been studied. A stable discharge inside a long anode at a potential of 4—5 kV was maintained by means of a hot filament from which a current of 300—600 μA was injected. As a result of electron space charge the potential at the axis of the anode was reduced to 1 kV. The electric-field gradient along the ionizer axis extracted ions in both directions, half of them going in the required direction. The ion beam at the exit of the ionizer with a strong magnetic field has a longitudinal polarization. An electrostatic mirror which changes only the direction of motion of the particles rotates the longitudinal polarization to transverse. An arbitrary polarization direction can be obtained if the polarized beam is transmitted through a system of crossed electric and

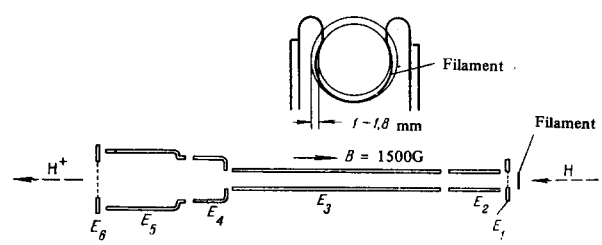

FIG. 12. Arrangement of ionizer developed at Auckland, New Zealand.

magnetic fields and a solenoid coaxial with the beam. An attempt has been made[57] to use an ordinary high-frequency ion source for ionization of polarized atoms, but multiple processes in it led to depolarization. A high-pressure arc discharge excited in a buffer gas (argon) in the center of the synchrocyclotron at Lyons turned out to be successful in ionization of polarized deuterium atoms.[58]

g) Production of negative ions by charge exchange of positive polarized ions. Negative polarized ions intended for injection into tandem accelerators and cyclotrons are obtained by charge exchange of positive ions with keV energies in a vapor-stream gas target[59] or in a foil[60]. The yield and polarization of the negative ions depend on the choice of target and the energy of the positive ions. For an ion energy of 40 keV the yield in a thin carbon foil (5 $\mu g/cm^2$) is about 1% and, within 2%, occurs without loss of polarization[28,53b,61]. A target of alkali metal vapor is more efficient. For an energy of 0.5—1.5 keV the negative ion yield is[62] 10% for potassium and at an energy of 0.5 keV 15% for cesium. For an energy of 2 keV the yield in potassium and cesium is 10%.

Depolarization during charge exchange in a gas or vapor can be suppressed by application of a strong magnetic field[15b]. This has been confirmed experimentally in the charge exchange of deuterons in potassium vapor[53c]. The tensor polarization of the positive deuterium ions, which amounted to $P_{33} = -0.94$, decreased to $P_{33} = -0.88 \pm 0.07$ in the negative ions in a field of 435 G and to $P_{33} = -0.35$ in zero field. The difference between the depolarization effects in a foil, on the one hand, and in gases on the other hand is due to the fact that the time of traversal through the foil is very small and the two-step processes which occur in a gas, in which two electrons are captured in successive collisions, are not possible in the foil. During the time between individual collisions a part of the nuclear polarization is transferred to the electron as the result of the hyperfine coupling.

Systematic studies of one- and two-electron charge-exchange processes in the energy region 1—20 keV have been carried out for positive hydrogen ions in alkali metals[63]. The maximal negative ion yield falls monotonically from 20% at 1 keV for cesium to 12% at 2.5 keV for sodium and to 6% at 4 keV for lithium. Schlachter et al.[64] obtained a yield of 21 ± 4% at 0.75 keV in cesium. Khirnyĭ and Kochemasova[65b] found that the greatest charge-exchange coefficient for protons into negative ions is observed in a cesium target at 0.3 keV (0.6 keV for deuterons) and amounts to 26 ± 2%. However, the advantages of cesium turn out to be almost unattainable as the result of the difficulties in obtaining intensity of a low-energy proton beam and transporting it through the charge-exchange channel. The experimental data on multiple-step charge-exchange processes in alkali metal vapor are described by the scheme given by Donnally[66].

h) Ionization by heavy particles. In addition to ionization of polarized atoms by electron impact, occurring according to the reaction

$$H(\uparrow) + e^- \to H^+(\uparrow) + 2e^-,$$

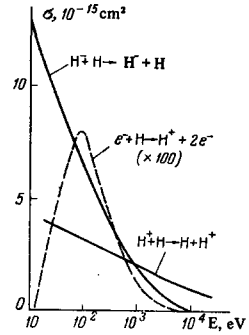

FIG. 13. Cross sections for ionization of hydrogen atoms as a function of incident particle energy.

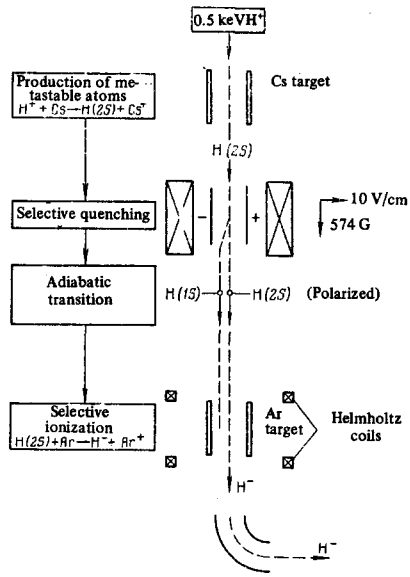

FIG. 14. Diagram of negative polarized ion source based on the Lamb method.

ionization by fast negative ions or by protons is possible,

$$H(\uparrow) + H^- \to H^-(\uparrow) + H, \qquad H(\uparrow) + H^+ \to H^+(\uparrow) + H.$$

The cross sections for these three processes are shown in Fig. 13 as a function of the particle energy. In one of the suggested schemes the interaction length of the particles was increased by application of crossed electric and magnetic fields[67]. The best overlapping of the beams occurs for an ion energy of about 100—200 eV. For ionization by protons, compensation of the space charge is possible by electrons injected in addition.

Worthy of special attention is the method[15b,67] of obtaining polarized ions by charge exchange of an unpolarized proton beam on the hydrogen atoms of a beam in which only the electrons are polarized. For an atom concentration of 3×10^{11} cm^{-3} in a length of 30 cm, 5-keV protons undergo exchange with a probability of 1%. If capture of the polarized electrons occurs in a strong magnetic field, then after adiabatic transition to zero field a beam of fast atoms is formed in which the protons have a degree of polarization $P \lesssim 0.5$. A method of obtaining negative ions has been discussed also by Haeberli[15c].

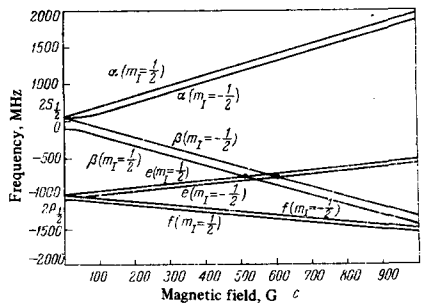

FIG. 15. Hyperfine-structure Zeeman effect of the hydrogen atom in the states $2S_{1/2}$ and $2P_{1/2}$.

