Rutherford Laboratory

Technical Leaflet

D9

POLARIZED PROTON SOURCE

Introduction

Protons possess a property called spin which can, for many purposes, be thought of as being similar to the spinning of a top. When the axis of spin is taken as the vertical direction, protons spinning clockwise are said to have spin up and those spinning anticlockwise spin down. An unpolarized beam of protons is one which possesses equal numbers of protons with the two directions of spin, whatever direction in space the spin is examined. A vertically polarized beam of protons possesses unequal numbers of protons with spin up and spin down, when examined in the vertical direction; it would, however, appear unpolarized if examined in a horizontal direction. A beam can be polarized in any direction desired, and the polarization in the vertical, transverse and longitudinal directions derived.

Nuclear forces, that is the short range interactions between elementary particles and nuclei, are, in general, spin dependent. Hence the spin dependence of the proton nuclear forces can not be measured by the scattering of unpolarized proton beams, but they can be by using polarized proton beams. The purpose of the polarized proton source (PPS) is to provide a beam of polarized protons which can be accelerated in the linear accelerator and used in nuclear physics experiments.

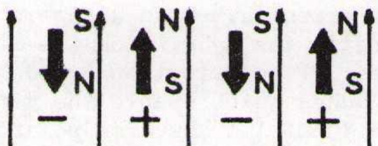
Simplified Theory

The operation of the PPS can be understood by reference to figure 1.

In the DISSOCIATOR hydrogen molecules are split into hydrogen atoms by electron bombardment in a radio frequency discharge. ($H_2 + e^- \longrightarrow H + H + e^-$).

The atoms behave like small bar magnets

In a strong magnetic field they are aligned with either positive or negative magnetic moment.

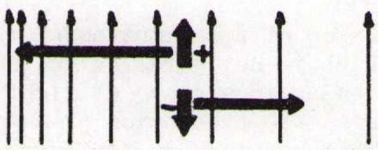


Magnetic Field

In a strong non-uniform magnetic field:

Positive magnetic moment atoms move into a stronger field.

Negative magnetic moment atoms move into a weaker field



Non-uniform Magnetic Field

Such a field exists in a sextupole magnet:

Zero field on the axis, maximum field at the radius of the pole tips.

The atoms are formed into a beam by the COLLIMATOR of the dissociator and pass into the magnet.

Positive magnet moment atoms are deflected away from the axis and are pumped away from the system.

Negative magnetic moment atoms are deflected toward the axis, oscillate about it and traverse the whole length of the magnet.

The atoms consist of a proton and an electron, both spinning. The negative magnetic moment atoms can exist in various spin states:-

In a STRONG magnetic field:-	Proton spin	Electron spin
50% of atoms	UP	UP
50% of atoms	DOWN	UP

Hence there is no polarization of the protons

In a WEAK magnetic field:	Proton spin	Electron spin
50% of atoms	UP	UP
25% of atoms	DOWN	UP
25% of atoms	UP	DOWN

Hence 75% of the protons have spin UP and 25% have spin DOWN (3 UP to 1 DOWN).

Thus the protons in the beam of negative magnetic moment atoms which emerge from the sextupole magnet will be polarized in a weak magnetic field.

These atoms now enter a uniform weak magnetic field in the IONIZER, where they are bombarded by electrons; and the atomic electrons are stripped off producing free protons. These protons are extracted by an electric field and form the polarized proton beam.

DIRECTION OF POLARIZATION

The direction of polarization is the direction in which the majority of the proton spins are oriented. This direction is defined initially by the direction of the weak magnetic field in which the atoms are ionized. The HELMHOLTZ COIL is used to give either UP polarization or DOWN polarization. Two more pairs of coils have now been added which enable the direction of polarization to be chosen at will. Thus a horizontal transverse polarization or a longitudinal polarization can also be produced. By using two or three pairs of coils simultaneously any desired direction of polarization can be obtained.

The direction of polarization of the proton beam can be ROTATED in a magnetic field (which is not parallel to the polarization direction); the direction of rotation being in a plane at right angles to the magnetic field. This is analagous to the precession of a gyroscope which is moving in a gravitational field. This rotation is performed with a SOLENOID through which the beam passes, and can produce any direction of transverse polarization (e.g. HORIZONTAL).

LONGITUDINAL polarization is produced by passing a horizontally polarized beam through a bending magnet adjusted to give the required deflection to the beam (e.g. 47 for 50 MeV protons).

