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The Production of Polarized Particles from an Atomic Beam by Quadrupole Strong Field Separation of Hyperfine Components

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Abstract. A device has been constructed for the production of polarized deuterons from an atomic beam. The design of the source is described. The alignment of the 10^{-8} A deuteron beam was established by observing the anisotropy of neutron distribution from the $T(d, n)He^4$ reaction. Experiments indicate its usefulness as a source of polarized protons, if the proton content of the residual gas ions is reduced.

General

The objective of this work is the production of a beam of partially polarized protons or deuterons. The probable existence of unforeseen technical difficulties led us to a simple design with large margins of error. Possible future applications in Basel allow the source to be operated at earth potential, hence no serious restrictions on size and energy consumption need consideration. An important simplification for the first development stage is made possible by the anisotropy of distribution and the polarization of the neutrons from the $T(d, n)He^4$ reaction [1] [1]) produced by aligned and polarized deuterons. The resonance cross section of 5b allows small currents to be employed. The deuteron resonance energy of 107 keV is convenient, and the target may be placed at high voltage with the neutron detectors at earth potential.

The course of the particles through the device is shown in figure 1. Atoms of hydrogen or deuterium are allowed to diffuse from a high frequency discharge tube through a region of differential pumping into a strong magnetic quadrupole field. The pole shoes of the magnet are parallel to the beam axis. Half of the hydrogen or deuterium atoms diverge in this field; the other half is confined to a circular cylindrical region defined by the pole shoes. The beam so formed passes into an orienting homogeneous field weak enough to allow strong coupling of electron and nucleus. A small part of it is ionized there by electron bombardment.

[1]) Numbers in brackets refer to References, page 88.

Protons so produced should have a polarization of at most 50%. Deuterons should have spin populations for $m_d = +1, 0, -1$ of 4/3, 4/3, 1/3 respectively for the ideal case. The resulting ions are accelerated to produce the desired nuclear reaction.

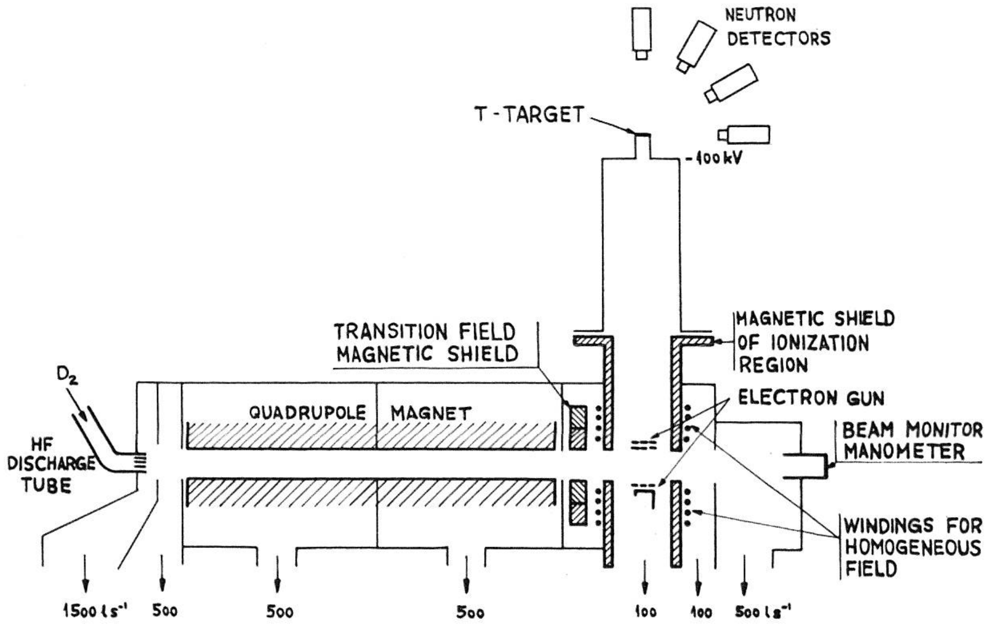

Figure 1
General scheme of the apparatus

The Gas Discharge and the Differential Pumping System

Hydrogen or deuterium gas, saturated at atmospheric pressure with H_2O or D_2O, is admitted into both legs of a V-shaped Pyrex tube of 11 mm inside diameter. An oscillator is capacitively coupled to the tube by two cylindrical electrodes, each located 110 mm from the notch of the V. The oscillator has a frequency of 20 MHz and dissipates about 200 W in the tube. Investigations of the dissociation have been undertaken with a calorimeter [2] and indicate a high degree of dissociation. The degree of dissociation is not sensitive to changes of either oscillator power, electrode position or gas current for usual operating conditions. The tube is cooled by air streams. Deuterium gas is produced by electrolysis of a heavy water solution of NaOD.

