Zeitschrift: Helvetica Physica Acta

Band: 34 (1961)

Heft: [6]: Supplementum 6. Proceedings of the International Symposium on polarization phenomena of nucleons

Artikel: Survey of methods of producing sources of polarized protons

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DOI: https://doi.org/10.5169/seals-513255

I.

Production of Sources and Targets of Polarized Nuclei

Survey of Methods of Producing Sources of Polarized Protons

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Introduction

For a deeper understanding of the interaction of nucleons with complex nuclei it is extremely helpful to carry out experiments with beams of polarized particles. As always, it is first useful to define what polarized particles are. The nucleons have a spin $I = 1/2$ which is connected with a magnetic moment μ_I. In an external magnetic field there exist two states, with quantum numbers $m_I = \pm 1/2$, respectively, referring to the spin axis pointing parallel or anti-parallel to the field direction. We speak of a fully polarized beam when all of its particles are in only one of these states. If we have a mixture, we define the degree of polarization by the equation

$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow} .$$

Thus 50% polarization ($P = 1/2$) means that $N_\uparrow = 3\,N_\downarrow$: the number of particles with spin 'up' exceeds the number of particles with spin 'down' by a factor of 3.

The protons from all conventional ion sources are unpolarized. What are now the possibilities for producing polarized nucleons? We distinguish here three methods of production;

1) polarization by nuclear scattering, using the strong spin-orbit coupling of nuclear interactions;
2) production of polarized nucleons in nuclear reactions;
3) production of slow polarized protons in a special ion source and subsequent acceleration to the desired energy.

The first two methods work for both protons and neutrons. They will be dealt with during the next days. Today we shall discuss the third point. My task is to give a survey of the different proposals for these special ion sources. Some have already come into operation, as we shall see from the following papers. All methods have in common that they polarize neutral H-atoms or H_2-molecules in such a way that the spin of the bound proton has a preference direction in an external field. This polarization of the proton is maintained when the neutral particle is ionized by electron impact or by light. The polarization is conserved during the acceleration as well. If I may say so, none of these methods is new in principle; they are all based on well-known facts of atomic physics. In order to create some understanding, I have to give a refresher course about the hydrogen atom and the hydrogen molecule [1][1]). Perhaps this is useful for some nuclear physicists of most strict observance.

Figure 1 gives the well-known energy levels of the hydrogen atoms. The ground state $1\,S_{1/2}$ splits into two hyperfine structure (hfs) levels $F = j \pm I = 0{,}1$ with a separation $\Delta\nu = 1420$ Mc/s. The ionization energy amounts to 13.5 eV. The first excited state splits into the fine structure levels $2\,S_{1/2}$, $2\,P_{1/2}$ and $2\,P_{3/2}$: $2\,S_{1/2}$ and $2\,P_{1/2}$ are separated by the Lamb shift, $\Delta\nu = 178$ Mc/s i. e. $\Delta E \simeq 7.3\ 10^{-7}$ eV. The $2\,S_{1/2}$ state, in the absence of external fields, is metastable with a lifetime of