3. THE LAMB METHOD

A method of obtaining a polarized ion beam based on the properties of a hydrogen atom excited to the metastable $2S_{1/2}$ state has been proposed by Zavoĭskiĭ[68b] in 1957 and also by Madansky and Owen[69]. The idea of the method is implicitly contained in the well known paper of Lamb and Retherford[70]. Initially the problems of realizing the Lamb method reduced to the search for an efficient means of obtaining hydrogen atoms in a metastable state and to exploring the possibility of their selective ionization. Donnally[71,72] showed that in charge exchange it is possible both to obtain a beam of metastable atoms and to accomplish the ionization process. One of the first schemes used[65a,c,73-76,77a] is shown in Fig. 14. A beam of metastable hydrogen atoms formed in charge exchange of protons in cesium vapor is directed into a magnetic field of 574 G and a weak electric field of about 10 V/cm. Here the atoms in the lower sublevels of the $2S_{1/2}$ state are de-excited by a transition to the ground state, and the excited atoms remaining in the upper sublevels undergo selective charge exchange to negative hydrogen ions. The process occurs in an argon target in a weak magnetic field. The negative polarized ion beam formed is suitable for injection into a tandem accelerator. For charge exchange of metastable atoms into positive ions, a target of molecular iodine vapor I_2 turns out to be most suitable[77b,78].

a) Energy levels of hydrogen and deuterium atoms with n = 2 in a uniform field. Figure 15 shows the energy levels of a hydrogen atom in the state with principal quantum number n = 2 in a magnetic field[13,15a]. The states of the $2P_{3/2}$ level lie approximately 10 000 MHz above the $2S_{1/2}$ state. The designations α, β, e, and f are taken from the paper of Lamb and Retherford[70]. The energy difference of the $2S_{1/2}$ and $2P_{1/2}$ levels in the absence of a field correspond to a frequency of about 1058 MHz.

b) Lifetimes. In the absence of electric and magnetic fields a hydrogen atom in the $2S_{1/2}$ metastable state decays by transition to the ground state in a time $\tau_{S_0} = 1/7$ sec, while the lifetime of the $2P_{1/2}$ state is $\tau_P = 1.6 \times 10^{-9}$ sec. Application of an electric field produces a Stark effect, as the result of which the $2S_{1/2}$ and $2P_{1/2}$ states are mixed and the lifetime of the metastable state is decreased. In electric and magnetic fields[75]

$$\tau_S = \tau_P \hbar^2 [\omega^2 + (\gamma^2/4)]/|V|^2, \qquad (5)$$

where $\hbar\omega$ is the transition energy, $\gamma = 1/\tau_P = 99.8$ MHz, $|V|$ is the transition matrix element

$$|V| = \int \langle \varphi_f | eEr | \varphi_i \rangle \, dr;$$

φ_i and φ_f are the wave functions of the initial and final states. Equation (5) is valid for the condition that the matrix element $|V|$ is such that $\tau_{S_0} \gg \tau_S \gg \tau_P$. In the absence of a magnetic field for E < 100 V/cm Eq. (5) takes the form[15a]

$$\tau_S = (19/E)^2 \, \mu\text{sec}.$$

c) Polarization in a metastable state. The most intense mixing of the $2S_{1/2}$ and $2P_{1/2}$ levels occurs in a field B = 574 G when the levels with $m_j = -(1/2)$ ($2S_{1/2}$) and $m_j = (1/2)$ ($2P_{1/2}$) cross. Because of the hyperfine structure the crossing actually occurs at two points—at fields of 538 and 605G. If the electric field is parallel to the magnetic field, levels with $\Delta m_j = 0$, i.e., $\alpha + e$ and $\beta + f$, are mixed. If $\mathbf{E} \perp \mathbf{B}$, levels with $\Delta m_j = \pm 1$, i.e., $\alpha + f$ and $\beta + e$, are mixed. The β and e levels cross in a field of 574 G, and therefore on application of a transverse electric field the lifetime of the β level becomes very short. The α and β lifetimes are[15a]

$$\tau_S = 1.13E^{-2}[(574 \pm B)^2 + 716] \cdot 10^{-9} \text{ sec}.$$

The plus sign refers to the α level, and the minus sign to the β level. In a field of 574 G

$$\tau_S(\alpha)/\tau_S(\beta) = 1 + (4\omega_{cf}^2/\gamma^2) \approx 1850.$$

Under typical conditions hydrogen atoms in a $2S_{1/2}$ state moving with a velocity 3.1×10^7 cm/sec (0.5 keV) pass through a magnetic field B = 547 G parallel to the velocity vector and through an electric field E = 15 V/cm perpendicular to the magnetic field. In a 4.6-cm path atoms in a state with $m_j = -1/2$ decay practically completely. Atoms in a $2S_{1/2}$ state with $m_j = 1/2$ decay only to the extent of 3.5%. On leaving the field only atoms polarized in the electron spin ($m_j = 1/2$) remain in the $2S_{1/2}$ state. On adiabatic transfer of the atoms to a weak magnetic field and subsequent ionization of the atoms, which are only in the $2S_{1/2}$ state, a polarized proton beam is produced with a polarization of no more than 50%.

d) Charge-exchange processes. The choice of charge-exchange processes which can be used to obtain metastable atoms is determined by the following parameters. The energy defect Q is the difference in the internal energies of the initial and final states of the process

$$H^+ + X \rightarrow H + X^+ + Q.$$

The velocity of H^+ ions at which the cross section reaches its maximal value is proportional to the energy defect Q, and the lower the Q, the higher the cross section. In addition, the charge-exchange cross section is large when the ionization potential of the atom X is small. The reaction

$$H^+ + Cs \rightarrow H_{2S} + Cs^+ + Q \qquad (6)$$

is characterized by an energy defect Q = 0.49 eV. According to the theory of Rapp and Francis[79] a sharp rise in the cross section for reaction (6) should be ob-

served at low energies down to 0.5 keV (6×10^{-15} cm^2) and a slow drop at high energies. In the other hand, for the reaction

$$H^+ + Cs \rightarrow H_{1S} + Cs^+ + Q$$

the energy defect is Q = 9.6 eV and at low energies charge exchange to the metastable 2S state should be dominant.

According to the data of Sellin (see refs. 80, 81) the charge-exchange cross section is $\sigma(2S) = 2 \times 10^{-14}$ cm^2 at 2 keV. The charge-exchange cross section $\sigma(2S) = 3 \times 10^{-15}$ cm^2 measured in the experiments of Donnally[71] has been improved[82a] and now the value is estimated to be $\sigma(2S) \approx 10^{-14}$ cm^2 in the energy range 0.3–3 keV. The cross section begins to drop at energies above 5 keV and at 10 keV is $\sigma(2S) \approx 10^{-15}$ cm^2. The cross section for charge exchange to the 2P state is three times larger than that to the 2S state. In the experiments of Donnally (see ref. 71) and Drak((see ref. 73) the yield of H_2S states was 10–15% for a proton energy of about 0.5 keV and for the optimal target thickness 5×10^{-3} Torr-cm. The anomalously small yield values reported by Cesati et al.[75] are apparently erroneous.

e) Production of negative ions. The Lamb method requires high selectivity in ionization of metastable atoms. The charge-exchange cross section must be greater than the cross sections for all other processes which remove metastable atoms from the beam. Donnally and Sawyer[71,72] have shown that negative ions which are formed in the reaction $H_2S + Ar \rightarrow H^- + Ar^+$ by action of atoms emerging from a cesium target with energy 0.5 keV are due almost completely to the transition of the atom from the $2S_{1/2}$ state.

Donnally[72b] has studied ten different gases with ionization potentials from 10 to 24 eV. The best gas turned out to be argon, with an ionization potential 15.8 eV. The energy defect of the undesirable reaction $H_1S + Ar \rightarrow H^- + Ar^+$ is 15.05 eV. The yield of $H_2S \rightarrow H^-$ charge exchange in argon for a target thickness 1.5×10^{-2} Torr-cm is 10%. In the first experiments[65a,73a,75] the negative ion current obtained was about $(2-4) \times 10^{-9}$ A. Later it was possible to increase the currents[65c,77a] to $(2-4) \times 10^{-8}$ A, and by neutralization of the space charge to obtain currents of about $(2-4) \times 10^{-7}$ A[83].

f) Production of positive ions. Here the most suitable target turned out to be iodine vapor[77b,78]. It is well known that the degree of selective ionization of H_2S^- atoms relative to H_1S^- is determined by the closeness in the electron affinity of the exchange atom (or molecule) to the ionization energy of the metastable atom (3.3 eV). If the electron affinity of the ion X^- in the reaction

$$H_{2S} + X \rightarrow H^+ + X^- \qquad (7)$$

is less than 3.3 eV, the potential energy of the system $(H^+ + X^-)$ at large relative distances will be higher than the potential energy of the system $(H_2S + X)$. As the particles approach, the potential energy of the system $(H^+ + X^-)$ decreases as the result of Coulomb attraction, and at some distance r_2S the potential energy curves cross. According to the theory of pseudocrossings[84], exchange of an electron occurs near this point

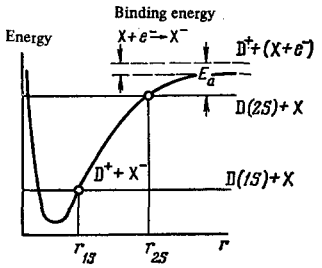

FIG. 16. Potential curve of the ionic system $D^+ + X^-$.