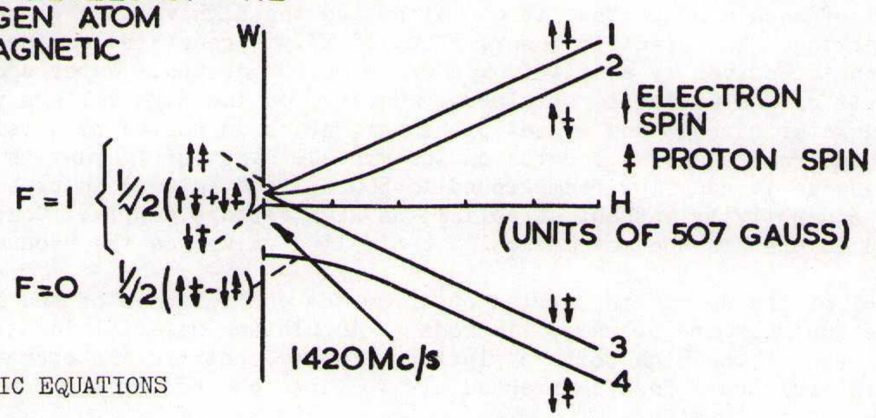
THEORY FOR SCIENTISTS

In a magnetic field, the ground state of the hydrogen atom is split into four hyperfine states as depicted in the Breit-Rabi diagram (see below). When the atoms are passed through a strong inhomogeneous magnetic field those in the hyperfine states 3 and 4 (F = 1, m,= -1 and F = 0, m,=0) with positive magnetic moment are deflected away from the axis on hyperbolic paths while those in the hyperfine states 1 and 2 (1,1) and (1,0) with negative magnetic moment perform an oscillatory motion about the axis. Because the proton and electron spins are decoupled in a strong magnetic field the nuclear polarization is zero. If, however, the atoms are passed adiabatically into a zero magnetic field after the inhomogeneous field region those atoms in state 1 (F = 1, m,=1) have complete and those in state 2 (F = 1, m,=0) have zero proton polarization, i.e. a resultant value of 0.50.

It is possible to obtain a higher polarization by inducing r.f. transitions between the hyperfine states and then ionizing in a strong field. If the transition probability from state 2 to state 4 is p_{24} the resultant polarization becomes p_{24}.

In a conventional atomic beam non-adiabatic transition, p_{24} is limited to 0.77 by the Maxwellian spread in velocities in the beam, but this limitation is avoided if an adiabatic passage method is used as suggested by Abragam et al and then $p_{24} = 1$. No r.f. transition system has been used on the present source but it is hoped to introduce this modification later.

ENERGY LEVELS OF THE HYDROGEN ATOM IN A MAGNETIC FIELD



SOME BASIC EQUATIONS

The field of a sextupole is $|H| = a r^2$

The force on an atom is $F = -\text{grad}\ W = \text{grad}\ (\mu_z |H|)$

and is always radial in a sextupole

$\therefore F_r = \frac{\delta}{\delta r}(\mu_z |H|) = 2a\mu_z r$

where $\mu_z \simeq \pm \mu_o$ (the Bohr magneton)

The solid angle of the magnet for accepting atoms entering the magnet at radius r. is

$$\delta\omega = \frac{2\pi\mu_o H_m}{MV^2} \left[1 - \left(\frac{r_o}{r_m}\right)^2\right]^{\frac{1}{2}}$$

where H_m = the field at the pole tip = 6 kilogauss

r_m = radius of the pole tip = 4 mm

$\frac{1}{2}mv^2$ = the kinetic energy of the atoms = 1/40 eV.

This corresponds to a focusing factor of 4.3
(to be compared with a measured factor of 4.0).

The calculated rejection efficiency of positive magnetic moment atoms is 98%.

Construction of the Source

The basic ideas for the design of the source were known prior to 1957 and in that year we started to design the PPS. By 1960 the vacuum chamber, dissociator, magnet and ionizer together with the complete pumping system had been assembled and fully tested in the laboratory. The construction of the ancillary equipment and the high voltage platform was undertaken during 1960. By February 1961 the source was complete and operation on the PLA began. The source has now been used for nuclear physics experiments for over 4000 hours.

Since it is essential to mount the PPS on the injector of the PLA at a potential of 500 KV to ground and to supply it with electric power, water and compressed air the installation is rather more complicated than shown in the illustration. The source is mounted on an insulated platform and enclosed in a metal shell of such a shape that it can withstand the high voltage without causing sparking. The electric power, about 15 KW, is generated on the platform by an alternator driven by a belt from a motor on the ground. Water cooling of various parts of the source is obtained by having, on the high voltage platform, an enclosed water circuit and a heat exchanger, which is cooled by a refrigerator circuit, whose compressor is located on the ground. The refrigerant is a good insulator and so it can flow from ground to 500 KV (and return) in pipes of low electrical conductivity without affecting the high voltage supply. Compressed air is used to operate the automatically controlled valves on the vacuum system.

