Substance	Frequency $\nu = 10^{-9}$	$b/C \times 10^{6}$ (Oer.)$^{-2}$	$\tau_s \times 10^{9}$ sec
$Gd_2(SO_4)_3 \cdot 8H_2O$	9.15	3.4	0.25
GdF_3	9.377	6.0	0.16
$GdCl_3 \cdot 6H_2O$	9.377	3.1	0.13
$GdBr_3 \cdot 6H_2O$	9.377	5.2	0.17
$GdI_3 \cdot 6H_2O$	9.377	1.0	0.9

right hand sides by the number of ions per cubic centimeter, we obtain per ion:

$$\chi''(H) = 0{,}6 \cdot 10^{-26} \frac{d(H)}{d_1} \text{ cm}^3;$$

where $H = 0$, $d(0) = d_1$ и $\chi''(0) = 0{,}6 \cdot 10^{-26}$ cm^3. (7)

Values of $\chi''(H)$ in absolute units, calculated from Eq. 7, are plotted along the right side of the ordinate in the figure. Having determined the experimental setup constant a by experiments in parallel fields using the method described above, we may then use this constant for the construction of absorption curves in absolute units for any angle between the high frequency and the stationary fields.

We also performed measurements of paramagnetic absorption at room temperature with perpendicular fields (paramagnetic resonance), using the substances indicated in the table. With stationary fields up to 8000 oersteds, all of these substances exhibited a single resonance absorption peak with a g-factor in the neighborhood of 2. A particularly strong paramagnetic resonance effect was observed in $GdI_3 \cdot 6H_2O$.

In conclusion, the author expresses thanks to I. G. Shaposhnikov for suggesting the subject and maintaining interest in the work.

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A Source of Polarized Nuclei for Accelerators

E. K. ZAVOISKII

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A possible method of obtaining beams of polarized nuclei by making use of the Lamb shift of the metastable level is described.

THE SPIN DEPENDENCE of nuclear forces over a broad range of energies has in the recent past been studied intensively in experiments on the scattering of nucleons by nuclei. It is well known that such experiments require double scattering of the nucleons because contemporary accelerators produce unpolarized beams.

It can be shown by a relatively easy calculation that all types of accelerators (electrostatic accelerators, linear accelerators, cyclotrons, proton synchrotrons and cosmotrons) are able to accelerate polarized particle beams without depolarizing them. An accelerator which can produce polarized particles whose spins form any given angle with the beam direction would enable us to perform many polarization experiments without double scattering.

Certain proposed sources of polarized protons for accelerators[1] make use of atomic hydrogen beams that traverse a strongly inhomogeneous magnetic field after which the polarized atoms are ionized outside of the magnetic field by collisions with electrons. The calculated intensities of such sources do not exceed 1 μa of proton current. Since in the majority of accelerators large particle losses

occur during acceleration (accelerator currents comprise 10^{-3} to 10^{-6} of the ion source current) the resulting currents will be extremely small except in the case of electrostatic accelerators, where particle losses are insignificant. Such sources also require a very high vacuum (10^{-6}-10^{-8} mm Hg) in the ionization region of the atomic beam and are not adapted to pulsed operation.

We shall show that it is possible to construct sources of polarized protons and some other nuclei by making use of the Lamb shift of the $2S_{1/2}$ and $2P_{1/2}$ levels and the metastability of the first of these levels.

It must be mentioned first of all that the Lamb experiment with a beam of atomic hydrogen can produce polarized proton beams if the hydrogen atoms with polarized electron spins in the metastable state are removed adiabatically from the magnetic field and ionized by either light or electrons. This is apparent from the fact that when the polarized atomic beam leaves the magnetic field it consists of 50% pure and 50% mixed states, and after ionization of the metastable atoms outside of the magnetic field a 50% polarized proton beam is obtained. It is thus possible to obtain 100% polarized protons if a rf field is used to keep only the atoms of the pure states in the beam and to ionize these. This method does not require a high vacuum in the region where the metastable atoms are ionized.

Let us consider a more efficient method of polarizing protons. An electron beam passes through a space filled with atomic hydrogen in a homogeneous magnetic field $H = 540$ oersteds subject to the conditions that: 1) the population of the $2S_{1/2}$ levels is considerably greater than that of the P states, and 2) the ionization is due principally to the $2S_{1/2}$ atoms. A resonance field in the gas can result in practically pure $2S_{1/2}$ states thus leading to almost 100% polarization of the protons.

The polarized protons can be extracted from the space by the usual method and directed into the accelerator. It is known that a magnetic field of 540 oersteds mixes one of the $2S_{1/2}$ sublevels with a $2P_{1/2}$ sublevel, as a result of which all the remaining atoms in the metastable state are polarized with respect to their electron spins.