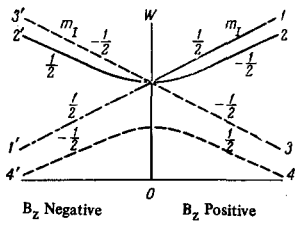

FIG. 17. Energy level diagram of the hydrogen atom on reversal of the magnetic field.

for certain particle velocities. The greater r_2S, the greater the charge-exchange cross section. On the other hand, r_2S must be comparatively small in order that the wave functions of the two atoms overlap sufficiently.

The selectivity of reaction (7) relative to the reaction

$$H_{1S} + X \rightarrow H^+ + X^-$$

is determined by the ratio $(r_2S/r_1S)^2$ (Fig. 16) or by the large cross section for dissociative electron attachment (in Fig. 16 E_a is the ionization energy of the deuterium atom in the $2S_{1/2}$ state, r_1S and r_2S are determined by the points of intersection of the potential energy curve with the levels of $D_1S + X$ and $D_2S + X$). The first successful experiments on observation of selectivity were carried out in ionization of D_2S^- atoms with energy 1 keV in gas targets of hydrogen, deuterium, and helium[77c]. Subsequently studies were made of the halogens, in which the electron affinity is 2.4–3.8 eV. The most intensively studied process is[77b,85]

$$D_{2S} + I_2 \rightarrow D^+ + I_2^- \ (D^+ + I + I^-).$$

The electron affinity of I^- is 3.07 eV, and of I_2^- 2.4 eV. The dissociation energy of I_2 is 1.54 eV. It was found that the polarization is almost independent of the iodine vapor pressure and decreases with increasing ion energy. Comparison of charge-exchange reactions in argon and iodine shows that the ion yield is a factor of two higher in an iodine target.

g) Methods of increasing beam polarization. A recently proposed simple method[86] of increasing the polarization of ions consists of directing a beam of metastable atoms with $m_j = 1/2$ into a region of magnetic field reversal and then to a region of strong longitudinal magnetic field of the reverse direction. If the atom crosses the region of field reversal rather rapidly on the scale of the Larmor precession, the atoms remain in levels which are a continuous extension of the energy levels in the region of negative magnetic field values (Fig. 17). Therefore it is sufficient to place the ionization region in a strong magnetic field to obtain a polarized proton beam. In the case of

deuterons this method gives only a vector polarization $P_3 = 2/3$, and the tensor polarization is zero. A different procedure is used to obtain tensor polarization. First the 1′ state is quenched in a second region with magnetic field B = 574 G and after ionization a vector polarization $P_3 = 1/2$ and tensor polarization $P_{33} = -1/2$ obtained. Finally, if the beam, after a second quenching, is transferred adiabatically to a weak field and ionization is carried out there, the tensor polarization is $P_{33} = -1$ and the vector polarization is zero[87]. The method of passage through zero magnetic field has been used in a number of laboratories[85,88,89].

Donnally[82b] suggested using a radiofrequency section with zero magnetic field for the purpose of exchanging populations between $2S_{1/2}$ (F = 1) and $2P_{1/2}$ (F = 1) states. Only atoms in a state with F = 0 remain in a metastable state. The ionization is carried out a strong magnetic field. This method was carried out at Rutgers[90]. The generator power at 1147 MHz was 0.5 W.

h) A source of negative polarized ions. Following Lamb's idea[91], a nuclear spin filter has been developed at Los Alamos[92] which selects one of the hyperfine-structure components of the metastable $2S_{1/2}$ state of a hydrogen or deuterium atom. Let us recall the energy-level structure of an atom in a metastable state placed in a magnetic field close to 538 G. The β state ($m_I = 1/2$) crosses the e state ($m_I = 1/2$). It is sufficient to apply a weak transverse constant electric field, so that atoms in β states rapidly transfer to the ground state of the atom. On the other hand, a longitudinal variable electric field with frequency about 1600 MHz, which corresponds to the α ($m_I = 1/2$) and e ($m_I = 1/2$) energy-level difference, induces de-excitation of the α states. The combined use of a constant electric field and one of this frequency has a quite different result. In particular, if polarized hydrogen atoms in a $2S_{1/2}$ metastable state pass through a system with a constant magnetic field of 538 G and a constant electric field with a smoothly rising longitudinal radiofrequency field, atoms in α states ($m_I = 1/2$) will be converted to a mixture of atoms of α and β states. Here those atoms which are in a metastable state with $m_I = -1/2$ undergo induced de-excitation to the ground state under the action of the radiofrequency field. The equilibrium mixture of α and β states with amplitudes a and b which is produced by a radiofrequency field of intensity R and a constant field of intensity V satisfies the condition $a/b \approx V/R$. Therefore, when the beam sees a radiofrequency field slowly rising and slowly falling along the resonator, the equilibrium mixture at the two ends of the resonator will consist only of the pure α state. This is equivalent to transmission by the resonator of only the α state. In order to produce a slow change in the radiofrequency field, the resonator is provided with

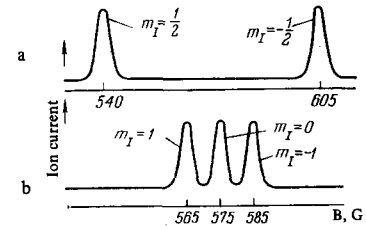

FIG. 18. Spin filter (ion current as a function of field for atoms of H (a) and D (b)).

large openings at the ends. A resonator of length 25 cm is excited at a frequency of 1609 MHz in the TM_{010} mode. The electric field supplied between the resonator walls, which are cut into four parts, is 10 V/cm.

Selection of states with different m_I is accomplished by establishing one of two magnetic field values. For the hydrogen atom the fields are 538 and 605 G. The required magnetic field uniformity is 0.03%. The transmission coefficient of such a system for the α state is 85% in hydrogen and 90% in deuterium. Components with undesirable m_I are essentially not transmitted to the system. Figure 18 shows the negative ion current obtained in such a spin filter as a function of the magnetic field[93]. The background component present for nonresonant magnetic fields is due to atoms which were in the ground state.

The metastable component for state 1 of hydrogen or deuterium gives a polarization P = 1 for hydrogen and $P_3 = P_{33} = 1$ for deuterium. The polarization of the background component is practically zero. The operating values of the magnetic fields in the ionization region of a pure metastable beam obtained in a spin filter are listed in Table III[92].

4. MEASUREMENT OF ION POLARIZATION

a) Fast ions. For an energy of 100 keV it is possible to measure the tensor polarization of deuterons. In accordance with the suggestion of Galonsky et al.[94], the T(d, n)^{4}He reaction is used. The analyzing power of this reaction corresponds to the channel quantum numbers $l = 0$, $J = 3/2(+)$, and the reaction cross section is determined by the expression

$$\sigma(\theta) = \sigma_0 [1 - 0.25 (3\cos^2\theta - 1) P_{33}],$$

where σ_0 is the cross section for an unpolarized beam, and θ is the angle between the particle momentum in the c.m.s. and the quantization axis. Usually 3.3-MeV α particles are detected. For $P_{33} = -1/3$, $\sigma(0°)/\sigma(90°) = 14/11$. The same properties are possessed by the mirror reaction[95] ^{3}He(d, p)^{4}He.

To measure the vector polarization of deuterons it is possible to use the scattering of deuterons by helium-4 nuclei[96] in the energy region from 3 to 9 MeV, and also the reaction[97] ^{12}C(d, p)^{13}C.