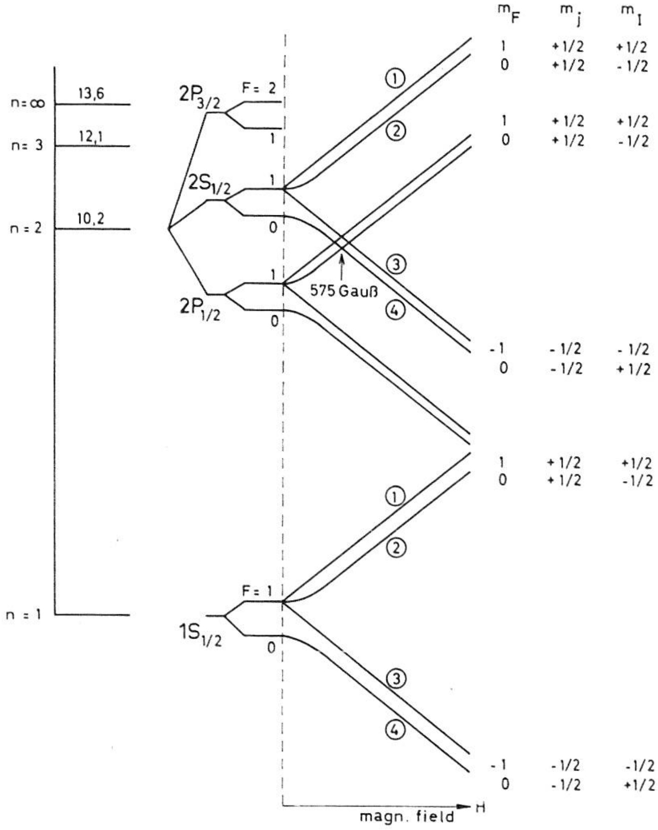

Figure 1
Energy levels and Zeeman splitting of the hyperfine structure states of atomic hydrogen.

[1]) Numbers in brackets refer to References, page 25.

about 0.1 second. The ionization energy in this state is only 3.3 eV. Both states, $1\,S_{1/2}$ and $2\,S_{1/2}$, can be used to produce polarized protons. We shall first consider the ground state.

1. Polarization Using the Hydrogen Ground State

1) *By means of Static Magnetic Fields*

If we bring the H-atoms into a magnetic field we observe the Zeeman effect of the hfs (see figure 1). Components 1 and 3 show a linear effect, whereas 2 and 4 have a quadratic dependence on the field strength H. If we are able to select particles in only one of these components, the first step of our task is solved, because m_I is defined. We can double the intensity if we use states 1 + 4 or 2 + 3.

The experiment was performed at first by RABI, KELLOGG and ZACHARIAS [2] using the molecular beam method and a Stern-Gerlach gradient field. The separation of the particles in the different levels is achieved by the force $\mu \cdot \partial H/\partial x$, where μ is the effective magnetic moment of the atom. It is plotted in figure 2 in units of the Bohr magneton μ_0 as a function of the magnetic field H. Components 1 and 3 have constant moments of opposite sign. Because of the decoupling of the electron spin from the proton spin, the magnetic moment of components 2 and 4 varies with H. At high fields it becomes very close to 1 magneton, but, unfortunately, the proton polarization in the components 1 and 2, or 3 and 4, respectively, has opposite sign. Therefore we can only use weak fields for the separation of the different components. To estimate the order of magnitude of the required field strengths, we have to remember that μ/μ_0 becomes about 0.5, when the interaction of the electronic moment with the external field $\mu_0 \cdot H$ is equal to $\mu_I \cdot H_k$ (H_k magnetic field at the place of the proton), which means $H \sim 500$ oersted. Low fields entail small gradients and hence the gradient field region has to be extended in order to get a minimum of spatial separation. This in turn gives rise to a small beam aperture and hence to relatively small intensities.

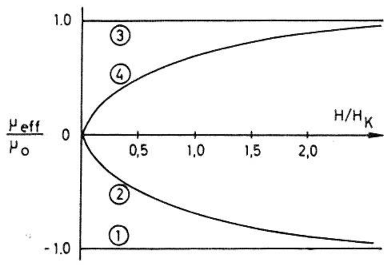

Figure 2
Variation of the magnetic moment with magnetic field for atomic hydrogen.

In order to overcome this aperture problem, it seems advantageous to use the separating properties of magnetic multipole fields, which can be treated as rotational symmetric lenses, focussing or defocussing, depending on the sign of the magnetic moment (FRIEDBURG, PAUL and BENNEWITZ [3]). The proposal to use such fields for a polarized proton source came from CLAUSNITZER, FLEISCHMANN and SCHOPPER [4].

The principle is the following (figure 3). Particles coming out of the oven slit are focused in a subsequent magnetic field if the force acting is $K = -cr$; in other words, if the potential energy is $\varphi \rightarrow r^2$.