Moreover, at the resonant frequency one of the remaining mixed metastable states makes a transition to the corresponding $2P_{1/2}$ sublevel and then to the $1S_{1/2}$ ground state during the P-state lifetime τ_p. In this way atoms are polarized in a $2S_{1/2}$ state. The polarized $2S_{1/2}$ atoms can be ionized either by light in the range $3700\ \text{Å} \geqslant \lambda \geqslant 1216\ \text{Å}$ or by by electrons in the energy range $13.4\ \text{ev} \geqslant V \geqslant 3.4\ \text{ev}$. We shall denote by n_H the number of hydrogen atoms per cm^3, p the hydrogen pressure, σ_s and σ_p the cross sections for electronic excitation of hydrogen atoms to $2S_{1/2}$ and $2P_{1/2,3/2}$ states respectively, τ_p the $2P_{1/2}$ lifetime, $\tau_s = \xi\tau_p$ the lifetime of the metastable $2S_{1/2}$ state under the given conditions, n_s^* and n_p^* the equilibrium concentrations of hydrogen atoms in $2S_{1/2}$ and $2P_{1/2}$ states, and n_s and n_p the number of atoms per second which enter $2S_{1/2}$ and $2P_{1/2}$ states per unit volume. We thus have

$$n_s^* = {}^1/_4 n_s \xi \tau_p, \quad n_p^* = n_p \eta_l \tau_p, \tag{1}$$

where η is the number of acts of emission and resonance absorption during the transitions of hydrogen atoms from the P to the $1S_{1/2}$ ground state and *vice versa*. η depends on the gas pressure and size and shape of the gas-containing vessel. The factor $1/4$ in the first equation of (1) takes into account the fact that the field H and the resonant rf field remove $3/4$ of all the metastable atoms from that state.

We obtain from (1)

$$n_s^* / n_p^* = 0{,}25 \xi \sigma_s (1 - k)/\eta_l \sigma_p, \tag{2}$$

where k is the fraction of metastable atoms in the pure state eliminated by the rf field. In first approximation we can set $k = 0$. The order of magnitude will be obtained in Eq. (3).

To obtain an estimate of σ_s and σ_p we can use Bethe's calculations in the Born approximation and neglect exchange effects. These calculations give $\sigma_s/\sigma_p \approx 0.1$ and $\sigma_s \approx 10^{-17}$ cm^2 when the energy of the electrons is near the threshold*. The exchange effects can evidently only increase σ_s.

The magnitude of ξ depends essentially on the electric field intensity E in the gas, the velocity of metastable atoms in the magnetic field H, the ion concentration, and the gas density. The dependence of ξ on E is given by the Lamb-Retherford formula.

$$\xi = h^2 (\omega^2 + {}^1/_4 \tau_p^2) V^{-2}, \tag{3}$$

where V is the matrix element of the energy of the perturbing field and $\hbar\omega$ is the splitting of interacting levels. The hyperfine splitting has little effect

* The cross section for $3P$ excitation is one order smaller than σ_s.

on ξ. The dependence of ξ on the velocity v of the atoms in the field H is also given by (3) since the moving atom is acted on by the electric field $\mathbf{E} = \mathbf{v} \times \mathbf{H}/c$.

The dependence of ξ on the ionic concentration is given by (3) if we use for the electric field the familiar expression $E = en_+^{2/3}$, where e is the electron charge and n_+ is the concentration of ions (or electrons) in the gas.

The relation between ξ and the gas pressure p can be represented by

$$\xi = L/\tau_p v, \tag{4}$$

where L is the mean free path of a metastable atom. Eq. (4) is valid only when the linear dimensions of the gas vessel are greater than L.

In (2) η can be estimated in accordance with Holstein's paper[2] from which it follows that η depends on the pressure, the linear dimensions of the hydrogen vessel, and the mean free path of photons at Lyman frequencies. Thus for a cylindrical tube of radius R

$$\eta = (1/1{,}6)\, k_0 R \sqrt{\pi \ln k_0 R}, \tag{5}$$

and for a layer of gas between parallel walls separated by the distance l

$$\eta = (1/1{,}875)\, k_0 l \sqrt{\pi \ln k_0 l}, \tag{6}$$

where $\kappa_0 = an_H/\sqrt{T}$, a is a constant and T is the temperature.

We shall now consider the density W of rf energy required to polarize the metastable hydrogen atoms. The probability $1/\tau_\omega$ of a transition resulting from the absorption of a quantum of frequency ω_0 is, of course,

$$\frac{1}{\tau_\omega} = \frac{2\pi e^2 W}{c\hbar^2} \frac{|(|e, r|)|^2}{(\omega - \omega_0)^2 + (1/2\,\tau_p)^2}, \tag{7}$$

where the required density W must be determined from the condition $\omega = \omega_0$ and

$$\tau_\omega / \xi\tau_p < 1 \tag{8}$$

in order that the hydrogen shall consist mainly of pure metastable atoms.

The value of W determined from (7) and (8) will correspond to the fraction φ of metastable atoms affected by the rf field:

$$\varphi = 1 - \exp(-\xi\tau_p/\tau_\omega). \tag{9}$$

We shall now determine the part played by depolarization of protons as a result of the interaction of the magnetic moments of metastable atoms and protons with hydrogen atoms. In order to estimate the relaxation time t we use the calculations of Gurevich[3], which can give only the order of magnitude for hydrogen:

$$t \approx \hbar^2 a_0 v / 15S(S+1)\mu^4 n_H \tag{10}$$

where a_0 is the atomic radius, μ is the Bohr magneton and S is the atomic spin.