Table III

Ion	Quantum number of state, m_I	Vector polarization P_3	Tensor polarization P_{33}	Magnetic field intensity, G
H⁻	1/2	1	—	6
H⁻	−1/2	−0,12	—	6
D⁻	1	1	1	6 6 or 60))
D⁻	0	0.012	−1.966	60
D⁻	−1	−0.984	0.952	60

The polarization of a proton beam is measured from the scattering of protons by target-analyzers calibrated by double proton scattering or by other methods. Thus, for example, the analyzing power of helium 4 is accurately known[98] in the energy region from 1 MeV to 65 MeV.

b) Slow ions. However, in the energy region below 1 MeV there are no efficient analyzers. To measure the polarization of protons with energy 0.5–500 keV the process of charge exchange of ions to a metastable $2S_{1/2}$ state has been suggested[99]. For the optimal proton energy of 10 keV about 10% of the ions which have passed through cesium vapor are converted to atoms which are in a $2S_{1/2}$ state. In order to avoid depolarization, the charge exchange is carried out in a strong magnetic field of intensity about 200 G for protons and 50 G for deuterons. The metastable atoms are then passed through a spin filter, at the exit of which only metastable atoms with a definite m_I value remain. The polarization along the z axis of the polarimeter is

$$P_3 = (n_+ - n_-)/(n_+ + n_-),$$

where n_+ is the number of metastable atoms with $m_I = 1/2$ and n_- is the number of the same atoms with $m_I = -1/2$. In order to measure the remaining components of the polarization vector, P_1 and P_2, the polarization vector **P** is rotated by 90° and the beam is then sent through a spin filter. The polarization of deuterons is determined by the formula

$$P_3 = (n_+ - n_-)/(n_+ + n_0 + n_-) \text{ and } P_{33} = 1 - [3n_0/(n_+ + n_0 + n_-)],$$

where n_+, n_0, and n_- are the fluxes of deuterium atoms in metastable states with $m_I = 1$, 0, and −1, respectively.

The intensity of filtered metastable atoms is measured from the yield of photons with wavelength 1216 Å in a strong transverse electric field of ~500 V/cm. The photons are detected in coincidence with a fast atom which is recorded by a proportional counter. A similar means of measuring the polarization of slow ions, proposed by Clausnitzer and Fick[100] and which consists of measuring the circular polarization of photons emitted in the quenching of metastable atoms, is based on the unique relation between photon polarization and nuclear polarization.

A very simple means of polarization measurement discussed by Haeberli[101] is as follows: after charge exchange in a weak magnetic field, states 3 and 4 are quenched, and then the number of photons arising in quenching of states 1 and 2 is recorded. For protons this number is proportional to $0.5 + 0.25P_3$, and for deuterons, to $(6 + 3P_3 - P_{33})/12$. In this method of determining polarization, two measurements are made: one with polarized ions, and the second with unpolarized ions. In a system consisting of two analyzers which are separated by a region of zero field[102], measurements are made without readjustment, with use of only a polarized beam.

5. SOURCES OF POLARIZED HELIUM-3 AND LITHIUM IONS

a) Polarized singly charged helium-3 ions. Polarized helium-3 ions are obtained both by the optical-pumping method[103] and by the spatial separation of atoms according to their spin states[104,105]. In the first case a high-frequency ion source has been used whose design permitted optical pumping. The expenditure of helium 3 was about 9 cm^3/hour. The greatest difficulty is associated with purification of the helium-3 gas. The beam of singly charged helium-3 ions with energy 300 keV had a degree of polarization P = 0.05. The beam intensity was 4 μA, and the emittance ≈1 cm-rad-$eV^{1/2}$. Since the electron shell of the ^3He atom is closed and its magnetic moment is zero, the action of a magnetic field on the atom occurs through the magnetic moment of the nucleus, whose value is about 10^3 times smaller than the electron magnetic moment. This leads to very small capture angles (see Eq. (3)). Therefore, in order to compensate this effect, the helium gas is cooled to a temperature of ~4°K before leaving the nozzle.

Vyse et al.[105] have described an atomic-beam source with a de Laval nozzle 0.025 mm in diameter. Saturation of the atomic flux is reached at a pressure P_{He} = 40–50 Torr. For a reservoir temperature of 6°K a flow from the nozzle with a Mach number M = 10 is achieved. The intensity of the ^3He atomic beam is $\approx 10^{18}$ at/sr-sec, and the average velocity 3.1×10^4 cm/sec. The expected current of polarized $^3He^+$ ions is 10 nA.

b) Sources of polarized lithium ions. Since lithium vapor is almost completely monotonic, the atomic-beam method with spatial separation of lithium atoms according to electron spin states is suitable[106]. In one of the designs of sources of polarized lithium ions[107] an atomic beam of ^6Li or ^7Li was formed by means of a de Laval nozzle 0.5 mm in diameter. The oven temperature was 850°C. The lithium nucleus polarization analyzer in the form of a scattering chamber was held at a high negative voltage. The polarization was measured in the reaction $^6Li(d, {}^4He)^4He$. When the $3 \longleftrightarrow 5$ transition is used, $P_{33} = -0.70 \pm 0.10$, and with the $2 \longleftrightarrow 6$ transition $P_{33} = 0.68 \pm 0.11$, while for the $3 \longleftrightarrow 5$ transition combined with a transition in a weak field $P_{33} = 0.66 \pm 0.11$. The expected depolarization in the magnetic field of the ionizer is not more than 4%. The observed depolarization is due to the low efficiency of the radiofrequency transitions or to depolarization in ionization on the tungsten surface (see also ref. 108).

Miers and Anderson[109] have described a polarized ion source for lithium (the natural distribution 93% lithium 7 and lithium 6) and cesium with a microcollimator atomic source. With ionization by electrons in a weak field, currents of 3.3×10^{-8} A were obtained for Li^+, 1.3×10^{-9} A for Li^{2+}, 6.6×10^{-7} A for Cs^+, 1.4×10^{-7} A for Cs^{2+}, and 6×10^{-8} A for Cs^{3+}. The degree of polarization was not measured. The nuclear vector polarization of $^7Li^+$ was estimated to be ≈ 25%, and the electronic polarization of $^7Li^{2+}$ ~ 9.4%.

6. A MAGNETIZED SINGLE CRYSTAL AS POLARIZER

In 1957 Zavoĭskiĭ[68a] proposed a method of obtaining polarized particles with use of a ferromagnetic foil magnetized to saturation as a source of polarized elec-

trons. However, only very recently has Kaminsky[110] reported the first successful experiments, which utilized channeling[111] of ions through a nickel crystal. A beam of unpolarized ions was passed along the ⟨110⟩ direction of a single-crystal nickel foil magnetized to saturation in the ⟨111⟩ direction in the plane of the foil. After charge exchange in the foil the atoms passed through a region of weak magnetic field in which, as the result of the hyperfine interaction, a portion of the electron polarization was transferred to the nucleus. In a subsequent charge exchange, positive or negative ions with a polarized nucleus are obtained. The experiments showed that nuclear polarization arises only on channeling of ions along one of the principal axes of the crystal. The energy loss in channeling is extremely small, and this permits separation of the polarized and unpolarized components. The experiments were performed with deuterons, a beam with angular collimation 0.02° being passed through a nickel foil of thickness 1.24 or 2.21 μ. The accuracy in alignment of the beam axis with the ⟨110⟩ crystal axis was 0.1°. Saturation of the polarization was observed in a field of 30 G. On leaving the foil the atoms entered a uniform magnetic field of ~10 G in which they moved for $(1-2) \times 10^{-7}$ sec. Ions not having undergone charge exchange were deflected by an electric field. The spectrum of the atoms consisted of two energy components. The energy of one component, which comprised 93% of all atoms, was chosen as 100–130 keV. This component was composed of the channeled particles. The energy of the unchanneled component, which amounted to only a few keV, was below the threshold of the T(d, n)^{4}He reaction. The tensor polarization of the channeled deuterons turned out to be $P_{33} = -0.32 \pm 0.01$. In control experiments with a polycrystalline foil, the polarization was practically zero; $P_{33} = -0.002 \pm 0.01$ for a foil of thickness 1.14 μ and $P_{33} = 0.003 \pm 0.01$ for a foil of thickness 1.87 μ. The crystal lattice was not damaged during 25 hours of operation with an intensity of channeled deuterium atoms of 0.5 $\mu A/cm^2$. To obtain positive (and respectively, negative) ions it is necessary to remove one electron from the deuterium atom (and respectively, to add one to it). If the polarized ion source is intended for a tandem accelerator, polarized negative ions are obtained by passing a beam of fast polarized deuterium atoms through a second charge-exchange foil. Here a polarized ion current of 10–25 nA/cm^2 is expected. Ebel[112] has given an explanation of the high deuterium polarization observed in Kaminsky's experiment[110].