The atomic gas produced in the tube diffuses through an annular opening [3] at the notch into the first pumping compartment. Its course may be seen in figure 2. A small fraction of the atoms passes through an aperture into a second pumping compartment, and still a smaller fraction passes into the quadrupole field. The first compartment is pumped by a Leybold 1500 l/s diffusion pump operated at booster pump conditions.

The second compartment and the two compartments of the magnet tank are each pumped by Balzers 500 l/s diffusion pumps. Typical operating conditions: gas inlet of H_2 saturated with H_2O is 0.3 Torr l/s; pressures in the discharge tube and the four compartments are respectively 0.3, 6×10^{-4}, 2×10^{-4}, 6×10^{-6} and 4×10^{-6} Torr. All pumps use silicon oil of type Dow Corning DC 704. All Balzers pumps are operated with heater power 1/3 greater than the catalog value.

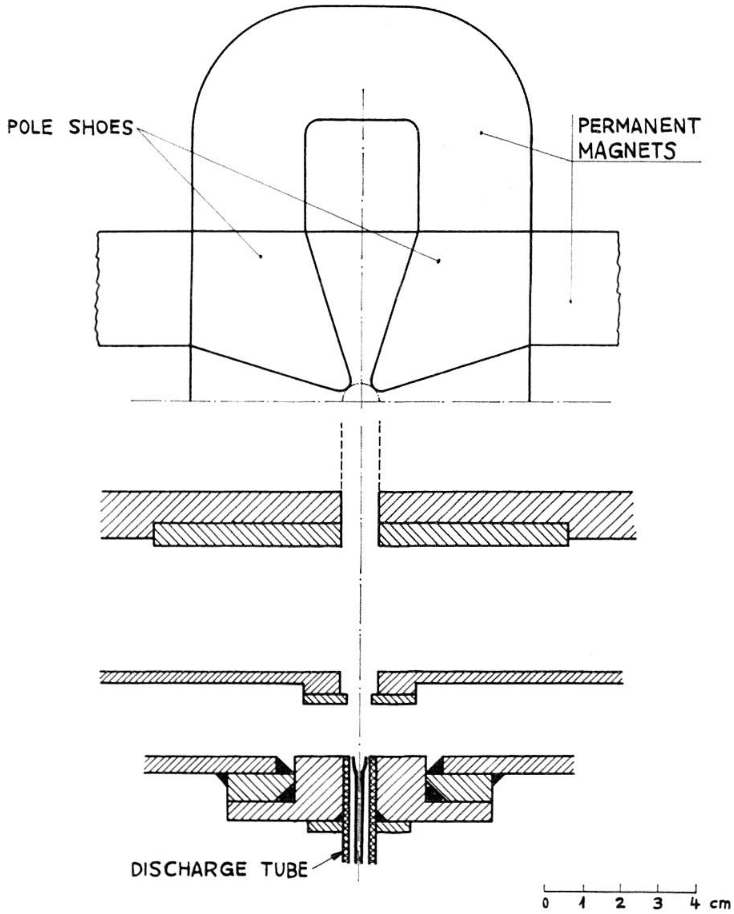

Figure 2
Gas inlet, apertures, magnet tank entrance and magnet cross section.

The Atomic Beam and the Quadrupole Magnet

The intensity of the atomic beam is calculated with the following assumptions: the magnitude of the field is proportional to the distance from the axis [4]; the atoms in the discharge tube have a Maxwellian velocity distribution; they enter the field through a ring opening with a mean radius equal to half the radius of the cylinder defined by the pole shoes (a maximizing condition); the weak field region of the quadrupole is negligible; those atoms whose trajectories pass outside the pole shoe cylinder are lost from the beam. The convergent atoms will be confined to the beam, if their initial velocity vectors fall within a solid angle that varies inversely as the square of the velocity. Averaging this solid angle over the velocity distribution gives

$$\Omega = 1.39 \frac{\mu_0 H_0}{kT}$$

where μ_0 is the Bohr magneton, H_0 the magnetic field at the pole shoe, k the Boltzmann constant and T the absolute temperature. The intensity [5] of the beam in atoms per unit time for completely dissociated gas is

$$I = \frac{n}{2} \bar{v} F \frac{\Omega}{4\pi}$$

where n is the density of atoms in the discharge tube, $\bar{v}$ the mean velocity of the atoms, $F = \pi r_0 \varepsilon$, the area of the annular opening, r_0 the pole shoe cylinder radius, ε the slit width and m the mass of the atom. The usual rule for estimating the maximum intensity of an atomic beam assumes the density n corresponds to a mean free path equal to the slit width, i. e.