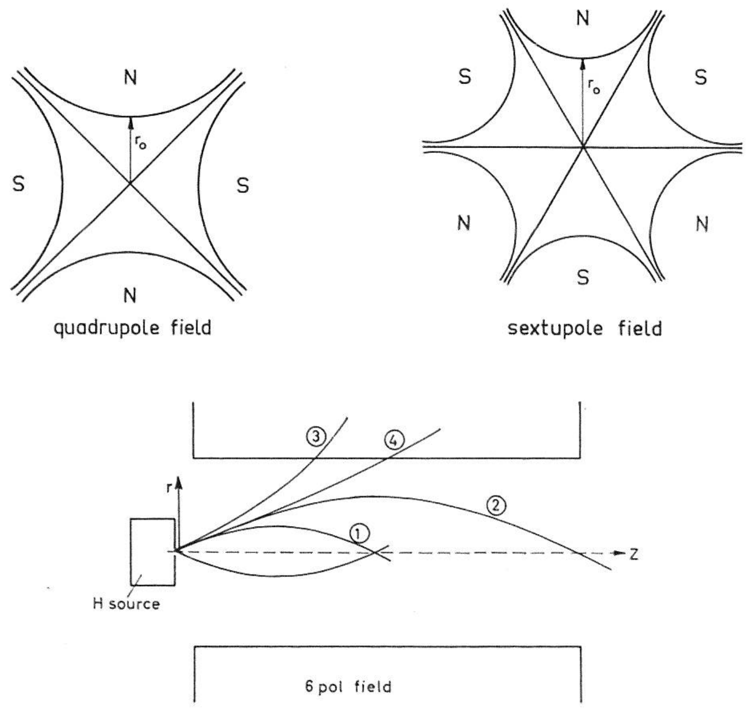

Figure 3

Schematic path of H atoms in the different Zeeman levels inside a sextupole field.

In the case of a linear Zeeman effect, the energy gain is $\Delta W = -\mu H$. From the focussing condition it is seen that H has to be proportional to r^2 and that only atoms with a negative magnetic moment are focused. This condition is fulfilled by a sextupole field (table I) for which $|H| = H_0 r^2/r_0^2$. In such a field, H-atoms in state 1 are focused, whereas states 3 and 4 are defocused because the magnetic moment is positive. Particles in state 2 are focused as well, but with a weaker and anharmonic force. To get a harmonic force on these particles, which have a quadratic Zeeman effect at least up to 500 gauss, one must use a magnetic quadrupole field. For such a field is $|H| \sim r$ and because $\Delta W = -\alpha H^2$ the condition for a harmonic potential is fulfilled for states with negative α.

For the state 1 this leads to a constant force. The paths of the different particles are schematically shown in figure 3. The separation of the states is achieved by means of a diaphragm behind the field region.

Table I

General magnetic potential of a multipole field

$\Phi \sim r^m \cos m\,\varphi$

4-pole	*6-pole*
$m = 2$	$m = 3$
$\Phi \sim r^2 \cos 2\,\varphi$	$\Phi \sim r^3 \cos 3\,\varphi$
$\lvert H_r \rvert = \left(\frac{H_0}{r_0}\right) r$	$\lvert H_r \rvert = \left(\frac{H_0}{r_0^2}\right) r^2$
$\operatorname{grad} H = \frac{H_0}{r_0}$	$\operatorname{grad} H = \frac{2\,H_0\,r}{r_0^2}$
General force on an atom $F = -\operatorname{grad}\omega = -\frac{\partial\omega}{\partial H}\cdot\frac{\partial H}{\partial r} = \frac{\mu\,\partial H}{\partial r}$	
Force on component	
$F_1 = -\frac{\mu_0\,H_0}{r_0}$	$F_1 = -\frac{\mu_0\,2\,H_0\,r}{r_0}$
$F_2 = -\frac{\mu_0\,H_0}{r_0}\,\frac{\xi}{\sqrt{1+\xi^2}}$	$F_2 = -\frac{2\,\mu_0\,H_0}{r_0}\,\frac{r\,\xi}{\sqrt{1+\xi^2}}$
for $\xi = \frac{H}{H_K} < 1$	
$F_2 = -\text{const}\;r$	$F_2 = -\text{const}\;r^3$
$F_3 = -F_1$	$F_3 = -F_1$
$F_4 = -F_2$	$F_4 = -F_2$

The focal length of the lens depends on the velocity of the particles; as they come out of the oven with a Maxwellian distribution this gives rise to a strong chromatic error. Hamilton and Pipkin [5] have shown that this effect could be nearly cancelled by using a sextupole field with decreasing inhomogeneity in the z direction. This is achieved by increasing the pole diameter r_0. Friedburg [6] has shown that an achromatic lens can be obtained by using a time-of-flight focusing method. In this case the magnetic field is not constant in time but rather pulsed in such a way that slow and fast atoms reach the focal point at the same time. Perhaps this method can be used with pulsed accelerators.