7. INJECTION OF POLARIZED IONS INTO AN ACCELERATOR

a) Cockcroft-Walton and linear accelerators. The simplest arrangement is to inject polarized ions into a Cockcroft-Walton accelerator producing several hundred keV. In this case the polarized ion source is placed at ground potential and the target at a high negative potential. For example, at Basel[113] deuterons have been accelerated to 600 keV, and in Moscow[25] at the Atomic Energy Institute 500-keV polarized protons have been obtained.

At Minnesota[23a] polarized protons were accelerated in a linear accelerator with a maximum energy of 68 MeV and a duty cycle of 1% in November, 1960[23c]. An intensity of 1.2×10^7 particles/sec was obtained at that time for 10 MeV, and 2.5×10^6 particles/sec at 40 MeV with a polarization of 30%. The neutral atomic beam traversed a 2 m path from the atomic source to a platform located at a potential of 500 kV. With the polarized ion source located on the high-voltage platform an average intensity of 4×10^7 particles/sec was observed at 40 MeV[55] (P = 0.55). The polarized ion source required a power of 36 kW which was transmitted to the platform through a two-meter insulated shaft rotated by an electric motor. At the Rutherford Laboratory polarized protons have been accelerated to 50 MeV. In 1969 the average intensity reached 2.3×10^9 particles/sec (the polarization was P = 0.67)[56].

b) Van de Graaff accelerator. Since the polarized ion source requires a high power and occupies considerable space, installation of the source in the high-voltage electrode of a Van de Graaff accelerator presents considerable difficulties. This has been possible so far only for the Washington University accelerator[95,114] which is unique in the sense that there is a large space for location of the polarized ion source. Recently several versions[115] of polarized ion sources have been proposed which require low power and are suitable for installation in a Van de Graaff accelerator.

c) Tandem accelerator. For injection of polarized ions into a tandem accelerator, the polarized ion source is located at ground potential, but negative ions are required for injection. Polarized ions were accelerated in a tandem accelerator for the first time at the University of Wisconsin[15b,116]. Initially the polarization of the accelerated beam was only 1/3 of the polarization of the injected beam. The expected polarization was completely achieved when the usual gas target in the high-voltage electrode was replaced by a carbon foil. For injection of a 1-nA beam of polarized negative ions, only 0.1 nA ion current left the accelerator and in the best case 0.03 nA entered the scattering chamber. The negative ion beam, which was obtained by charge exchange of positive ions in a foil, had a very high emittance. Charge exchange in alkali metal vapor gives a substantially greater yield and less beam scattering. Negative ions obtained in this way have been accelerated in the tandem accelerators at Erlangen[54], Zurich[53b], and Khar'kov[117].

The Lamb method gives a negative ion beam with very low emittance. Recently negative ion sources working on the Lamb method have been installed in the tandem accelerators at Wisconsin[76], Los Alamos[92], Notre Dame[89], and Rutgers[90]. Table IV lists the parameters of the polarized particle beams accelerated in tandem accelerators.

d) Cyclotron. Injection of polarized particles into a cyclotron is an extremely difficult problem as a result of the fact that acceleration of the ions begins at the center of the accelerator. In the first experiments an atomic beam was directed to the center of the accelerator and ionized in the central region. This method is suitable for deuterons, since the unpolarized background in this case is rather small[58,118,119]. To obtain polarized protons a substantial improvement of the

Table IV

Laboratory	Particles and energy	Method of obtaining negative ions	Negative ion current	Current to target	Beam polarization
Los Alamos	p, d; 12 MeV	Lamb method	300 hA H^-, $m_I = 1/2$, 600 hA D^-, $m_I = 1$, 450 hA D^-, $m_I = 0$	107 hA p 208 hA d	Polarized component 86–90% for p and 74–80% for d
Notre Dame	d, 12 MeV	» »	4 hA	$7 \cdot 10^{-2}$ hA	
Rutgers	p, 10 MeV	» »	5 hA	0.8 hA	$P = 0.5$
Wisconsin	p, d; 12 MeV	» »	31 hA H^- 185 hA D^-	p, 3 hA d, 65 hA	P = 0.85 For p $P_3 = 0.57$, $P_{33} = 0$
			70 hA D^-	d, 20 hA	$P_3 = 0$, $P_{33} = -0.75$
Zurich	p, d; 12 MeV	Charge exchange in sodium vapor	10–20 hA	1.5 hA	$P_3 = 0.5$, $P_{33} = \pm 0.75$
Erlangen	p, d; 12 MeV	Charge exchange in potassium vapor	10 hA	p, 1.5 ha; d, 2 hA	$P = 0.74$, $P_{33} = 0.55$
Khar'kov	d, 5 MeV	Charge exchange in mercury vapor	3 hA	0.2 hA	$P_{33} = -0.29$

Table V

Laboratory	Accelerated particles and energy	Method of ionization and injection	Internal beam current, nA	Extracted beam current, nA	Injection efficiency, internal current/ionization current	Polarization
Saclay	d, 22 MeV	Ionization in center, inverse magnetron		$3 \cdot 10^{-2}$		Unpolarized background 25%
	d, 22 MeV	Ionization in center, arc discharge in CO_2		5		Unpolarized background 50%
	d, 22 MeV	Penning ionizer at center		2		
	p, 3–29 MeV	Ditto		$4 \cdot 10^{-2}$		$P = 0.65$
	p, 3–29 MeV	External injection along radius	200	70	$4 \cdot 10^{-2}$ With bunching	$P = 0.85$ – 0.90
Grenoble	p, 60 MeV	Axial injection with deflector	45	30	$(2.2-3) \times 10^{-2}$ With bunching	$P = 0.6$ – 0.7
Lyons, synchrocyclotron	d, 12 MeV	Ionization in center, arc discharge in argon		$8 \cdot 10^{-3}$		Unpolarized background 15%
Birmingham	d, 12 MeV	Axial injection with mirror	20	4	10^{-1} with bunching	
Berkeley	p, 55 MeV	То же	145	60	$7.2 \cdot 10^{-2}$ With bunching	$P = 0.8$
Řež, Czechoslovakia	d, 13, 5 MeV	External injection with charge exchange		$7.5 \cdot 10^{-3}$	$2.5 \cdot 10^{-5}$	$P_{33} = -0.31$

vacuum conditions at the center of the cyclotron is required[21b].

The current in an accelerated beam can be increased if the ionization of the beam takes place outside the cyclotron. Several schemes have been proposed for feeding polarized ions into a cyclotron. The group at Saclay[120] has developed a system of injecting ions into the median plane with compensation of the Lorentz force by a transverse electric field. About 40% of an ion beam with energy 5.4 keV reached the center of the accelerator. A radial injection system has been installed in a variable energy cyclotron. The intensity of the polarized proton beam was increased from 0.1 nA with ionization of the atoms at the center to 40 nA. A radial injection scheme for a sector cyclotron has been developed at the Lebedev Institute in Moscow[121]. The ion beam drifts to the center of the cyclotron along the boundary between the high and low magnetic field. Both vertical and horizontal focusing occurs. In the Czech cyclotron[50a] an injection scheme is used with charge exchange of polarized ions into fast atoms in a gas target and stripping in a foil at the center. This method has been analyzed also in a previous article.[122] The most efficient method suitable for both cyclotrons and synchrotrons reduces to axial injection of ions through an aperture in the pole of the electromagnet[123]. At the center of the cyclotron the ions are deflected by 90° by an electrostatic field and are then captured into the acceleration cycle. The parameters of polarized particle beams accelerated in various cyclotrons are given in Table V.