$$\varepsilon = \frac{1}{\sqrt{2}\, n\sigma}$$

where σ is the collision cross section. A slit width of 1 mm was used. Application of this rule gives

$$I = \frac{1{,}39}{\sqrt{\pi m k}} \frac{\mu_0}{\sigma} \frac{H_0 r_0}{\sqrt{T}}$$

Evaluation of this formula for c. g. s. units (the value of σ has been taken for H_2) gives

$$I = 3.3 \times 10^{14} \frac{H_0 r_0}{\sqrt{AT}} \text{ s}^{-1}$$

where A is the atomic weight. The density of the beam is

$$\varrho = 6.2 \times 10^{9} \frac{H_0}{T r_0} \text{ cm}^{-3}.$$

The substitution of the experimental values $H_0 = 10^4$ gauss, $T = 300°$ K and $r_0 = 0.5$ cm with a correction factor of 0.7 to account for the location of the discharge tube exit ring outside the quadrupole field, gives an intensity for hydrogen of 5.4×10^{16} s^{-1} and a density of 2.3×10^{11} cm^{-3}; this corresponds to a pressure in the beam of 7×10^{-6} Torr.

The length L of the quadrupole insures the removal from the beam of all divergent atoms that have no angular momentum relative to the axis (the most difficult case) and speeds less than 2.5 times the mean velocity in the beam. This gives

$$L = \frac{5}{\sqrt{2}} (1 + \sqrt{2}) \sqrt{\frac{k T}{\mu_0 H_0}}\, r_0$$

or again evaluating,

$$L = 1.04 \times 10^3 \sqrt{\frac{T}{H_0}}\, r_0 \text{ cm} .$$

For the conditions mentioned earlier $L = 90$ cm.

Permanent magnets attached to four pole shoes of 90 cm length produce the field. Figure 2 shows the shape and arrangement of the magnets. The 32 permanent magnets are spaced far enough apart to give a pumping resistance with reasonable relationship to the speed of the pumps. The permanent magnets were magnetized in place on the pole shoes. The manufacturer [6] surpassed by 10% the original goal of 10^4 gauss at the pole shoes.

A longer quadrupole presents only the disadvantage of attenuation by scattering. A quadrupole field may be utilized for containing an atomic beam that must be transmitted to a high potential terminal; a series of permanent quadrupole magnets are spaced to divide the total voltage, and the confining property of the quadrupole field is essentially maintained.

Measurements of the Atomic Beam Intensity

Intensity measurements have been made by directing the beam into an ionization manometer. To interpret the manometer reading a correction must be made for pressure build-up in the glass cylinder of the gauge, the ionization cross section of hydrogen and the divergence of the beam outside of the quadrupole field. Recombination of atoms is not considered, since the ionization cross section of H_2 is nearly twice that of H. The correction for beam divergence is the weakest part of the interpretation. The molecular beam obtained when no gas discharge is present has also been measured for comparison, although its intensity is much lower.

The compartment in which the measurements are made has an entrance for the beam, a liquid air trap, a second manometer located out of the beam path to monitor the residual gas pressure and a 500 l/s diffusion pump. The small increases in residual gas pressure are subtracted from the reading of the inpath manometer. This compartment follows the ionization compartment, thereby reducing the diffusion of beam gas back into the ionization region and serving as an atomic beam monitor. A beam of predicted value would raise the residual gas pressure by

1×10^{-6} Torr. The residual pressure without beam is of the order of 10^{-7} Torr.

The measured maximum intensity is 15% of the predicted value. Intensity plotted against gas inlet shows saturation at the same gas currents for the H and H_2 beams; furthermore, the maximum H_2 beam is about 20% of its predicted value. These measurements indicate beam loss due to a scattering, incomplete dissociation, erroneous interpretation of the manometer reading and incorrect assumptions for the predicted value.

