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POLARIZED ION SOURCES FOR CYCLOTRONS

Invited Paper

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Abstract

Since their advent six years ago polarized ion sources have been successfully installed in 15 accelerators of various types around the world, including FF, FM, and isochronous cyclotrons. The advantages of sources over nuclear reactions for providing polarized particles are (1) greater intensity, (2) control of polarization mode and direction, and (3) freedom from background radiation from the primary target. Currently operating polarized ion sources can produce several tenth-microamperes of up to 80% polarized protons or 100% polarized deuterons and negative ion currents a thousand times smaller. Basic principles and recent developments in polarized ion source design and technology will be reviewed, with particular reference to the problems peculiar to cyclotrons. Some of the major contributions to polarized ion source development have been made at cyclotrons laboratories, first at CERN and later at Saclay, where the powerful adiabatic passage process for inducing hyperfine transitions has been extensively developed. More recently, the achievement of axial injection at Birmingham and the successful acceleration of polarized particles in the isochronous cyclotrons there and at Saclay indicate that polarized ion spources installed on this latest range of cyclotrons could provide the most powerful tool yet for examining nuclear polarization phenomena in the intermediate energy region.

Introduction

By now the principles of "conventional" polarized ion sources (those based on the Stern-Gerlach separation of the hyperfine states in an atomic beam[1]) are fairly well known and their design has been described in detail in many publications, conference proceedings[2, 3] and reviews.[4] In particular, Thirion[5] and Powell[6] have discussed the acceleration of polarized ions in cyclotrons. This talk, therefore, will not cover the design of conventional sources in great detail, but will be concentrated on

- (i) recent development in conventional sources
- (ii) polarized ion sources based on the selective quenching of metastable hydrogen atoms
- (iii) problems and peculiarities of using polarized ion sources with cyclotrons.

Do their operational advantages justify the expense and complication of building polarized ion sources? Experimental evidence indicates that they do. Sources are now in operation on 15 accelerators around the world including the cyclotrons at Saclay and Birmingham; others are under construction at Milan, Grenoble and Lyon, or are being planned at many other cyclotron laboratories.

While scattering from an internal target is attractive in its simplicity and has been able to provide adequately intense polarized beams for many experiments, polarized ion sources are undoubtedly capable of producing more intense beams still. For instance, at ORIC where beams of 2×10^8 28% polarized protons have been produced with a 10 μA beam on an external target an improvement by at least two orders of magnitude can be expected with a conventional polarized ion source. Sources are in fact at a particular advantage in the intermediate energy region (10 - 100 MeV) as the polarization produced by scattering is low at forward angles where the cross-section is high.

Besides this advantage of

(i) higher intensity

polarized ion sources also give

(ii) control over polarization magnitude and direction; reversing the spin direction between runs enables instrumental asymmetries to be eliminated

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(iii) control over the relative amounts of vector and tensor polarization in the case of deuterons
(iv) freedom from first-scattered radiation which may block or produce undesirable background in the detectors when double scattering is used
(v) energy resolution and beam emittance as good as those of the primary beam from the accelerator.

"Conventional Polarized Ion Sources"

These sources are basically atomic beam systems scaled up to increase the beam intensity; they consist of an atomic beam source, a magnetic and/or radiofrequency state selector and an ionizer, all in a differentially pumped high vacuum system. Such a polarized ion source[5] which injects an atomic beam radially into the 22 MeV synchrocyclotron at Saclay and has been in operation since 1962 is illustrated in Figure 1. Figure 2 shows an alternative scheme in use at Birmingham, utilizing axial injection.

Atomic Beam Sources

The molecules in hydrogen or deuterium gas are broken up into atoms by electron bombardment in an electric discharge, generally an rf electrodeless discharge in a pyrex glass tube, as metals catalyze atomic recombination. The arrangement is similar to that of an rf ion source, except that no extraction voltage is applied at the exit aperture. In general the discharge is capacitatively coupled at the higher pressures (above 0.5 torr) and inductively coupled below. Up to 90% dissociation has been reported in clean tubes using sufficient power. Magic surface treatments, water vapor and moderate cooling all reduce the power required, but cooling the gas leaving the discharge with liquid nitrogen has a bad effect on the degree of dissociation.

Exit apertures take some form which can produce a directed beam, limiting the number of atoms emerging off the beam axis, as these raise the residual gas pressure and reduce the beam intensity by scattering. For molecular flow this is achieved by using long narrow channels, for fluid flow by a shaped nozzle. In practice, these remain ideal cases as the source pressures used are in the intermediate region where the mean free path is of the same order of magnitude as the aperture diameter. Nevertheless, effusion channels (sometimes several thousand 0.1 mm capillaries stacked together[6]) have been found to give the best results where pumping is limited and source pressures are below 0.3 torr, while holes or nozzles[7] have been found best above that pressure.

Generally speaking, the higher the source pressure the higher the forward beam intensity available; however, the maximum useful pressure is probably below 5 torr because the increasing importance of three-body recombination in the body of the gas at higher pressures limits the atomic fraction of the beam. The pressure that can be used depends on the pumping speed available; with cyclotrons the source may be at ground potential so there are not the same power and space limitations on pumping that are associated with Van de Graaffs linacs, etc. Sources utilizing multi-channel nozzles are claimed to yield atomic beam intensities of up to 10^{16} atoms/sec through the separating magnet for a source pressure of 0.2 torr and gas flow of 0.3 cc/sec at STP. The highest corresponding figures for nozzles are $5\text{-}9 \times 10^{16}$ atoms/sec for a source pressure of 2 - 3 torr and gas flow of 6 - 9 cc/sec. An important part of the nozzle design is matching the first collimator (or "skimmer") to the nozzle at such a position that attenuation of the beam by scattering is minimized in the first of the differential pumping regions.[16]

State Selection

The Stern-Gerlach separation of an atomic beam into its separate spin states in an inhomogeneous magnetic field depends on the different forces exerted on their different magnetic moments. In a strong magnetic field the magnetic moment μ_B of an electron in a hydrogen atom is decoupled from the nuclear magnetic moment μ_N; since μ_B is about a thousand times larger than μ_N the splitting of an atomic hydrogen beam in an inhomogeneous magnetic field will depend almost entirely on the electron spin projection.

Atoms with electron spin parallel to the magnetic field (spin "up") have a negative magnetic moment and are deflected towards weaker fields; spin "down" atoms are deflected towards stronger fields. In polarized ion sources, as in masers, the traditional "two-pole" Stern-Gerlach magnet has given way to 4 and 6-pole magnets, for reasons of intensity; the axial symmetry ensures that spin up atoms are always deflected towards the axis (focused) while those with spin down are deflected away (defocused) and lost from the beam. Multipole magnets in use range from 30-80 cm in length and achieve maximum pole-tip fields of 6-10 kOe over apertures of 6-10 mm; separating efficiencies of over 95% are obtained. Shorter magnets, acting as thin lenses, may be used when large object or image distances are required or acceptable; however, there is considerable dispersion because of the Maxwellian velocity spread in an atomic beam. Electromagnets may be used in de luxe systems; they give greater flexibility, and enable an estimate of beam polarization to be made independently of scattering by comparing intensities with the magnet on and off.