The value of t obtained for the relaxation time of proton magnetic moments must be considerably larger than given by (10) for electron spins, and proton depolarization will be brought about largely by charge transfer to neutral atoms.

A numerical estimate of t according to (10) for electrons shows that depolarization due to magnetic interaction is negligible even at relatively high gas pressures*.

Let us now consider the part played by charge exchange in the depolarization of protons extracted from the gas. We denote by l the linear dimensions of the gas volume from which polarized protons are pumped. Denoting the charge-exchange cross section of the protons by σ_0, they will undergo charge exchange $0.5\, ln_H\sigma_0$ times in their path, so that when $0.5\, ln_H\sigma_0 \ll 1$ the depolarization of a proton beam is given by

$$\Delta = {}^1/_4\, ln_H\, \sigma_0, \tag{11}$$

since after the charge exchange the proton spin can with equal probability be parallel or antiparallel to the field H. A similar estimate can be made of the order of magnitude of proton depolarization in the gas through charge exchange with the hydrogen atoms. Denoting the mean proton lifetime in the volume of gas by t_0 we obtain the number $\bar{n}$ of proton charge exchanges:

$$\bar{n} = \sigma_0 n_H v t_0. \tag{12}$$

The lifetime t_0 evidently depends on the electric field strength in the gas, the spacing of the elec-

* Van Vleck's formula also gives a large value for the relaxation time t.

trodes, and the dimensions of the hydrogen-containing vessel.

Let us consider the ionization of metastable atoms by light of wavelengths 3700 Å $\geqq \lambda \geqq$ 1216 Å. We assume that the gas container is illuminated and the photon flux density is N_{ph} so that the number n^+ of protons formed per second per cm^3, with $n^+ \ll n_s$, will be

$$n^+ = 0{,}25\, n_s^* \int_{\lambda_1}^{\lambda_2} \sigma_{ph}(\lambda) dN_{ph}, \qquad (13)$$

where $\sigma_{ph}(\lambda)$ is the photoionization cross section of a metastable hydrogen atom, $\lambda_1 = 3700$ Å. $\lambda_2 = 1216$ Å. and dN_{ph} is the photon flux density in the wavelength interval $d\lambda$. A similar calculation is made of electronic ionization of metastable atoms for a given electron velocity distribution.

The preceding calculations enable us to choose the optimum conditions for the intensity and polarization of a proton source. Thus, for given geometry, Eqs. (2), (4), and (5) or (6) determine the hydrogen pressure, after which all other parameters of the source are easily obtained. These equations show that the source intensity is limited principally by the diffusion of resonant emission in the hydrogen, which results in a large increase of the P level population.

There are several experimental methods of reducing the effect of resonant Lyman radiation diffusion. For example, the region of the gas where intense excitation of $2S_{1/2}$ and $2P$ levels occurs (in a gas discharge, part of a Wood tube etc.) can be separated from the ionization region of $2S_{1/2}$ atoms by apertured plates which easily pass metastable atoms and greatly reduce the resonant radiation through absorption in the walls of the apertures [Eq. (6)]. The mean free path of the metastable atoms must exceed the thickness of the plate. Atoms in P states cannot pass through the plates because of their very short lifetime. This arrangement produces in the space behind the plate a large concentration of atoms in metastable states with a small admixture of atoms in P states.

The strong diffusion of Lyman radiation can also be employed to polarize protons. Two procedures are possible: 1) An increased concentration of pure $2S_{1/2}$ states as a result of rf-induced or spontaneous transitions from $2P$ states and the ionization of atoms in metastable states, and 2) the use of the low population of $2S_{1/2}$ compared with $2P_{1/2}$ levels, which apparently should occur at relatively large hydrogen pressures when $\eta \gg 1$ and $\xi \ll \eta$. In the latter case P states can be excited by electrons with less than 13.4 ev of energy, but the applied magnetic field must be such that one of the hyperfine sublevels of the $2P_{1/2}$ state will overlap or be close to a $2S_{1/2}$ hyperfine sublevel in order that the population of pure $2P_{1/2}$ states shall greatly exceed that of the mixed states. If under these conditions the hydrogen atoms are ionized only out of P states by Lyman radiation (which is of great density because $(\eta \gg 1)$ or by electrons, the protons will be polarized. The degree of polarization depends on the relative populations of the $2P_{1/2}$ and $2P_{3/2}$ levels and for equal concentrations cannot exceed 9%. The use of radio frequencies which reduce the population of mixed P states through transitions to $2S_{1/2}$ can greatly increase the degree of polarization.

We note in conclusion that protons issuing from the source will move parallel to the axis of quantization (the magnetic field H); but auxiliary magnetic or electric fields can produce any desired angle.

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