The Homogeneous Field

Ionization of the atoms takes place in a weak homogeneous field, which determines the direction and the magnitude of the polarization or alignment. To minimize the effects of beam divergence, ionization occurs as near the exit of the quadrupole as possible. Choosing the direction of the homogeneous field parallel to the direction of ion acceleration simplifies the magnetic shielding. This has no disadvantages for the $T(d, n)He^4$ reaction, as it is produced by S-wave deuterons, but a 90° rotation of spin is required for a proton experiment. The magnetic shielding is shown

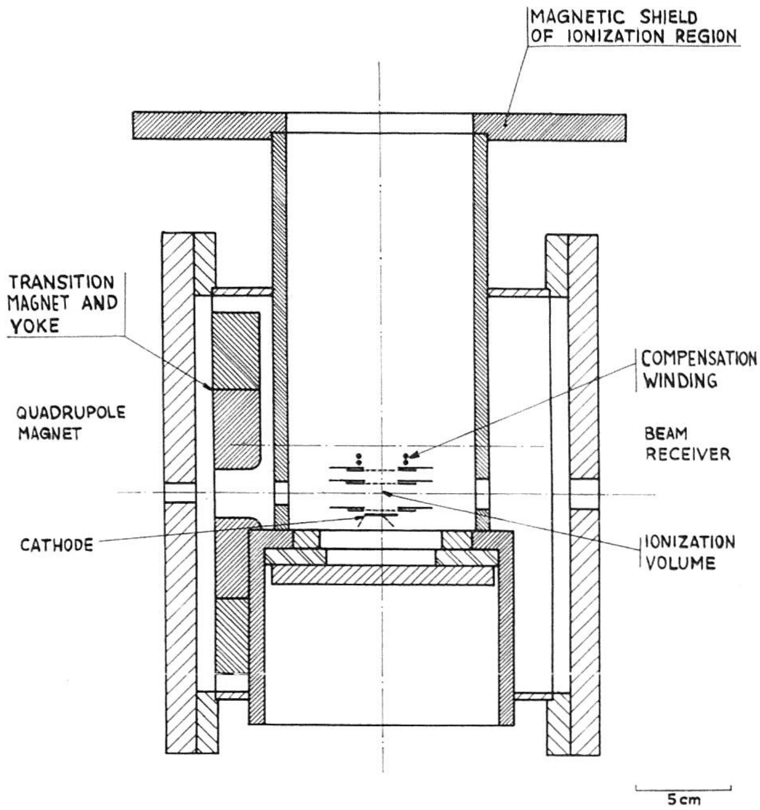

Figure 3
Ionization compartment

in figure 3. It consists of an iron ring of 9.2 cm^2 cross section and 15 cm mean diameter; it is located 2.6 cm beyond the quadrupole. The ring is dimensioned to absorb the entire measured stray flux of the quadrupole. The ring also serves as the yoke for a transition dipole field of about 60 gauss. Non-adiabatic transitions are not feared, if the field does not become too weak, since changes of the magnetic field direction experienced by the atoms are slow compared to the Larmor period. The beam passes next into the ionizing region, which is enclosed in an iron cylinder. The ring-cylinder combination reduces the field in the ionization region to 0.6 gauss, but the field direction is not the cylinder axis. Additional current windings on the cylinder correct this, thereby increasing the field to 5 gauss. From the point the beam enters the transition field to the point where it leaves the ionization cylinder, the field is essentially parallel and directed downward.