For spin half particles the polarization is a vector defined by

$$\underline{P} = \langle \underline{\sigma} \rangle = N_+ - N_-$$

where $\underline{\sigma}$ is the Pauli spin operator and $N_\pm$ are the fractional populations with spin up and down relative to the polarization axis. The beam emerging from the separating magnet is almost completely polarized in electron spin (i.e., exists in a single spin state) but still unpolarized in nuclear spin I (I = 1/2 for the proton, I = 1 for the deuteron). The 2I + 1 nuclear spin substates remain equally populated.

Two methods have been used to produce nuclear polarization:

(i) passing the atoms adiabatically (without change of state) from the strong magnetic field of the separating magnet into a weak magnetic field for ionization. The increasingly strong hyperfine coupling between the electron and nuclear spins in weaker fields shares the electron polarization with the nuclei. For hydrogen atoms (Fig. 3) where states 1 and 2 (equally populated) are selected by the magnet the electron polarization falls from 100% to 50% in to zero field, while the proton polarization rises from zero to 50%; a similar effect is observed for deuterium. In practice the magnetic field is not actually reduced to zero in the ionizing region as depolarization would result from the degeneracy of the states there; a field of a few oersted is maintained there to define the polarization axis. An arrangement with three mutually perpendicular Helmholz coils enables any direction to be chosen.

(ii) by inducing transitions between certain hyperfine states by means of radio-frequency fields. The transitions interchange the populations of the states, and if these are differentially populated, as they are in an atomic beam which has undergone Stern-Gerlach separation, a suitable choice of transitions may enable high nuclear polarizations to be obtained. For instance, in the case of hydrogen atoms the transitions between states 2 and 4 will yield nearly 100% proton polarization if the atoms are subsequently ionized in a strong magnetic field. In low magnetic fields where states 1, 2 and 3 are nearly equi-spaced a transition may also be effectively induced between states 1 and 3 yielding -100% proton polarization. Switching from one transition to another may thus be used to reverse the sign of the vector polarization, a useful technique in eliminating instrumental effects in asymmetry measurements -- especially where a polarized atomic beam is drifted to the center of a cyclotron for ionization and the direction of the magnetic field there cannot be reversed.

Radio-Frequency Transition Methods

Abragam and Winter[8] pointed out that for polarized ion sources it is convenient to induce transitions by the "adiabatic passage" rather than the "exact resonance" method conventional in molecular beam work. Exact resonance transitions take place in a homogeneous magnetic field and are capable of yielding very precise frequency measurement. However, the transition probability depends on the time the atom spends in the rf field, so that for an atomic beam with the normal velocity distribution it is not possible to exceed a transition probability of 76%.

Adiabatic passage transitions, on the other hand, require the "static" field to pass slowly through the resonance value while the atom is in the rf field. In the method's original application by Bloch[9] to nuclear induction experiments in bulk matter, this was achieved by imposing a small audio-frequency oscillation on the static field. With an atomic beam the same effect is achieved by passing the atoms through a magnet with a tapered aperture so that the magnetic field strength varies along the beam path. The advantages over exact resonance are that

(a) the conditions to be satisfied are about 100 times less rigorous
(b) if the conditions are satisfied 100% transition probabilities can be achieved.

All that is required is that both the dc and rf fields seen by the atom change more slowly than the spin precession frequency γH (γ is the gyromagnetic ratio). For the transition inverting the spin of a spin-half particle the conditions turn out to be just

$$\gamma H_1^2 \gg dH/dt$$

$$\gamma(\Delta H)^2 \gg (dH_r/dt)_{max}$$

where the static field H varies by $2\Delta H$ over the length of the rf region and H_1 is the maximum value of the rotating rf field H_r. The same conditions are valid for transitions between any states p and q not involved in other transitions provided we attribute them to fictitious spin-half particles with gyromagnetic ratio γ' in a static field H' and rotating field H_1' related to the real fields H and H_1 by

$$-\gamma' H' = -\omega_{pq}(H)$$

$$-\gamma' H_1' = -V_{pq}(H_1)/\hbar$$

where ω_{pq} is the frequency and V_{pq} the matrix element for the transition. Evaluation of the two conditions indicates the existence of a satisfactory region in H_1-ΔH space, and in general they can be easily satisfied for all but the fastest atoms. The lack of precision required is indicated in Figure 4 showing the wide range of magnetic field over which the Auckland group could measure a high transition probability.[10] A transition of 99.5 ± 0.5% has been measured for one transition at Saclay,[11] and a lower limit of 96 ± 3% has been assigned to the system in the polarized proton source at the Rutherford Laboratory linac.[12]

Polarized Deuteron Beams

Before discussing methods of obtaining different modes of deuteron polarization, it will be worthwhile to try to shed a little light on that mysterious subject itself. The three spin states of a deuteron (spin projection $m_I = +1, 0, -1$) make its polarization rather more complicated than that of the two-state proton. In fact the polarization of a beam of deuterons require a 3 x 3 density matrix for its full description; this may be expressed as a linear combination of 9 independent Hermitean matrices, of which we may conveniently associate one with beam intensity, three with vector polarization, $\langle T_{1k} \rangle$ or $P_i = \langle S_i \rangle$ and five with tensor polarization, $\langle T_{2k} \rangle$ or $P_{ij} = (3/2)\langle S_i S_j + S_j S_i \rangle - 2\delta_{ij}$. The T_{JM} operators transform like the spherical harmonics Y_{JM} under rotations; although these give what is probably the most physically significant description of deuteron polarization there are unfortunately at least three different definitions of their relative and absolute magnitudes in use. Instead we shall use the symmetrized polarization parameters P_i and P_{ij} defined in terms of the spin operators S_i given by Schiff.[13]

In most practical cases the number of non-zero polarization components may be reduced by a suitable choice of axes. In particular, when there is axial symmetry, as there is for the beam from a polarized ion source about the defining magnetic field along say, the z-axis, the only non-zero components beside the unit matrix are:

$$\langle T_{10} \rangle \sim P_z = N_+ - N_-$$

$$\langle T_{20} \rangle \sim P_{zz} = 1 - 3N_0 = -2P_{xx} = -2P_{yy}$$

In this case it is sufficient to know the relative fractional populations of the three states (N_+, N_0, N_-). P_z is generally referred to as the "vector polarization" and P_{zz} as the "tensor polarization" or "alignment" giving the relative populations of the middle and outer states.