It depends on the special arrangement whether quadrupole or sextupole fields are better. FLEISCHMANN was the first to propose the quadrupole; KELLER [7] discussed this question in detail by calculating the particle path in both field types. His arrangement consists of a strong field which adiabatically goes over into a weak one. For this arrangement a sextupole of a given length is slightly superior to a quadrupole. On the other hand, the sextupole field is more complicated to produce and needs more power.

2) *Polarization by Means of an rf Field*

As we have seen above, it is relatively easy to separate the two electronic states $m_j = \pm 1/2$ in a strong Stern-Gerlach or multipole field and to eliminate by means of a diaphragm all atoms in the states 3 and 4 (figure 2). Thus the beam contains only atoms in states 1 and 2 polarized according to the electronic moment but unpolarized in the proton moment.

ABRAGAM and WINTER [8] proposed to transfer all atoms in state 2 into state 4 by means of a radio-frequency field $H_1 \cos \omega t$ parallel to a constant field H_0 (adiabatic passage methods). Then the proton spin direction is the same for all atoms. For a transition frequency of 240 Mc/s they calculate for the necessary field strength $H_1 = 1$ gauss. Even if the population of the states 2 and 4 were equalized rather than interchanged by the *rf* field, the resulting proton polarization would be 1/2.

For a Stern-Gerlach magnet separating the two electronic states, TIMOFEEV and FOGEL [9] propose a special field distribution with an exponential increase of H.

2. Polarization of Protons Using the Hydrogen 2S State

Proposals for polarizing protons using the $2\,S_{1/2}$ state came from ZAVOISKII [10] and MADANSKY and OWEN [11]. They make use of the Lamb shift. The principle of these methods is already contained in the famous paper of LAMB and RETHERFORD [12] on the fine structure of the excited hydrogen atom.

As already mentioned, the $2\,S_{1/2}$ and $2\,P_{1/2}$ states are separated by the Lamb shift. The lifetime of atoms in the $2\,P$ state is calculated to $\tau_p = 1.6 \cdot 10^{-9}$ s, whereas without external field the $2\,S$ state is metastable ($\Delta l = 0$). The decay time τ_s amounts to about 0.1 s which corresponds to a decay length of ~ 100 m at thermal velocity of the atom.

An external electrostatic field mixes the $2\,P$ into the $2\,S$ state, so that a field of 10 V/cm already reduces τ_s to about $5\,\tau_p$. The metastable S level is therefore quenched and the decay length is shortened to ~ 0.01 mm.

A magnetic field has two effects upon the atom. At first we observe the Zeeman effect of the hyperfine structure, $S_{1/2}$ and $P_{1/2}$ levels split in four components as shown in figure 1. Secondly, a particle traversing a magnetic field sees a motional electric field of the order $E = (v/c)H$ which causes the quenching effect. At a field of 575 gauss the level ($m_j = -1/2$) of the $2\,S$ state crosses the $m_j = 1/2$ of the P state. An atom in either of the components 3 or 4 now has a decay length of ~ 0.5 mm, while for components 1 and 2 the decay length is still ~ 90 cm. It is obvious that this highly differential behaviour may produce a beam of particles in which the population of the $n = 2$ level is entirely in the states 1 and 2, which are polarized in the electron moment. Both proposals make use of these effects. They start with a beam of atomic hydrogen partially excited to the $n = 2$ level, which subsequently enters a field of 575 gauss. If the particles are removed adiabatically out of the field, the protons in component 1 remain completely polarized. The coupling between the electron and proton magnetic moments becomes effective again, so that at low fields the particles in component 2 are unpolarized because $m_f = 0$. By means of an rf resonance field, we can induce transitions between the state 2 and the corresponding P level. In this way one can, in principle, remove the unpolarized particles from the beam and achieve total polarization.