8. STORAGE OF POLARIZED IONS

The polarized ion sources developed give an average current of polarized ions of at the most 5–15 μA. Without yet discussing the problems associated with preserving the polarization during acceleration to high

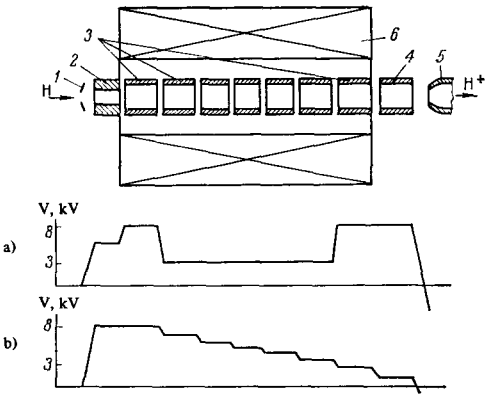

FIG. 19. Ionizer with storage of polarized ions.

energies, we can say that with such injection currents the intensity of polarized particle beam possible turns out to be too low. Estimates[124] made for the Brookhaven 30-BeV synchrotron for an injected current of 5 μA give an expected yield of 6×10^8 polarized protons per pulse. It is expected that substantial increase in the intensity in the polarized beam per pulse will be achieved by storage of polarized ions in the time intervals between the pulses, and injection of them at the moment of capture into the acceleration cycle.

Coiffet[125] has recently proposed an ionizer with storage of ions in a quadrupole electrostatic trap. The calculations presented show that up to 10^9 ions can be stored in the system and that a current of about 10 μA can be obtained by extracting them in 10 μsec. Donets and Plis[126] describe a means of storing polarized ions in an electron beam moving in a strong longitudinal magnetic field inside a subdivided drift tube. A possible arrangement of the ionizer is shown in Fig. 19, where 2 is the anode, 5 is the extracting electrode, and 6 is a solenoid. The electron beam emitted from the ring cathode 1 enters a strong magnetic field, is compressed to a beam of circular cross section, ionizes the atomic beam moving coaxially with it inside the drift tube, and hits the electron collector 4. The ions are accumulated inside the drift tube region 3 which is bounded by two electrodes with potentials higher than the remaining electrodes. In the radial direction the ions are held by the electric field produced by the space charge of the electron beam. The potential distribution along the radius of the tube has a parabolic shape and corresponds to a well potential. The ions execute radial oscillations with an amplitude determined by the place of ionization. If the electron space charge is maintained constant during accumulation of the ions, the depth of the radial potential well will decrease with time, which will lead to an increase in the radial oscillations of the ions and to loss of ions to the electrodes. Therefore it is necessary to increase the density of electrons, for example, by increasing the electron current. This is achieved by increasing the potential of the anode according to a law determined by the rate of ionization of the atomic beam. Figure 19a shows the potential distribution of the electrodes under storage conditions. For definiteness we have assumed that the ions are stored at a potential U = 3 kV and the potential of the end electrodes of the drift tube is 8 kV. For rapid extraction of the ions, a pulsed potential gradient is produced along the drift tube (Fig. 19b). Estimates show that the maximal number of ions which can be stored in an ionizer of length l for these electropotentials is

$$N_i^m = 9.3 \cdot 10^9 l,$$

where l is measured in cm.

The accumulation mode must begin with a current I_e^0 which for a pure electron beam produces a potential drop on the axis relative to the surface of the anode $\Delta U \approx 100$ V. For $\Delta U = 100$ V and U = 3 kV this current is $I_e^0 = 0.36$ A. The accumulation time depends on the density of atoms in the beam and the degree of overlap of the atomic and electron beams. For achievable atomic densities of 3×10^{11} at/cm^3 and a length $l = 20$ cm the accumulation time is $t_a \approx 2 \times 10^{-3}$ sec. In this case about 2×10^{11} ions are stored in the ionizer. By extracting the ions in 40–50 μsec we obtain a pulsed current of 800 μA. In principle it is possible to inject an atomic beam transverse to the electron beam. In the region of intersection with the atomic beam the drift tube is made gridded. If an ionizer of this type is used, it is possible to produce a polarized proton source based on ionization of a beam of hydrogen molecules with polarized nuclei[4b,127]. First molecular ions H_2^+ are formed which are held in the trap so that we obtain protons on secondary ionization. The problem of preserving the polarization of the ions during the storage time is still unclear. Achievement of a successful pulsed ionizer will open up the possibility of accelerating polarized particles in proton synchrotrons.

Lapidus et al.[128] have discussed a scheme for storing polarized ions in an electron ring with subsequent acceleration in a collective accelerator—the smokatron[129]. If an atomic beam with polarized nuclei is directed into an electron ring, then polarized ions will be produced and stored in the ring. Since the pressure in a beam of polarized hydrogen atoms is 10^{-6}–10^{-7} Torr, we can expect that the intensity of a beam of accelerated polarized protons will have the same order of magnitude as the unpolarized beam. The electron ring has a strong intrinsic magnetic field, so that for oscillations of a proton in the potential well of the ring a time-varying magnetic field acts on each proton spin. The requirement of preserving the polarization of the ions imposes a limitation on the total number of electrons in the ring. With the parameters adopted for the ring accelerator at the Joint Institute for Nuclear Research, in order that a polarization $P \gg 90\%$ be preserved, it is necessary that $N_e \leq 3 \times 10^{13}$. The expected intensity of polarized accelerated ions is about 3×10^{11} particles per pulse. For operation of the ring accelerator at 100 pulses per second, the average intensity of polarized protons will be 2×10^{13} sec^{-1}.

9. ACCELERATION OF POLARIZED IONS

In acceleration of polarized ions by constant or high-frequency electric fields, no difficulty arises with preservation of the polarization. Polarized beams of protons and deuterons have been successfully accelerated also in cyclotrons at low energy. In linear accelerators using magnetic quadrupoles for focusing, the

particle spins undergo precession in each magnet, but since the precession angles are small and the polarities of the magnetic alternate, depolarization does not occur[130]. In the case of cyclic accelerators at high energy the particle spins precess in the accelerator guide field, and since the guide-field components can have a frequency which is in resonance with the spin precession frequency, resonance depolarization occurs. Resonance depolarization is analyzed by means of the equation of motion of an individual particle in the electromagnetic field[131]

$$ds/dt = (e/m\gamma)\,[s\,[B + G\,(\Gamma_{\parallel} + \gamma B_{\perp})]] + (e/m)\,[s\,[Ev]]\,[G + (1+\gamma)^{-1}], \quad (8)$$

where $g = \mu_{nuc}/(e/2m)I$ (μ_{nuc} is the magnetic moment of the particle, I is spin, m is the particle mass); this definition of the gyromagnetic ratio differs from that ordinarily used[26], $g = \mu_{nuc}/(e/2m_p)I$, where m_p is the proton mass); $G = (g/2) - 1$ (the values of g and G for a number of nuclei are given in Table VI); $\mathbf{B}_{\parallel}$ and $\mathbf{B}_{\perp}$ are the components of the magnetic field **B** directed parallel and perpendicular to the particle velocity **v**, respectively; **s** is the spin vector; $\gamma = (1 - v^2)^{-1/2}$, $\hbar = c = 1$; **E** is the electric field. The effect of the electric field on the depolarization is usually extraordinarily small and can be neglected.