The polarization state of such a beam is represented by a point inside the triangle in Figure 5; the lengths of the perpendiculars to the sides indicate the fractional populations of the states. From the equations above we can also see that orthogonal P_z and P_{zz} axes can be superimposed on the triangle. The restriction of polarization values to a triangle here may be generalized in the case of polarization produced in simple nuclear reactions, where $\langle T_{22} \rangle$ may also be the non-zero, to restriction within a cone cutting the polarization ellipsoid (the "Lakin inequality"[14]).

The Saclay group[5, 8, 11] has been chiefly responsible for developing the adiabatic passage transition method, particularly for deuterium atoms. They use a sequence of three transition systems (Fig. 1) in various combinations, giving them the six different modes of polarization indicated by the small triangles in Figure 5. By switching regularly every 2 μsecs between these combinations in phase with the detection equipment they are able to eliminate instrumental asymmetries and isolate the effects of pure vector and pure tensor polarization. With this scheme, using a single separating magnet, it is possible to reach any polarization value inside the dashed hexagon in Figure 5. Referring to the Breit-Rabi diagram for deuterium (Fig. 6) we see that three hyperfine states are selected in the magnet; no matter how many rf transitions are subsequently made, we can never shunt these selected atoms into fewer than three states. As there are only two states available for each nuclear spin state, no more than 2/3 of the atoms can ever be put in the same spin state, hence the restriction to the hexagon.

An alternative scheme which can yield beams in pure deuteron spin states, with the loss of some intensity, has been proposed by Clausnitzer, Hess and von Ehrenstein[15] and is under construction at Argonne. It is similar in principle to the "flop-out" methods of atomic beam magnetic resonance. Instead of one, two multipole separating magnets are used, each being followed by a choice of rf transition. The first transition enables a fourth hyperfine state to be rejected in the second magnet; the remaining atoms can then be shunted into two states with the same nuclear spin projection using the second transition. The polarization can be switched regularly between the three pure spin states represented by the vertices of the triangle, and other modes of polarization can also be used. The one-third reduction in intensity only partially offsets the improvement in polarization since the quality factor of a polarized beam (inversely proportional to the time required to obtain a given accuracy in an asymmetry measurement) is (polarization)^2 x intensity and this is 50% greater than for single magnet systems. Whether this improvement will be obtained in practice remains to be seen -- certainly the gap between the magnets must be kept as short as possible to minimize any mismatch between them.

Ionizers

Ionization of the atoms is accomplished by electron bombardment. In general the designers of the first generation of polarized sources were content to avoid the complications of rf transition systems and obtain a modest polarization by ionizing in a nearly-zero magnetic field. With the success of these sources, however, and the users continual demands for higher polarization, rf transition systems are becoming a common feature, and have required the development of ionizers which will operate efficiently in a strong magnetic field.

At Saclay, where the polarized atomic beam is drifted to the center of the cyclotron, a Penning ionizer has always been used. An arc ionizer was found to give greater currents but complete depolarization.

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In other sources the magnetic field has generally been provided by a solenoid surrounding the ionizer. Two ionizers of this type which have been successfully used by Glavish et al[3] at Auckland and by Banford et al[3, 12] at the Rutherford Laboratory are illustrated in Figures 7 and 8; various operating parameters are listed in Table 1.

TABLE I

Strong Magnetic Field Ionizers

Laboratory	Auckland	Rutherford	Birmingham
Mag. Field(Oe)	1400	2000	180
Anode voltage(V)	100-250	5000	585
Emission(mA)	25-40	0.1	25
Stored current(mA)	50-80	4000	50
Potential dep$^{\underline{n}}$(V)	20-50	4000	
Ion energy(eV)	5000	1000	11500
Energy spread(eV)	20-50	400	
Ion current(μA)	0.5	0.54	0.017
Ionizing eff$^{\underline{y}}$(%)	0.041	0.028	0.06
Beam emittance*	2*(85%)	1.1*(100%)	6(100%)

*The emittance units are cm. rad(eV)$^{1/2}$. The starred figures may refer to one quarter rather than the total phase space area.

In both cases a grid pulls off a small current of electrons from a tantalum filament into the ionizing region, a cylinder 1.5-2.5 cm in diameter and 20 cm long. There they spiral tightly round the magnetic field lines, being reflected back and forth between the ion extraction and filament-grid fields, until space-charge limitation prevents the current building up any further. It is important that the solenoidal field should be homogeneous and that the filament be immersed in it; increasing the magnetic field improves the ionization efficiency in both ionizers. The space charge potential depression confines the ions to the region of the axis where they are removed by field penetration from the extracting electrode and focused by an ion optical system integral with the ionizer.

What is remarkable about these two ionizers (or perhaps fortuitous) is that in spite of their very different anode voltages and contained electron currents, their ionization efficiencies and beam emittances (though not ion energy spreads) are so similar. The Auckland philosophy has been to use a hollow electron beam rather than filling the whole ionizing cylinder; this should permit a higher space charge, and therefore ionizing efficiency, for a given anode voltage, and should give a flat potential depression inside the electron beam, reducing the divergence of the extracted ions. The ability of the Rutherford Laboratory ionizer to contain about 80 times as many electrons is presumably a consequence of the higher voltage and the three-halves power law.

Although the efficiency of these ionizers, a few times 10^{-4}, sounds rather poor, it must be remembered that hydrogen has one of the lowest atomic ionization cross sections. The ion current from the RHEL ionizer is 2.4 times as great as the best obtained from any weak magnetic field ionizer working in the same apparatus. At the same time the use of rf transitions increased the proton polarization by a factor of 1.9 to 66% so that the P^2I quality factor for the source has been improved by a factor of 8.6 overall.[12]

The Birmingham ionizer described by Powell[3] is a little different from the other two. It operates in the 180 Oe stray field of the cyclotron; this is just strong enough to decouple the nuclear and electron spins in deuterium atoms though it would not do for hydrogen atoms. The idea behind the design is to minimize the ion beam emittance by neutralizing the electron space charge and ionizing the atoms in a virtually field-free region -- that defined by the tank and the grids of the anode and pre-extractor (Fig. 9). Atkinson's measurements[17] show that the space charge should be neutralized in such a system at a presure of 3 x 10^{-6} torr. A drift field of about 2V/cm is maintained between the anode and pre-extractor grid to remove the ions, which are then accelerated to 11.5 keV in a nearly parallel field into the six einzel lenses of the axial injection system (Fig. 2).

If the ions that have been produced are not to be wasted the emittance of the ion beam must match the admittance of the accelerator. The emittances of all three ionizers described here are adequate in this respect. The Auckland ionizer is matched correctly for a van de Graaff; the Rutherford Laboratory beam is 50% acceptable to the 500 kV HT injector to the linac, and the

Birmingham emittance is much smaller than the 16 cm. rad $(eV)^{1/2}$ admittance of the axial injection system and the 17 cm. rad $(eV)^{1/2}$ transmittable phase space of the cyclotron.