However, we have to take into consideration that the beam contains a large number of atoms in the ground state $n = 1$, all unpolarized. Only by a selective ionization of the particles in the $n = 2$ level we can get a 50% or higher polarized proton beam. For this selective ionization we use the fact that the ionization energies for the two levels are 3.3 and 13.5 eV respectively. So the energy of the ionizing electrons is restricted to $3.3 \rightarrow 13.5$ eV or, using photo-ionization, the wavelength of the ionizing light has to be $3700 > \lambda > 1260$ Å.

The available proton current depends mainly on the efficiency of the excitation of a H beam.

The normal methods, using electron impact or high temperature in the oven ($\sim 10^{-3}$ or less), are too inefficient to compete with the methods described in Section 1. For this reason the method proposed by MADANSKY and OWEN for obtaining a high intensity $2\,S$ beam is interesting. These authors propose to start with a beam of protons with an energy of the order of 10 keV. This beam is passed through a chamber filled with hydrogen or another gas (Cesium vapour would perhaps be effective) at a pressure of the order of 10^{-4} mm Hg. The cross-section ($\sim 0.1\,\pi\,a_0^2$) for electron pick-up by a proton provides an efficient mechanism for the production of the metastable atoms. If this way proves to be successful, the whole method of producing polarized protons is expressionally simpler and more elegant compared with the deflection methods of Section 1.

3. Polarization of Protons Using H_2 Molecules

Another possibility of getting polarized protons is by ionizing polarized ortho-hydrogen molecules. H_2 in the ortho-state has no electronic moment; the entire magnetic moment of the molecule is due to the protons, which have parallel spins. Because the lowest rotational state of the molecule allowed for the ortho-state is $j = 1$, the rotation effects have to be taken into account, but fortunately they are very small; thus a beam of ortho-molecules splits in a Stern-Gerlach field in three components $m_I = \pm 1,0$. By selecting one state by means of an obstacle or diaphragm, we get a beam of H_2 with both proton spins pointing in the same direction. This method has two disadvantages; due to the low magnetic moment (only nuclear moments!) a strong inhomogeneity of an extended Stern-Gerlach field is necessary (see RAMSEY [1]). Secondly, the residual gas in the apparatus is the same as in the beam but unpolarized. No differential ionizing process is possible and the background problem seems hard to overcome.

GARWIN, who advocated this method [13], estimated that according to the results of RAMSEY, it should be possible to get 2×10^{13}/s polarized H_2 molecules. Sending such a beam into a highly effective ion source, he hopes to get $0.1\ \mu A$ of polarized protons. He discusses also the storage of such protons in the ion source for use in pulsed accelerators, but his calculations about the depolarization and the efficiency look too optimistic.

4. Depolarization Effects

We have seen that it is possible to obtain beams of neutral atoms or molecules containing polarized protons. The question is now whether their polarization is maintained during the ionizing process and the acceleration afterwards. The problem was discussed by MASSEY in his book 'Atomic Collisions', with the result that the interaction time of the atom with the ionizing electron or photon is too short for any appreciable depolarization. The already working proton sources of the CERN and Basel groups prove it. FRIEDMANN's [14] success in getting polarized photo-electrons from oriented potassium atoms is also a good check.

As TOLHOEK and DE GROOT [15] showed, the acceleration of protons by a pure electric field should not cause any depolarization. This is also true if a homogeneous magnetic field is present.

More serious are the following effects which need to be discussed in detail:

i) depolarization by motion in an inhomogeneous magnetic field;
ii) depolarizing collisions with hydrogen or other atoms or with electrons in the ion source.

SCHLIER treated this question in a summary [16], concluding that the collision effects, if any, can be avoided.

For the first point he found that during the acceleration of protons in a synchro-cyclotron like the CERN machine, the effect was negligible. In that special case, the probability of depolarization is only $P \sim 10^{-6}$. For synchrotrons, especially machines with field free sections or strong focusing machines, the depolarization could, however, become really serious.

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