Control of the source is carried out from the control room of the P.L.A. Some of the controls are operated via rods of insulating material located inside one of the legs of the high voltage platform. Other controls are operated by supplying 15 lbs/square inch compressed air to pipes connecting the control desk and switches on the platform.

Performance of the Source

Polarization

Theoretical capability	0.50
Loss of polarization due to positive magnetic moment atoms.	0.02

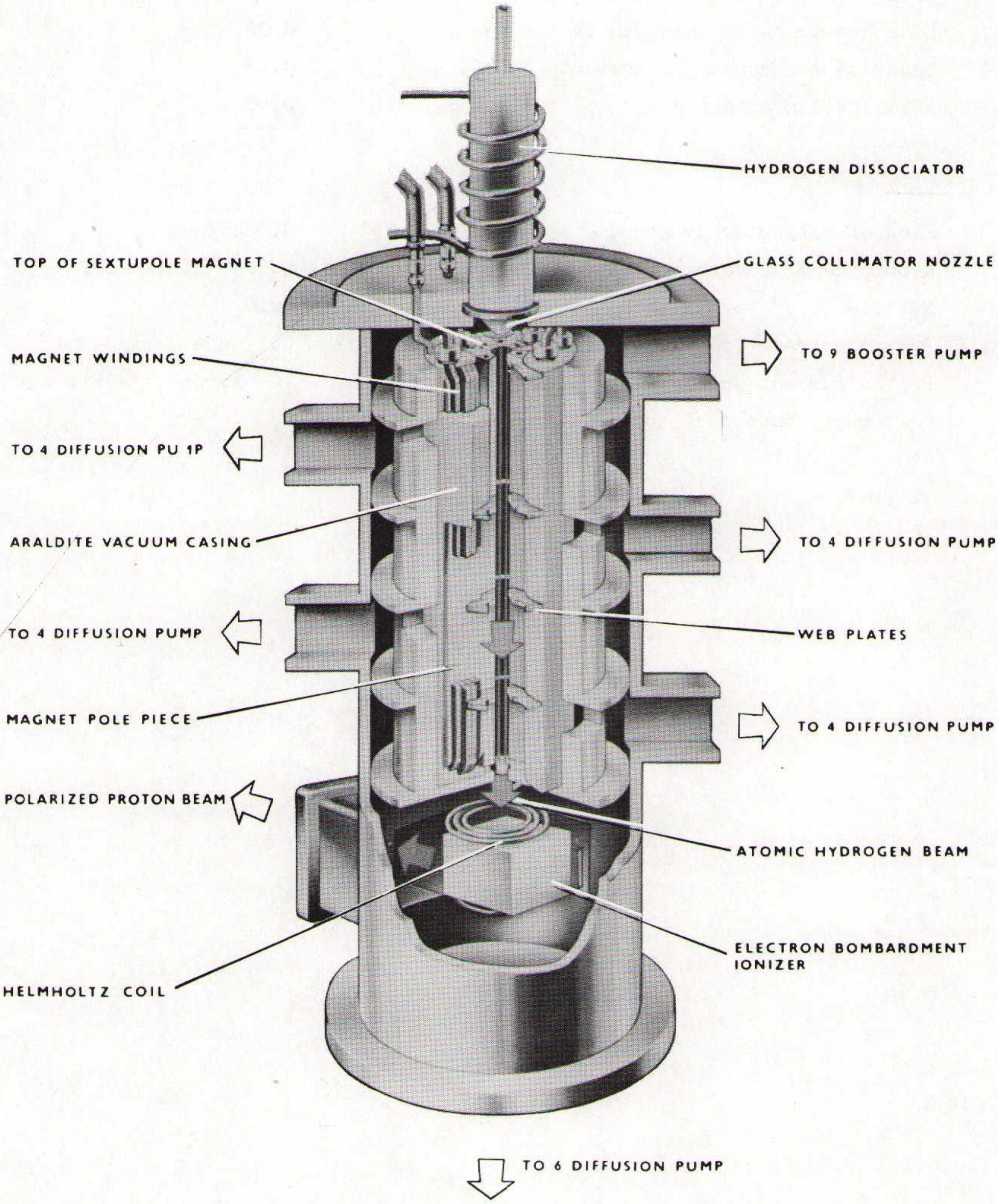


FIGURE 1 POLARIZED PROTON SOURCE

Loss of polarization due to Helmholtz field	0.01
Loss due to background gas in ionizer	0.06
Loss due to focusing magnets in P.L.A.	0.02
Polarization obtained	0.40

Intensity

Flow of molecular hydrogen	0.2 cc/sec
Atomic beam traversing the magnet	5×10^{15} atoms/sec.
Efficiency of the ionizer	8×10^{-4}
Proton current from the ionizer	0.12 u A
Proton current accelerated (mean)	10^{8} (protons/sec).
(Duty factor of accelerator 0.01)	