Negative Ions From Conventional Sources

H^- or D^- ion beams can be produced from conventional polarized positive ion sources by charge exchange processes. Haeberli et al[18] obtain conversion efficiencies of up to 1% for electron pickup by polarized protons or deuterons in a carbon foil at 50 keV. This yields currents of up to 10^{-3} μA H^- or D^- ions for acceleration in a tandem (the transmitted current is never smaller than this because of the small admittance of the accelerator). Within statistics the measured polarization is the same as for the positive ions. (As in the case of ionization, electron pickup occurs so quickly that there is negligible depolarization). An incidental result of Drake's and Donnally's recent work[19] on charge exchange in caesium and potassium vapor cells (described more fully below) indicates that much higher conversion efficiencies may be achieved. At 700-1000 eV 15-25% of a deuteron beam was converted to D^- in 10 micron-cm of caesium, with a negligible change in beam emittance.

Conventional Sources - The Present Situation

The present capabilities of conventional polarized ion sources are perhaps best summarized by quoting specifications which potential manufacturers are offering:

ion current (guaranteed)		1.0μA
polarization: deuterons	(P_z)	±90%
"	(P_{zz})	±60%
protons	(P_z)	±80%
total beam emittance 8 cm. rad $(eV)^{1/2}$.		

Figure 10 shows the intensities of the polarized beams from various accelerators which use polarized ion sources; also shown are some of the most intense polarized beams produced by scattering. It may be noted that the intensities reflect the capabilities of the accelerator far more than those of the source! The quality of most sources approaches the specification given above.

Polarized Ion Sources Based on Selective Quenching of Metastable Hydrogen Atoms

The fine and hyperfine structure of the first excited state of the hydrogen atom is shown in Figure 11. Atoms excited to the $2P_{1/2}$ state decay to $1S_{1/2}$ ground state with an effective lifetime of $\tau_p = 1.6 \times 10^{-9}$ secs by emission of a 1216Å Lyman-alpha photon; atoms in the $2S_{1/2}$ state, on the other hand, higher in energy by 1058 Mc/s (the Lamb shift) are metastable in the absence of an electric field, being only able to decay by double quantum emission, for which the lifetime is 1/7 sec. In the presence of an electric field, however, the Stark effect mixes the 2S and $2P_{1/2}$ states, so that atoms originally in the pure 2S state lose their metastability. The 2S lifetime becomes[21]

$$\tau_s = \tau_p \hbar^2 (\omega^2 + 1/4\, \tau_p^2)/V^2$$
$$= 0.32 \times 10^{-9} (\nu^2 + 50^2)/E^2 \text{ sec}$$

where $\hbar\omega = 10^6 h\nu$ (Mc/s) is the separation of the interacting 2S and $2P_{1/2}$ states and V is the matrix element of the perturbing electric field (E volts/cm). The two 2S hyperfine "β" states with electron spin down therefore have a minimum lifetime in a magnetic field of about 575 Oe where they overlap the two $2P_{1/2}$ "e" states. In the same field $\nu_{\alpha f} = 2150$ Mc/s so that the lifetime of the two 2S "α" states with electron spin up is $(1+4\,\omega_{\alpha f}^2 \tau_p^2)$ or 1850 times longer. If now a beam of metastable atoms is passed through a 575 Oe field in a time intermediate between the α and β state lifetimes, all the β atoms will be quenched to the ground state leaving the remaining metastable atoms with 100% electron polarization. This could be converted to nuclear polarization in the same ways as for the Stern-Gerlach method, either by bringing the atoms adiabatically back into a low magnetic field or by inducing rf transitions. That the βe crossing could be the means of producing a polarized atomic beam was first pointed out by Lamb and Retherford themselves.[20] The method is, of course, applicable to deuterium as well as to hydrogen.

The first attempt to produce a beam of polarized ions by this method was made by Madansky and Owen.[22] Although they were able to observe electric quenching, they were

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unsuccessful in their main aim because they were unable to produce

(i) an intense enough beam of metastable atoms
(ii) a method of selectively ionizing the metastables in preference to the ground state atoms in the beam.

Donnally and his co-workers[23] have succeeded in finding solutions to both of these problems. By means of the resonant charge exchange process

$$p + Cs \rightarrow H(2S) + Cs^{+}$$

(the ionization energies of Cs and H(2s) are nearly the same so that the Q-value for the reaction is nearly zero) they were able to obtain a 15% conversion efficiency to H(2S) with negligible pickup to the ground state. Then a second charge exchange process of the pseudo-crossing type with argon

$$H(2S) + A \rightarrow H^{-} + A^{+}$$

was found to convert 4% of the metastables to H^- ions -- a 0.6% overall conversion efficiency from protons to H^- ions. This maximum efficiency occurs for a particle velocity of 3.1×10^7 cm/sec; i.e., for 500 eV protons or 1000 eV deuterons. The angular divergence of the H^- beam was $\pm 0.25^{\circ}$; in general the H^- beam emittance should be little worse than that of the primary proton beam. Drake and Krotkov[19] have just recently obtained 2% overall conversion efficiencies and have found that the D^- ions produced are indeed polarized. The beam obtained in their test apparatus had an intensity of 4×10^{-3} μA and a tensor polarization $P_{zz} = -0.19 \pm .01$. Although this intensity is low it is already larger than the H^- beams at present obtained from conventional polarized sources.

That the polarization they observe is only 60% of the theoretical value is due to two effects:

(i) the ion beam is 15% diluted by unpolarized D^- ions produced from ground state atoms
(ii) it is very difficult to pass fast (1 keV) atoms adiabatically from the 575 Oe field into a very weak field for electron pickup in the argon cell. Without a roughly exponentially decreasing field in this region depolarization is almost complete.

The second problem at least should be solved in the full-scale polarized ion source being built by McKibben and Lawrence[24] (Fig. 12) since the 575 Oe field extends over the argon cell; because provision is made for inducing rf transitions electron pickup has to take place in a strong magnetic field anyway. It is hoped that the magnetic field will also serve to inhibit the competing reactions in the caesium and argon cells, and hence allow the vapor thickness and conversion efficiency to be further increased.

As in Donnally's and Drake's apparatus the magnetic field is longitudinal to avoid quenching the metastable atoms in their motional electric field.

$$\underline{E} = \underline{v} \times \underline{H}/c \simeq 180 \sin(v, H) \text{ (V/cm)}$$

for H = 575 Oe and $v = 3.1 \times 10^7$ cm/sec. Using the lifetime formula given above the decay lengths for the two states are

$$\lambda_{\alpha} = (220/E)^2 \text{ cm} \qquad \lambda_{\beta} = (5/E)^2 \text{ cm.}$$

Clearly the divergence of the beam may cause some β quenching even in a longitudinal magnetic field; α atoms on the other hand are long lived unless the field is transverse. Quenching by positive ion space charge in the region of the caesium cell also becomes a problem when more intense beams are considered and McKibben intends to provide space charge neutralization there.