The ratio of the spin precession frequency to the cyclotron frequency depends on the relative orientation of the magnetic field and the particle velocity. For transverse fields this ratio increases with increasing energy, and therefore at certain energies the spin precession frequency becomes equal to the frequency of the horizontal components of the magnetic field and then resonance depolarization sets in[132].

In the acceleration process a particle moves along a trajectory $\mathbf{r}_\lambda(t)$ whose parameters are characterized by the index λ. From the known spatial distribution of the magnetic field in the accelerator $\mathbf{B}(\mathbf{r})$ we can find for each λ the function $\mathbf{B}_\lambda(t)$. Then, solving Eq. (8), we find $\mathbf{s}_\lambda(t)$. Here the absolute value $|\mathbf{s}_\lambda(t)|$ always remains constant. As the polarization vector of a beam of particles moving in space along different trajectories it is natural to take the quantity[133]

$$\mathbf{P}(t) = \sum_{\lambda} a_\lambda \mathbf{s}_\lambda(t),$$

where $a_\lambda \geq 0$ are weighting coefficients proportional to the number of particles near the trajectory $\mathbf{r}_\lambda(t)$. As the depolarization of a beam of particles having an initial polarization $\mathbf{P}(t_0) = \mathbf{P}_0$ we designate the quantity

$$[\,|\mathbf{P}_0| - |\mathbf{P}(t)|\,]/|\mathbf{P}_0|. \quad (9)$$

Here, if the change in direction of the polarization vector $\mathbf{P}(t)$ during acceleration is such that this direction remains fixed in space independently of the acceleration cycle, this reorientation is not dangerous for the experimenter.

In the first approximation the depolarizing resonances can be separated into two groups[134]: intrinsic resonances and resonances produced by distortions of the magnetic field. Intrinsic resonances are produced by vertical oscillations, and their location is determined by the condition

$$G\gamma = \pm Q_z \pm kN, \quad (10)$$

Table VI

Nucleus	Spin I, in units of ħ	μ_{nuc} in units of nuclear magnetons, $\mu_{nuc} = e\hbar/2m_pc = 5.05 \times 10^{-24}$ erg/G	g	G
^{1}H	1/2	2,793	5.586	1,793
^{2}H	1	0.857	1.714	−0,143
^{3}H	1/2	2,979	17.9	7.95
^{3}He	1/2	−2.128	−12.75	−7,37
^{6}Li	1	0.822	4.93	1.46
^{7}Li	3/2	3,256	15,2	6,6

where N is the number of periodic elements of the accelerator magnetic-field structure, k is a positive integer or zero, and Q is the number of free oscillations per revolution. The existence of deviations of the median surface from a plane leads to the following distortion resonances:

$$G\gamma = \pm l \pm kN, \quad (11)$$

where l is the number of the harmonic function which describes the deviation of the median surface from a plane at a given radius. The most general equation for determination of the particle energy for which resonances occur has the form

$$G\gamma = \pm p \pm qQ_z \pm rQ_r,$$

where p, q, and r are positive integers or zero and the condition

$$G\gamma = \pm rQ_r$$

is not satisfied. Synchrotron oscillations leads to new resonances or simply broaden the existing resonances and, as a rule, are not taken into account.

If the injected particles initially have a vertical polarization, then after passing through a resonance[135] the vertical component has the form

$$s_z = 2\exp(-\pi\omega^2/2\Gamma) - 1, \quad (12)$$

where

$$\Gamma = G\,(d\gamma/d\theta)\,\omega_c^2, \qquad \omega_c = eB_0/m\gamma.$$

For resonances in cyclotrons, produced by distortions of the median plane, the frequency is

$$\omega = (1 + G\gamma_{res})\,(b_{res}/B_0)\,\omega_c,$$

where b_{res} is the resonance component of the magnetic guide field. In the case of an intrinsic resonance, ω depends on the amplitude of the resonance component of vertical oscillations Z_m^{res}. The quantity s_z in the general case is averaged over the amplitudes of vertical oscillations. If the resonance is strong (ω large), the spin vector executes a complete revolution in 180° and $P_z^{fin} = -1$. The sign of the polarization changes to the reverse value. From the experimenter's point of view no loss in polarization occurs. If $\omega^2/\Gamma \ll 1$, it follows from Eq. (12) that

$$s_z \approx 1 - (\pi\omega^2/2\Gamma) = 1 - (|s|^2/2);$$

here the quantity $|s| = \omega(2\pi/\Gamma)^{1/2}$ is equal to the horizontal component of the spin vector. The intermediate case in which $|s| \approx 1$ is the most favorable.

In a cyclic accelerator the injected particle beam ordinarily has a vertical polarization, i.e., the particle spin is perpendicular to the velocity vector. Therefore the appearance in the particles of a horizontal spin

component signifies that the beam has undergone depolarization. It is true that we are assuming here that the fate of different particles is completely different and in this sense the beam is an incoherent mixture. However, if all particles have the same fate, and in particular execute an identical number of revolutions during acceleration and undergo rapid extraction from the accelerator, the depolarization (9) loses its danger for the experimenter. This means that in such an accelerator it is possible to inject a beam with horizontal polarization. A similar situation exists for electron synchrotrons[133,136]. On the other hand, in proton accelerators the synchrotron oscillations, and also the impossibility of accurate repetition of the magnetic-field pattern from cycle to cycle, make it impossible to preserve the polarization for a horizontally polarized beam. Derbenëv and others[137] have discussed the general case of passage through a depolarization resonance for arbitrary initial conditions, and also passage through several resonances. This information is of interest for analysis of the behavior of the polarization in storage rings. The dynamics of the orbits of an individual accelerator determine the relative intensity of the possible resonances. We will discuss the various types of accelerators.

a) The cyclotron. Acceleration of ions in cyclotrons occurs to a low energy and $\gamma \approx 1$. Resonances ordinarily arise from variation of the frequency of vertical or horizontal oscillations. Calculations[138] of the proton depolarization give a very small value. Depolarization of deuterons in the three-sector cyclotron at the University of Birmingham, accelerated to 12 MeV, also have turned out to be extremely small[123b,139]. Budyanskiĭ et al.[140] have estimated the depolarization of protons on extraction from a cyclotron. Here the precession frequency can change from the initial value in the cyclotron at radius r_i to the value given by the magnetic field at the exit from the cyclotron chamber at radius r_f. The precession frequency therefore can pass through resonance values. Nevertheless the probability of depolarization turns out to be small.

b) The synchrocyclotron. The most dangerous resonances are those due to median-plane distortions characterized by indices $l = 2$ and $l = 3$. From Eq. (11) for $k = 0$ the resonance energies are found to be $\gamma_1 = 1.116$ and $\gamma_2 = 1.673$. For the Rochester synchrocyclotron[141] the amplitude of the second harmonic of the deviation of the median surface from a plane is 1.2 cm, and this leads to an appreciable depolarization. Similar results have been obtained for other synchrocyclotrons[16c,142]. For acceleration without depolarization of polarized ions in a synchrocyclotron the magnetic shield should be carefully shimmed.

c) Synchrocyclotron with spatial variation of the magnetic field. The requirements on the permissible values of the harmonics of the deviation of the median surface from a plane are rather severe[16d,e]. For example, for the planned synchrocyclotron at the Laboratory of Nuclear Problems, Joint Institute for Nuclear Research[143], the resonance conditions are described in the form

$$\pm 1.793\gamma = \pm l \pm 4k.$$

For the first resonance ($\gamma_1 = 1.16$, $r = 113$ cm) the harmonic with $l = 2$ is most dangerous, and for the second resonance ($\gamma_2 = 1.673$, $r = 259$ cm) the harmonics with $l = 1$, 2, and 3. In order to hold the depolarization to a level of 10%, these harmonics must be no more than 1 mm[16e].

d) Synchrotron. The intrinsic resonance condition has the form of Eq. (10). Calculations[135] for the Saturn accelerator show strong resonance depolarization. In accelerators with strong focusing the depolarization resonances also turn out to be strong. According to estimates by Zenkevich[144] distortion resonances provide almost complete depolarization both in the 7-BeV accelerator at the Institute of Theoretical and Experimental Physics and at the 76-BeV accelerator at the Institute of High Energy Physics. Ernst[133] has discussed the effect of intrinsic resonances for synchrotrons with strong focusing. It is shown that an intrinsic resonance in the frequency of vertical oscillations will lead to complete depolarization of the proton beam in the CERN synchrotron. Here it is asserted that distortion resonances give a much smaller contribution to the depolarization than is assumed in other papers[134,144]. More accurate calculations are necessary before a final conclusion can be given.