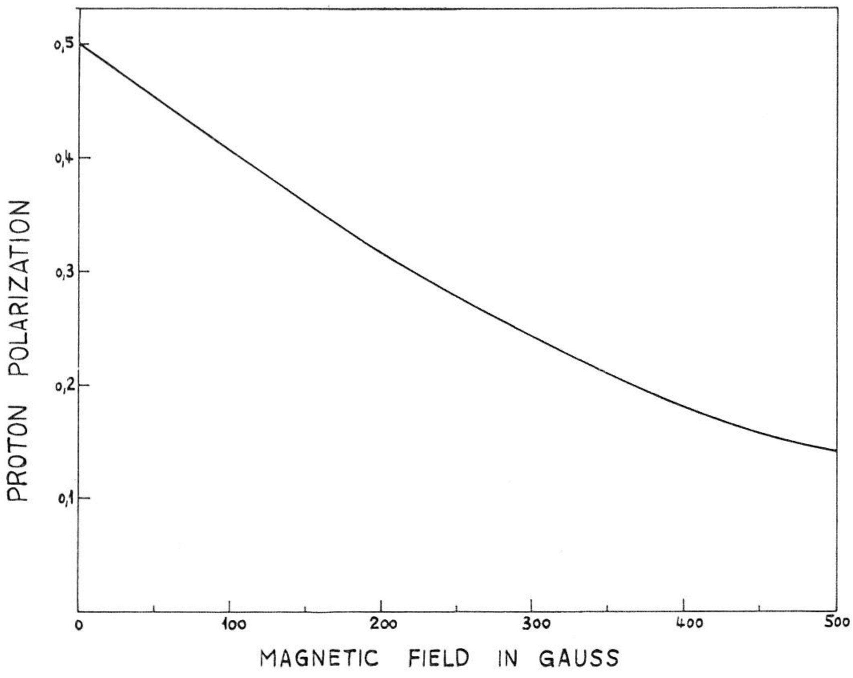

Figure 4
Proton polarization as function of field strength

The magnetic field of the heater current in the electron gun is not negligible. Its spiral form allowed an approximate calculation of its field in the ionization volume [7]. An additional winding is mounted on an electrode of the electron gun; the field resulting from the spiral and compensation winding is similar to that of a Helmholtz coil, has a value of 5.5 gauss at the center of the beam and has no angular deviations greater than 30°.

The nuclear spin populations of the hyperfine components of the beam that are mixed states were calculated as functions of magnetic field. For H atoms this is conveniently expressed as proton polarization and is shown in figure 4. For D atoms the populations of the three m_d states are plotted in figure 5.

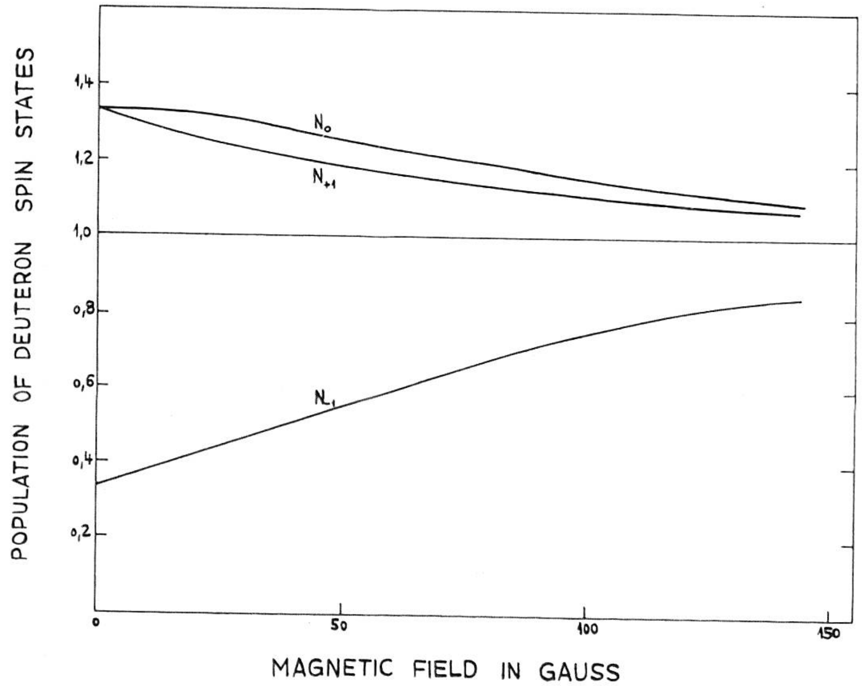

Figure 5

Populations of m_d states as function of field strength

Ionization, Residual Gas Ions

Electron bombardment ionizes the atoms of the beam virtually without depolarization [8]. Measurements of the atomic ionization cross section [9] σ_i show that for electrons with energy U greater than 100 eV a value satisfactory for design purposes is

$$\sigma_i = \frac{1{\cdot}37 \times 10^{-15}}{U} \ln \frac{U}{0.325} \text{ cm}^2 .$$

The current i_p of ions from the beam, bombarded at right angles by a cylindrical electron beam of the same diameter D, is

$$i_p = j\,\sigma_i\,V\varrho$$

where V is the volume common to both beams (0.67 cm^3), j the electron current density. For the measured density, electrons of 300 eV and an electron current density of 0.1 A cm^{-2}, the ion current from the atomic beam would be 0.075 μA. Figure 3 shows the arrangement of the electrodes in the electron gun. The plate holding grid no. 1 and the supports of the tungsten filament are liquid cooled. A weak electric field between grids 1 and 2 accelerates the ions out of the ionizing region; a stronger field between grids 2 and 3 stops the electrons and further accelerates the ions. Potentials for the electrodes are as follows: cathode 0; grid 1, + 300 V; grid 2, + 125 V; grid 3, − 475 V. The volume in which the residual gas is ionized is larger than the bombarded volume of the beam by a factor of 1.6.