The most serious problem is in obtaining intense beams of positive ions at 500 or 1000 eV with good emittance. To equal the performance of conventioanl polarized ion sources and produce 1μA of negative ions 100μA of positive ions might be required within 10 cm. rad $(eV)^{1/2}$ (the rf transition quenches half the metastables reducing the maximum conversion efficiency to 1%). This appears quite reasonable, but to obtain 10 or 100 times more current than this will probably require efficient space charge neutralization in the ion source and an improvement in the charge exchange yields in the magnetic field.

No process has been found yet which will produce positive ions from metastable atoms as readily as negative ions. However, this may actually be an advantage for cyclotrons, for as the UCLA and Manitoba cyclotron groups have recently demonstrated[25] the use of H^- ions enables variable energy beams to be obtained with 100% extraction efficiency.

Problems Peculiar to Cyclotrons

I. Injection

As the transmitter of a polarized ion beam a cyclotron has one great advantage over other accelerators -- the source may be at ground potential; consequently the size of the source and the power used by it need not be limited.

Before methods of injecting ion beams into a cyclotron had been worked out, the only way of using a polarized ion source with a cyclotron was to drift the polarized atomic beam to the center in the median plane. Although it is difficult to get much atomic beam into the ionizer by this method it has been successfully used at Saclay[5] for a number of years.

The various methods of ion injection are going to be described by Powell[26] and others later in this session. I shall only remark here that where the cyclotron magnet has an axial hole, axial injection appears to be the most favorable method for injecting polarized ions; the Birmingham group[2, 26] report an overall transmission efficiency of 2%. The injected ions have to be longitudinally polarized along the axis; with a strong field ionizer the natural arrangement is therefore for atomic beam axis and magnet axis to be coincident.

II. Depolarization

The most serious problem occurs during acceleration, as there is the danger of resonant depolarization if the magnetic field seen by the particle has components oscillating at the precession frequency of the spin, ω_p. Perturbing oscillations will be driven by (i) periodic variations in the field (intrinsic resonances) (ii) random field inhomogeneities (imperfection resonances). The possible harmonics are linear combinations of the cyclotron frequency ω_c and the axial and radial betatron frequencies, $\nu_z\omega_c$ and $\nu_x\omega_c$, so that the general resonance condition is

$$\omega_p/\omega_c = \gamma(g/2-1) = k + \ell\nu_z + m\nu_x$$

where k, ℓ and m may take any integral values, $(g/2-1) = 1.79$ for protons and -0.143 for deuterons, and γ is the total energy of the particle in units of its rest mass. Since $\gamma \simeq \nu_x$ each resonance is represented approximately by a straight line on a ν_z-ν_x plot; if we also draw in the ν_z-ν_x curves for the cyclotron at different energies we may locate the energies and radii at which depolarizing resonances occur in the same way as for coupled resonances.

Several resonances may be met in the course of acceleration; whether they produce serious depolarization or not will depend on the time spent in resonance and the strength of their driving terms. The first factor is indicated by the parallelism or closeness of the resonance line and the ν_z-ν_x curve; the second by the integers k, ℓ and m. The sum ℓ+m, called the order of the resonance, indicates the order of the driving term $x^m z^\ell (\partial/\partial x)^m (\partial/\partial z)^\ell H$ in the Taylor expansion of the field H. The strongest terms are the lowest order intrinsic resonances with k a multiple of the periodicity of the magnet.

Studies of resonant depolarization in isochronous cyclotrons have been made by several authors[27-30] and reviewed by Powell.[3] The important resonances seem to be few in number and the same for all the cyclotrons -- presumably because they were all three-sector machines and their betatron frequencies lay in the same range. For protons there were the intrinsic resonance $(k, \ell, m) = (3, -1, -1)$ and the imperfection resonances (1, -1, 1) (2, -1, 0) and (0, -1, 2); for deuterons only the imperfection resonances (0, -1, 0) and (-1, +1, -1). In general the estimated depolarization is <0.1%, though for deuterons which pass through the (0, 0, -1) resonance six time to reach 65 MeV in the Berkeley 88" cyclotron the tensor and vector depolarizations are 1.0% and 0.34% respectively.[29] The intrinsic proton resonance (3, -1, -1) which would be expected to be the most serious has not been estimated to give any significant depolarization for

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any of the cases so far studied. It appears likely that, even if a serious resonance were found for the normal field configuration, this and hence ν_x and ν_z could be altered sufficiently to obtain rapid passage through the resonance and avoid the depolarization.

Experimentally, polarized deuterons have been accelerated to 12 MeV at Birmingham[3] and polarized protons to 29 MeV at Saclay[3] without any measurable depolarization. In fact, at Birmingham the magnetic field was distorted to values which should have increased the depolarization by a factor 100 without any being observed.

III. Polarization Control

One of the more inflexible features of a cyclotron is its magnetic field direction. The quantization axis of the extracted ion beam must be in one of two directions -- for a horizontal median plane cyclotron, up or down. Control over the polarization from the source is limited to reversal of vector polarization or interchange between different modes of tensor polarization. A vertical quantization axis is fortunately the most experimentally convenient; beams may be bent in bending magnets without change of polarization and asymmetries measured over horizontal scattering tables. If, however, longitudinal polarization is required, as for a measurement of spin rotation parameters, the beam must be bent through a certain angle θ_c with the polarization axis transverse to the magnetic field. This necessitates either bending the beam through a large angle in the vertical plane or else rotating the quantization axis by 90° to the horizontal in a solenoid and then bending it through the correct angle in the horizontal plane. The correct bending angles θ_c to produce longitudinal from transverse polarization are any odd multiples of

$$\theta_c = \pi/(g-2)\gamma = 50.3^\circ/\gamma \text{ for protons}$$

$$= 629^\circ/\gamma \text{ for deuterons}$$

In the case of deuterons the principle axes of the polarization ellipsoid precess by the same angle in a plane perpendicular to the field; if a large bending angle is used significant amounts of the previously zero-valued elements of tensor polarization will appear.[14]