Recently, in connection with the acceleration of deuterons in synchrotrons, Bernard et al.[145] have considered the possibility of accelerating polarized deuterons. Because of the low value $G_d = -0.143$, depolarization of deuterons sets in at higher energies than for protons. For example[16a], in the JINR 10-BeV synchrotron the principal resonance occurs at an energy determined by the condition

$$0.143\gamma = Q_z.$$

For $Q_z = 0.89$, the energy is $\gamma_{res} = 6.2$. This value is higher than the maximum achievable value $\gamma_{max} = 5.93$, which corresponds to a deuteron momentum of 11 BeV/c. Resonances produced by magnetic-field distortions lie at even higher energies. Beurtey[67] has shown that polarized deuterons can be accelerated practically without depolarization both in the CERN proton synchrotron and in Saturn.

Cohen[130b] has proposed a method of removing the effect of intrinsic resonances in synchrotrons by means of pulsed quadrupole magnets placed in the straight sections to change the betatron-oscillation frequency rapidly as a resonance is approached. Marmier[146] suggests a pulsed displacement of the beam by turning on current in additional windings located on the pole faces. For extraction of polarized particles from a synchrotron it is possible to use the method of scattering or resonance extraction if the energy on extraction does not satisfy the depolarization condition[146].

10. ACHIEVEMENTS OF INDIVIDUAL LABORATORIES

a) Berkeley, California. The 88-inch cyclotron at Berkeley has a polarized source of hydrogen and deuterium ions[123a,147]. H_2 or D_2 molecules are dissociated into atoms in an electrodeless high-frequency discharge (f = 20 MHz); the generator power is 1.5 kW. The quartz dissociator has a U shape. The pressure in the discharge is about 2 Torr, and the consumption of gas about 0.2 liter-Torr/sec. The atoms leave a

de Laval nozzle 2.5 mm in diameter; at a distance of 4 mm there is an aperture of the same diameter as the nozzle. The next 4-mm diaphragm is located at the entrance to the six-pole magnet and is at a distance of 7 cm from the first aperture. The pressure in the region of the nozzle is 10^{-2} Torr, and for this pressure the mean free path of the hydrogen atoms is 1 cm. The pressure in the collimation region after the first aperture is $\sim 10^{-4}$ Torr; in order to avoid polymerization of oil, the pumping is carried out by mercury vapor pumps. The six-pole magnet has a length of 50 cm, and the aperture increases from 7 mm at the entrance to 16 mm at the exit. At the exit the polarized atom beam has a diameter less than 1 cm. The magnet region is pumped by an oil diffusion pump to a pressure of 2×10^{-6} Torr.

In order to obtain nuclear polarization the following high-frequency transitions are used:

$p: 1 \to 3$, $B_0 = 5$ G, $f = 7.5$ MHz, $P = 1$;
$d: 1 \to 4$, $= 8$ G, $= 7.5$ MHz, $P_3 = -2/3$, $P_{33} = 0$;
$3 \to 5$, $= 80$ G, $= 331$ MHz, $P_3 = 1/3$, $P_{33} = -1$;
$2 \to 6$, $= 80$ G, $= 485$ MHz, $P_3 = 1/3$, $P_{33} = 1$.

Reversal of the ionizer magnetic field changes the sign of the vector polarization. The atomic beam is analyzed in the same way as at Auckland[52] in a length of 12 cm in a magnetic field of 1500 G. The ion beam is accelerated to an energy of 5–15 keV and is focused by an achromatic ion-optical system at the entrance of the axial injection system. The ionization efficiency is estimated to be 10^{-3}, and the emittance at the crossover is about 5 cm-rad-eV$^{1/2}$. After optimization of the source and axial-injection-system parameters, a polarized proton current of 3 μA was obtained from the source[47]. The best results up to 22 MeV, which were obtained in Berkeley in August of 1969, are listed in Table VII. The polarization was measured by scattering in carbon at 16.7 MeV. Before injection of the polarized protons the polarized beam, which was obtained by (^{4}He, p) scattering, had an intensity of 0.02 nA.

b) Los Alamos[92,148]. A source of negative polarized ions based on the Lamb method was installed in a 12-MeV tandem in 1969[92]. Primary positive ions are extracted from a duoplasmatron by a voltage of 5–10 kV and then slowed down to 500 or 1000 V. A magnetic lens permits transmission of 10-mA currents of p or d. Cesium vapor surrounds a grid from which on ion bombardment electrons are emitted which provide 96% neutralization of the space charge. The cesium chamber has a length of 10 cm and a diameter of 1 cm. Then follow deflecting plates of length 21.5 cm which produce a field of 10–20 V/cm, and a spin filter. After the spin filter is placed an argon chamber of length 32 cm with an entrance diameter of 5 cm and an exit diameter of 6.4 cm. A minimal field is used for ionization in order not to increase the beam emittance[149]. For hydrogen a field of 6 G was used, and for deuterium 6 G ($m_I = 1$) and 60 G ($m_I = 0$). For injection into the tandem, negative ions are accelerated to 100 keV, and the entire apparatus is placed at this voltage.

Table VII

	Ion source		
	Polarized		Duoplasmatron
Injection energy	12 keV	12 keV	10 keV
Ion source current	1.4 mA	2 mA	40 mA
Accelerated current	50 hA	145 hA	3.6 mA
Extracted current	20 hA	60 hA	1.8 mA
Ratio of extracted current to source current	1.5%	3%	4,5%
Polarization	70%	80%	0
Bunching	No	Yes	No

The experimentally determined beam emittance at the source exit is ~ 1 cm-rad-eV$^{1/2}$, which is substantially less than the acceptance of the tandem. The greatest proton current at the target was 107 nA, and the greatest deuteron current 208 nA. The polarized part was 86–90% for protons and 74–80% for deuterons. On decreasing the argon flow by a factor of three the polarization values turned out to be maximal: 93% for protons and 86% for deuterons. The consumption of cesium in the source is less than 0.1 g/hour, and cleaning of the apparatus during disassembly presents no difficulties. The source operates many hours without servicing, and the polarization changes by less than 1% during a run.

11. CONCLUSION

It is evident from the above that the technology of obtaining and accelerating polarized ions is a rapidly developing area of accelerator physics. During the period 1960–1970 new principles for obtaining polarized ions with different masses and charges were formulated. The practical realization of these suggestions and the perfection of the well known methods are being carried out at an ever increasing rate in dozens of physics laboratories throughout the world. As the result of the increase in ionization efficiency the intensity of beams of positive polarized ions of hydrogen and deuterium has reached 5 μA. A technique has been developed for charge exchange of ions through a metastable state of the atoms, for obtaining negative polarized ions of hydrogen and deuterium. The intensities achieved are 0.6 μA of D^- and 0.3 μA of H^-. The use of quantum transitions permits controlled variation of the vector and tensor polarization of the ions over a wide range. Polarized ions have been successfully accelerated in linear accelerators, tandem generators, and cyclotrons. The parameters achieved are close to those needed by physicists for carrying out accurate polarization experiments. For synchrocyclotrons the problems of injection and shaping of the main magnetic field apparently will be solved in the near future. In the case of proton synchrotrons the difficulties are more basic. It is possible that progress in the field of high and superhigh energies will be achieved simultaneously with accomplishment of the acceleration of particles by the collective method. In this case the readjustment of an electron ring accelerator (smokatron) for acceleration of a polarized beam will be fundamentally simple and may not involve great technical difficulties.

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