Residual gas in the ionization compartment constitutes an obstacle for application of the device as a polarized proton source. Five separately pumped vacuum compartments precede the iron cylinder enclosing the electron gun. The ionization cylinder and its surrounding tank are each pumped by a Balzers 100 l/s diffusion pump. The diffusion pumps of the ionization compartment and beam receiver have a mechanical pump separate from the other diffusion pumps. All seals use rubber *O*-rings, and degassing procedures are correspondingly limited. Large surfaces at liquid air temperature are maintained in the vicinity of the gun. Calculation indicates little diffusion of H_2 or D_2 into the ionization cylinder. This is substantiated by no observable rise in pressure ($\Delta p < 5 \times 10^{-8}$ Torr) in the cylinder when an operational gas current is admitted to the first compartment. Protons constitute 2% of the residual gas ions, molecular hydrogen about 1%. Experiments with a residual gas primarily of molecular hydrogen gave the ratio $H^+/H_2^+ = 0.15$; this was reduced to 0.08 by use of an oxide cathode, indicating that processes other than dissociation of H_2 by the tungsten filament are important. These measurements lead us to suspect hydrogenous compounds as the origin of a large part of the protons.

An increase in the proton current and a decrease in the molecular hydrogen ion current are observed when the gas discharge is switched on. These changes are roughly in the right proportion to indicate the replacement of the molecular by the atomic beam. The proton increase, which immediately follows the switching of the oscillator, is independent of compartment pressure; the proton current from the residual gas is 5 to 10 times greater than the increase, depending on the compartment pressure. The large proportion of residual gas protons makes the device unsuitable in its present condition as a source of polarized protons but allows observation of the neutrons produced by deuterons from the atomic beam.

Application to the $T(d, n)He^4$ Reaction

The ions produced by the electron gun are accelerated through 100 kV without deflection onto a thick target of tritium in titanium. No separation of ions is made, since few molecular deuterium ions are expected from the residual gas and other ions produce no radiation that might be confused with 14 MeV neutrons. This causes rapid formation of a carbon layer on the target. The disadvantages are offset by additional simplicity and the elimination of a large scatterer near the target. The large volume in which the ions originate is responsible for a beam of about 15 mm diameter at the target.

Neutrons are detected by photomultipliers with plastic scintillators located 30 cm from the target. Unpolarized deuterons are obtained by admitting molecular deuterium into the ionization compartment. The ratio of reaction cross sections $\sigma(0)/\sigma(\theta)$ is measured by comparing the neutron counting rates produced by deuterons from the atomic beam and from the molecular gas admission. Corrections for the different distributions in the laboratory coordinate system for the 100 keV and 50 keV deuterons are negligible when compared with the resolving power of the detectors. No appreciable increase in neutron counting rate from residual gas ions is observed to result from previous admission of molecular deuterium to the ionization compartment. Typical neutron counting rates: atomic beam ionized 530 min^{-1}; residual gas ionized with normal gas admission to the first compartment but no atomic beam 200 min^{-1}; residual gas ionized without gas admission 180 min^{-1}; no ionization but accelerating voltages present 50 min^{-1}.

These results show that more than twice as many neutrons originate from ions of the atomic beam as from the residual gas and molecular beam. The partial pressure of the atomic beam may be calculated by comparing the neutron counting rates for the atomic beam and the unpolarized deuterium, taking into consideration different yields and ionizing volumes. The result agrees with the pressure measured by the manometer that monitors the atomic beam. The current on the target can be estimated from the fraction of the total pressure attributed to the atomic beam and the total positive ion current. This calculation gives a value of 10^{-8} A.

We have investigated the effect of various field conditions on the value of $\sigma(0°)/\sigma(90°)$, using two detectors simultaneously. The magnetic shielding and the field from the cathode prevent a controlled change of the direction of the homogeneous field, and the magnitude could not be increased to values allowing a significant change of $\sigma(0°)/\sigma(90°)$ with increase of the magnetic field without changing the field coils. Nevertheless, $\sigma(0°)/\sigma(90°)$ showed values close to unity, if the field in the iron cylinder was decreased below 1 gauss.