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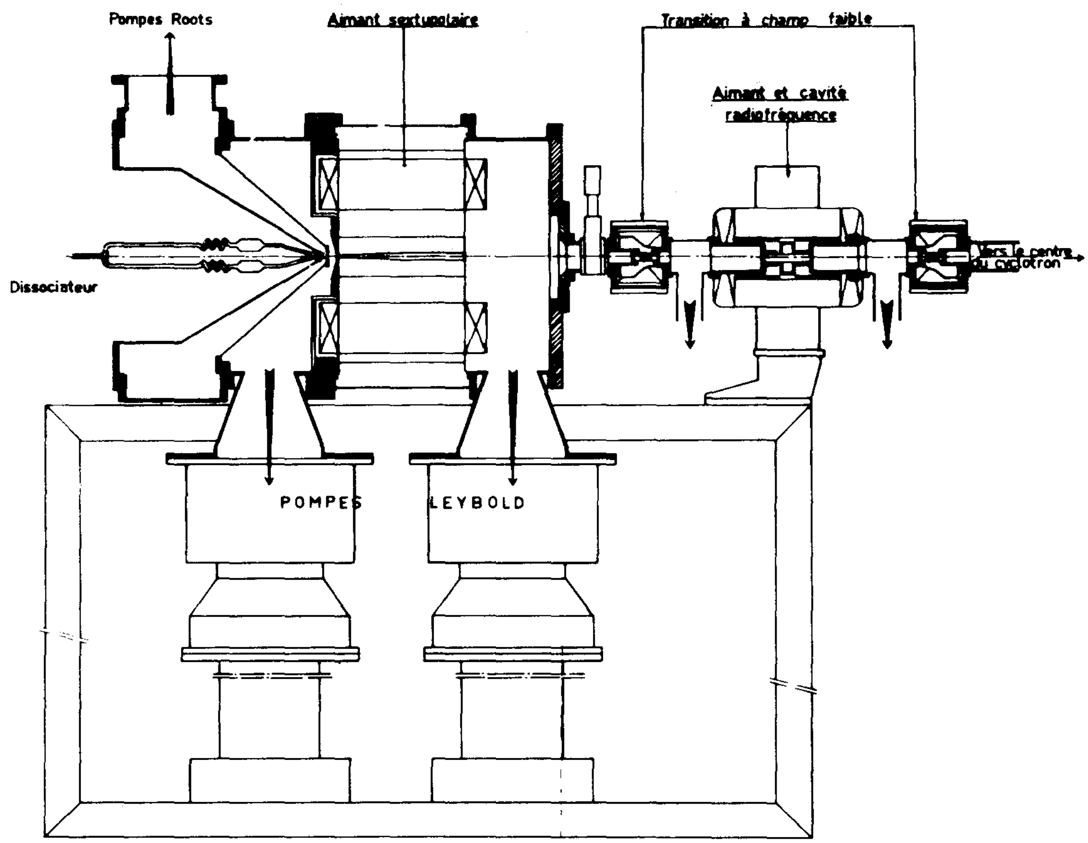

Fig. 1. The Saclay polarized deuteron source.

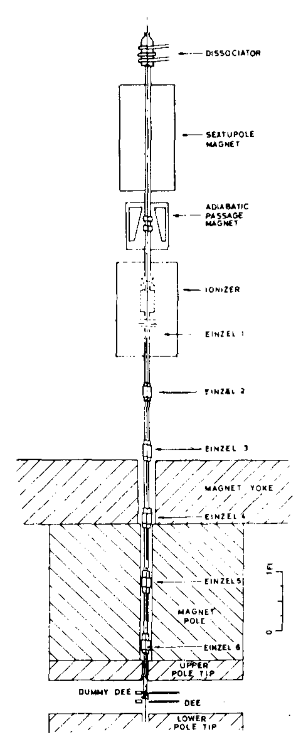

Fig. 2. The Birmingham polarized deuteron source and axial injection system.

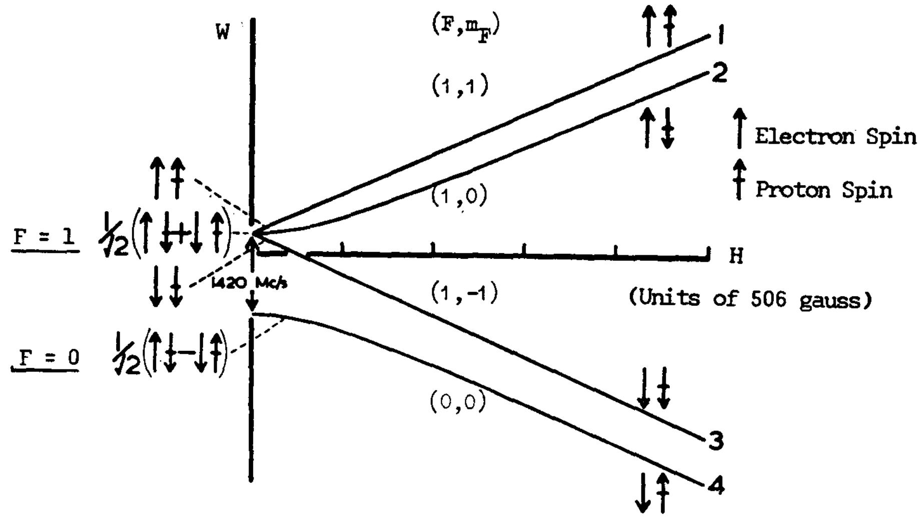

Fig. 3. Energies of the hyperfine states of the atomic hydrogen ground state in a magnetic field.

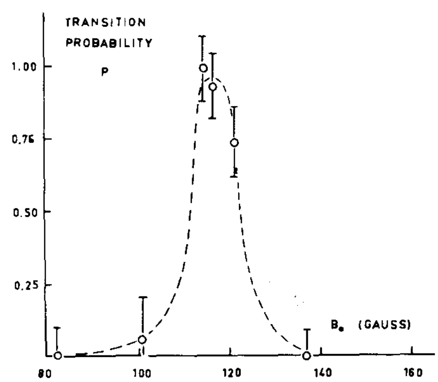

Fig. 4. Measured transition probabilities for the Auckland rf transition unit as a function of the magnetic field.

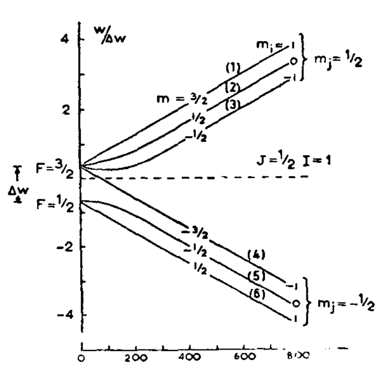

Fig. 6. Energies of the hyperfine states of ground state deuterium atoms in a magnetic field.

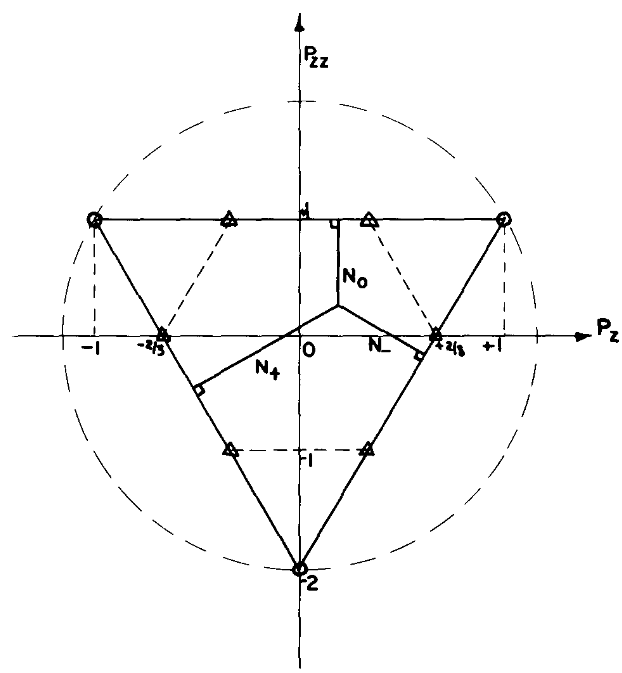

Fig. 5. Axially symmetric deuteron polarization -- its relation to the fractional state populations.
-Δ- polarization obtainable with one separating magnet
o polarization obtainable with two separating magnets

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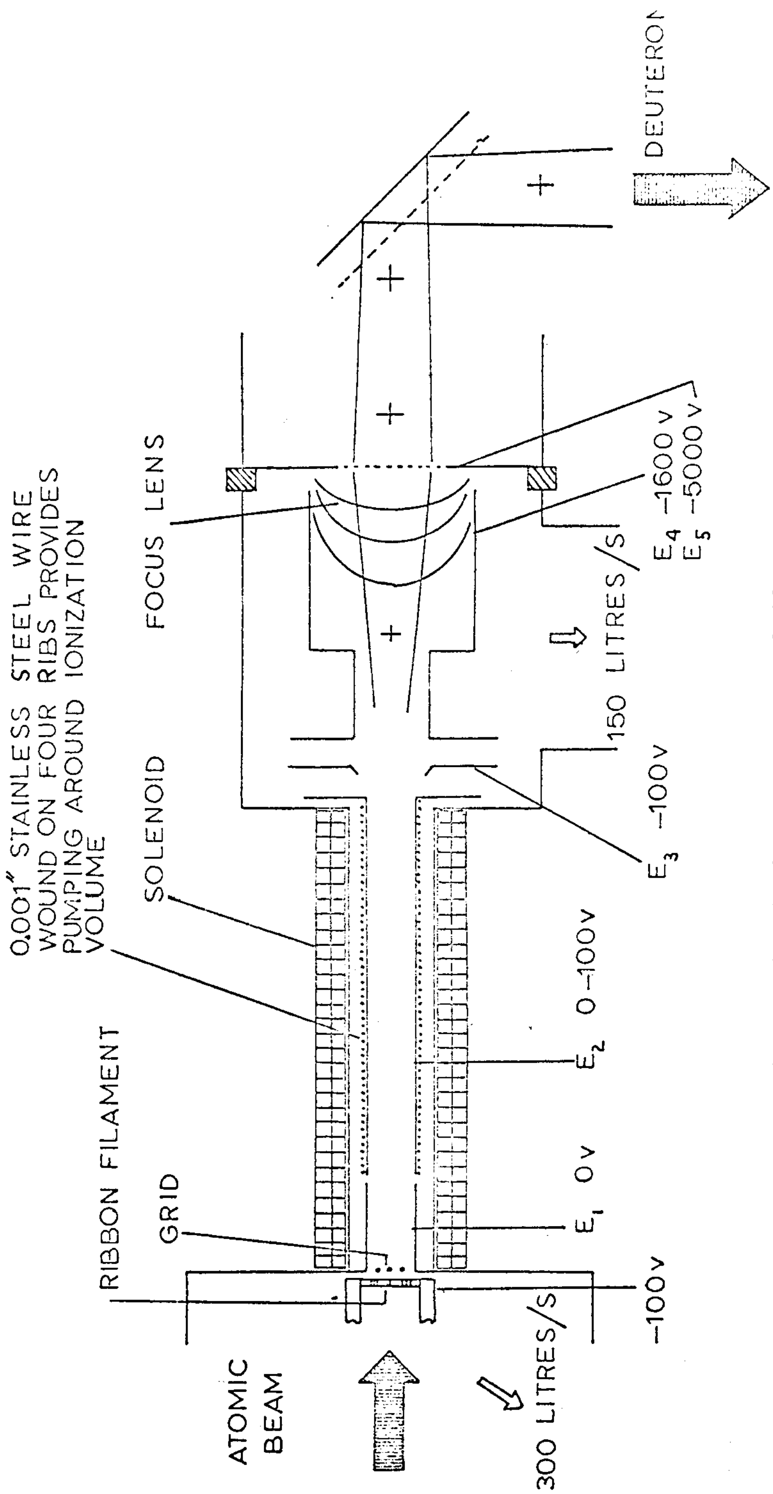

Fig. 7. Auckland strong magnetic field ionizer

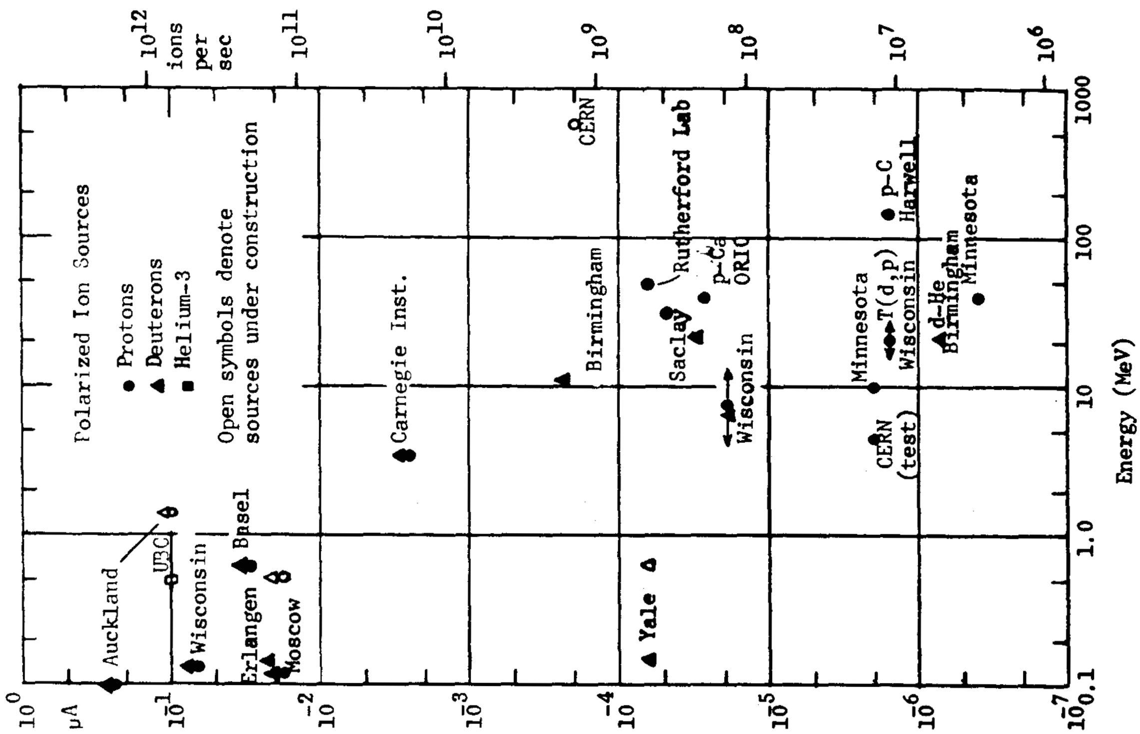

Fig. 10. Polarized beam intensities versus accelerator energy.