Three points of the angular distribution were measured simultaneously with four scintillation counters. Figure 6 shows the measured values of $\sigma(0)/\sigma(\theta)$. A convenient parameter, G, is the population ratio of spin state 0 to the sum of the populations of states $+1$ and -1. For ionization in a weak parallel field, G is very nearly 4/5. A value of G was calculated for each experimental point; the weighted average is $0{\cdot}73 \pm 0{\cdot}02$. Curves for $G = 0{\cdot}8$ and $0{\cdot}73$ are also shown in Figure 6. The average value is smaller than 0·8, as one might expect, since the homogeneous field in the ionization volume is not exactly parallel; we think all other sources of depolarization are less important.

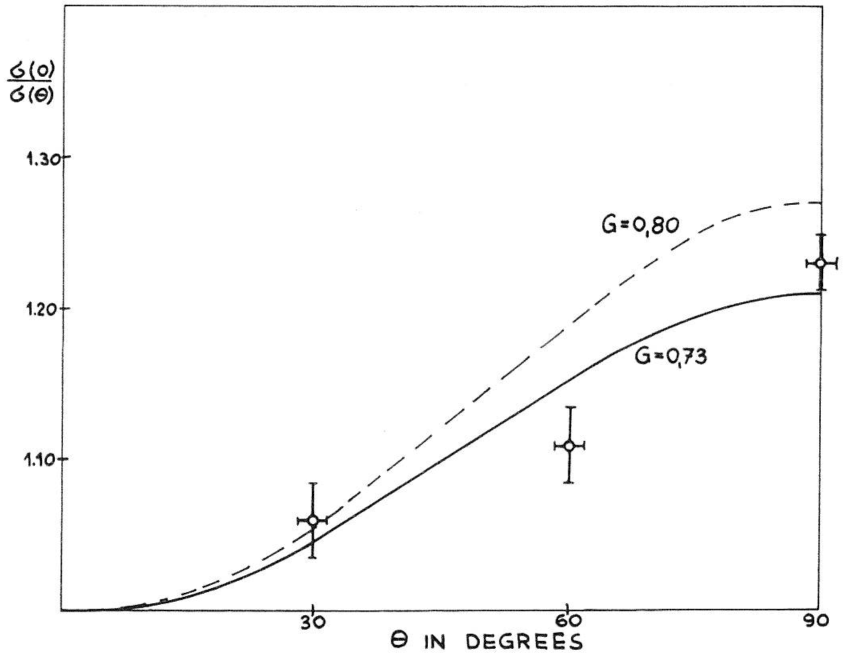

Figure 6
Angular distribution measurements

Conclusions

The experiments show that polarized deuterons can be obtained from an atomic beam in sufficient numbers for useful purposes. The device operated satisfactorily with little attention from the operators. The individual runs give no evidence for fluctuations of $\sigma(0)/\sigma(\theta)$ except those due to counting statistics. A reduction in size and energy consumption as well as an increase in polarized current seem technically possible, as does the elimination of the large number of protons from the residual gas.

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REFERENCES

[1] A. Galonsky, H. B. Willard, and T. A. Welton, Phys. Rev. Let. *2,* 349 (1959).
[2] H. G. Poole, Proc. Roy. Soc. *163 A*, 404 (1937).
[3] R. Keller, CERN 57–30 (August 1, 1957); R. Keller, L. Dick, and M. Fidecaro, CERN 60–2 (January 29, 1960).
[4] H. Friedburg, Z. Phys. *130,* 493 (1951); H. G. Bennewitz, and W. Paul, Z. Phys. *139,* 489 (1954); G. Clausnitzer, R. Fleischmann, and H. Schopper, Z. Phys. *144,* 336 (1956).
[5] N. F. Ramsey, *Molecular Beams,* Oxford (1956).
[6] Gesellschaft der Ludwig von Roll'schen Eisenwerk AG., Klus, Switzerland.
[7] C. L. Bartberger, J. Appl. Phys. *21,* 1108 (1950).
[8] N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions,* Second Edition, p. 65, Oxford (1949).
[9] W. L. Fite and R. T. Brackmann, Phys. Rev. *112,* 1141 (1958).