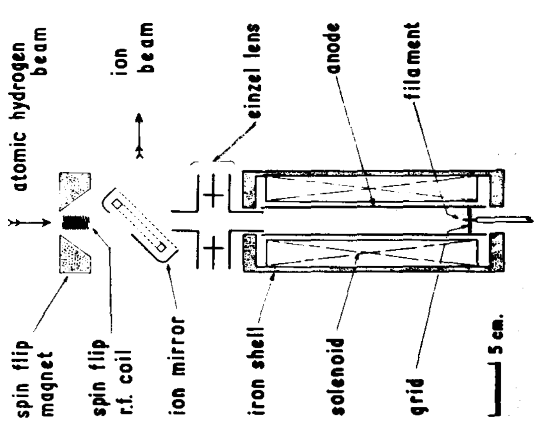

Fig. 8. Rutherford Laboratory strong magnetic field ionizer.

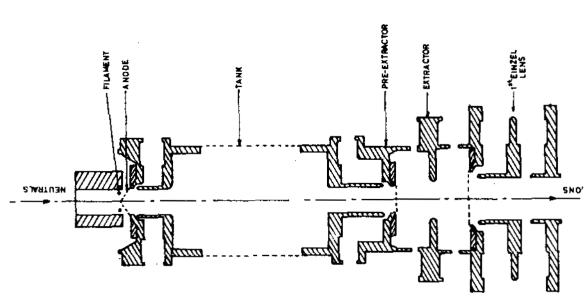

Fig. 9. Birmingham strong magnetic field ionizer.

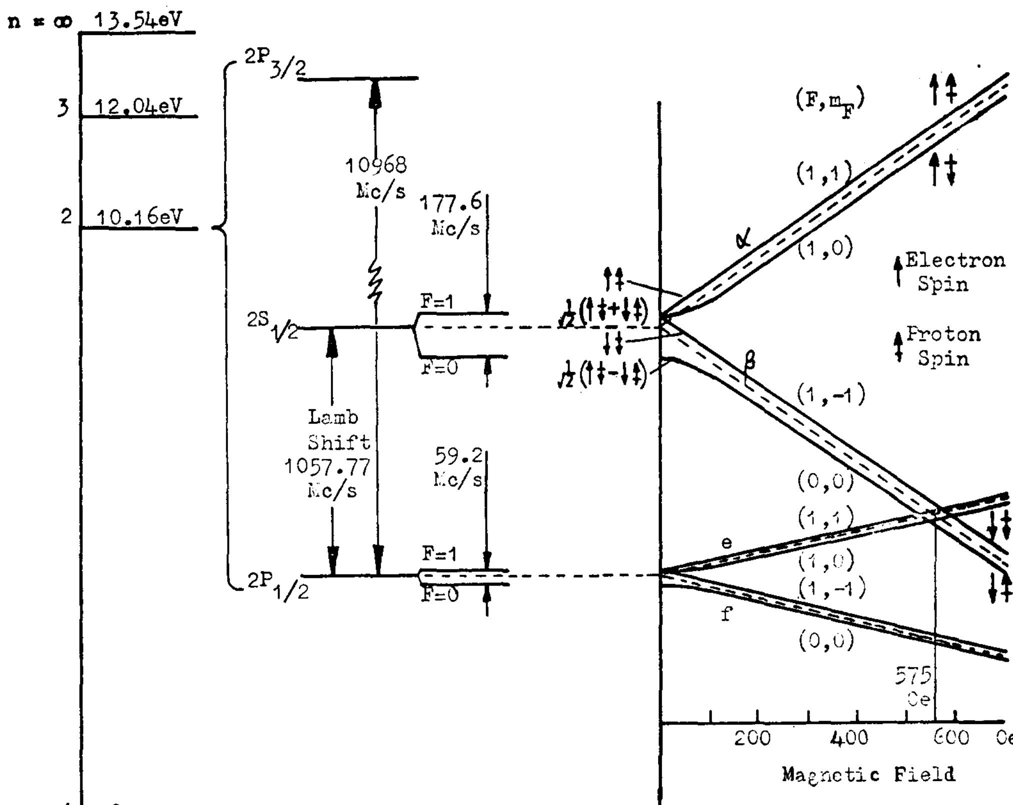

Fig. 11. Energy levels of the hydrogen atom and hyperfine structure of the 2S and $2P_{1/2}$ states. F and m_F are the total angular momentum and its projection.

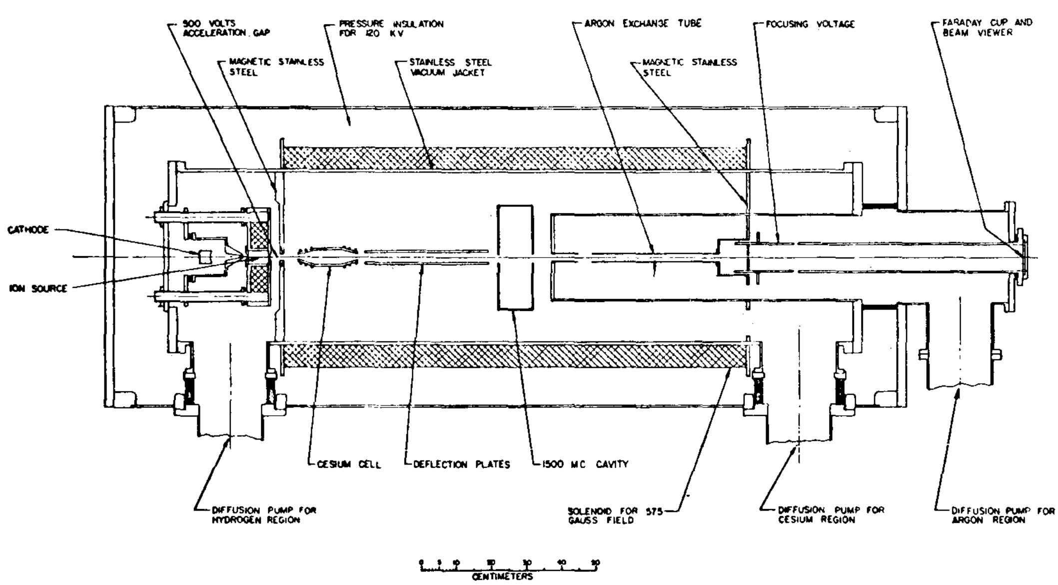

Fig. 12. Polarized ion source based on metastable atom quenching under construction at Los Alamos.