Production of Polarized Protons from a Beam of Atomic Hydrogen by Quadrupole Weak Field Separation of one Hyperfine Component

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I should like to describe now which line we have followed in Erlangen to separate one of the four hyperfine components of hydrogen from a beam of atomic hydrogen.

We intend to separate one of the two components with constant magnetic moment. For this we need a weak inhomogeneous magnetic field with as strong a gradient as possible. This can be produced by a magnetic 4-pole field. We have used such a field in all our experiments. As a source of hydrogen atoms we first used a Wood's discharge, then we made a new step, namely by introducing a Laval nozzle. I will describe this later.

With our original atomic beam apparatus [1][1]), it was found that the residual gas contains considerable amounts of hydrogen. This is present in the form of H_2, H_2O and hydro-carbons from the oil vapours of the diffusion pumps. The H_2 and the H_2O coming mainly from the Wood's discharge can be removed by pumps with a higher pumping speed. The hydrocarbons from the oil vapor still remain. Even at a partial pressure of 10^{-8} Torr more protons would be produced in the ionizer from these molecules than from an atomic beam whose density corresponds to a pressure of 10^{-9} Torr. This results mainly from the fact that the electrons used for ionization occupy a much larger volume than the atomic beam. We have tried to overcome these difficulties in three ways.

Firstly we have replaced the oil diffusion pumps by high speed mercury pumps and have used very narrow channels.

Secondly we have increased the intensity of the atomic beam by using a Laval nozzle.

Thirdly: The volume which is crossed by the electrons in ionizing the beam is made as small as possible and the vacuum around the ionizer is being made extremely good and free of hydrogen. We intend doing this by a bakable thin walled can inside the vacuum. This can be separately

[1]) Numbers in brackets refer to References, page 34.

evacuated by a Vacion pump and heated by an electric current through the walls (800 A. at 8 V). The atomic beam will enter through a channel and will leave through a second channel into a second getter pump used as a beam catcher. Before showing a diagram of our setup, I should like to say something about the forming of an intense beam of hydrogen atoms. Which ways are there of forming an atomic H-beam?

Firstly one can use a simple opening in a thin wall. The admissible pressure is determined by the condition that the mean-free path is larger than (or equal to) the diameter of the opening. This is called the critical pressure. The atoms leave this opening with a cosine-distribution. At a certain distance a diaphragm is located to select the beam.

Secondly: In order to decrease the unused gas-flow one can use a long channel as beam-opening. This will produce similar intensities in the forward direction. Several such channels in close formation are called a Zacharias Oven.

Thirdly: As far back as 1941 it was stated by PAUL [2] that the pressure can be increased beyond the critical pressure. One has to use very strong pumps and small distances from the oven to the Abschäler, as we call it (i. e. pealer or beam separator). However the slope of increase of intensity is much smaller beyond the critical pressure than below. KELLER[1]) has obtained 12 times the intensity to be expected at the critical pressure. At higher pressures, however, the degree of dissociation of his HF source decreases. In all the atomic beam sources mentioned so far one can calculate the intensity of the atomic beam quite accurately. It can be shown that there is an upper limit which cannot be exceeded. Particularly in the weak field separation method where it is desired to produce a much stronger atomic beam, another way has to be found: One can use a *Laval nozzle.* This was introduced into the atomic beam technique by KISTIAKOWSKY and SLICHTER [3] and by W. BECKER, now in Karlsruhe [4] The nozzle can be described as follows: (figure 1).

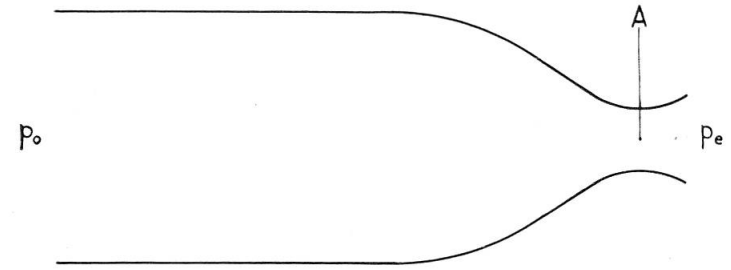
The cross-section gradually decreases, reaches a minimum and continuously increases. Let the pressure at the intake end be called p_0 and the pressure at the exit end p_e. Now let us consider the conditions at the point A where the nozzle has its smallest cross section. A gas flow is called a 'Laval flow', if the velocity of the gas at A equals the velocity of sound under the conditions in A. We call this sound velocity $c(A)$. It depends especially on the temperature at A.

If we lower the pressure p_0 relatively to p_e until the velocity $v(A)$ at A equals $c(A)$, then the pressure in A is called 'Laval pressure p_L' and becomes

$$p_L = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \cdot p_0, \quad \text{where } k = c_p/c_v .$$

[1]) This volume page 48.

If p_e is lowered further more, $v(A)$ is not influenced and also the particle flow remains the same. For a higher p_0 still $v(A)$ equals $c(A)$, but the particle flow is increased, mainly by the higher density of the gas.



velocity $v(A) = c(A)$

Figure 1

The *angle* of the opening of the nozzle behind the point of smallest cross-section must be chosen correctly, otherwise the beam is disturbed due to eddy phenomena.

The Laval beam has a characteristic *velocity distribution*. A foreward velocity is superimposed on the Maxwellian distribution and the width of the distribution is diminished.

The *dissociation* ahead of the nozzle can be done by means of an electrical arc and this is what we have been trying so far.

But it is also possible to dissociate the hydrogen using high frequency. In this connection I should like to draw your attention to a technical development of the Valvo Company in Hamburg, which concerns a high frequency "electronic torch". In the high frequency plasma torch one finds a discharge similar to a direct current glow discharge, but which in this case is energized by high frequency. It can be used for every diatomic gas up to a pressure of one atmosphere. For the discharge one needs a high frequency of very high intensity. The electrodes can be designed in the form of a coaxial wave guide, which is water-cooled. The plasma torch itself is very clean but there are material problems connected with the use of it, and volume recombination by three particle collisions has to be taken into account. The high frequency of the Valvo-torch is 2400 MHz [5].

What is the difference between using a Laval nozzle and using a normal atomic beam?

Firstly: Much more gas enters the atomic beam vacuum and directly in front of the Laval nozzle much stronger pumps are required. Behind the first diaphragm, the Abschäler, as we call it, conditions remain prac-

tically the same as usual. This means that the Abschäler now acts as the new atomic oven opening, but there is a directed flow after the nozzle, instead of a cosine-distribution.

Secondly: Since the dissociation has to be done in a relatively high pressure volume recombination will heat up the gas and therefore the particles have a much higher velocity. This has the effect that the deflection of the particles is more difficult and that they remain only for a shorter time in the ionizing region of the ionizer. In this connection it should be noted that with a high frequency torch the gas temperature is lower than in an arc discharge. (It would appear not quite impossible that in an arc discharge with higher pressure fast atoms are formed by charge exchange and lead to the formation of neutral particles with an extremely high velocity.)

I will now describe *our experimental setup*. First of all I should like to mention the names of my collaborators: H. P. JOCHIM, W. KLINGER, G. FRITSCH, E. WEBER, W. FINK. The apparatus is shown in figure 2, from which can be seen the pumping speed in the different sections, the distances between the diaphragms, the position of the magnets and the location of the Molybdenumoxyd-detector and of the ionizing region.

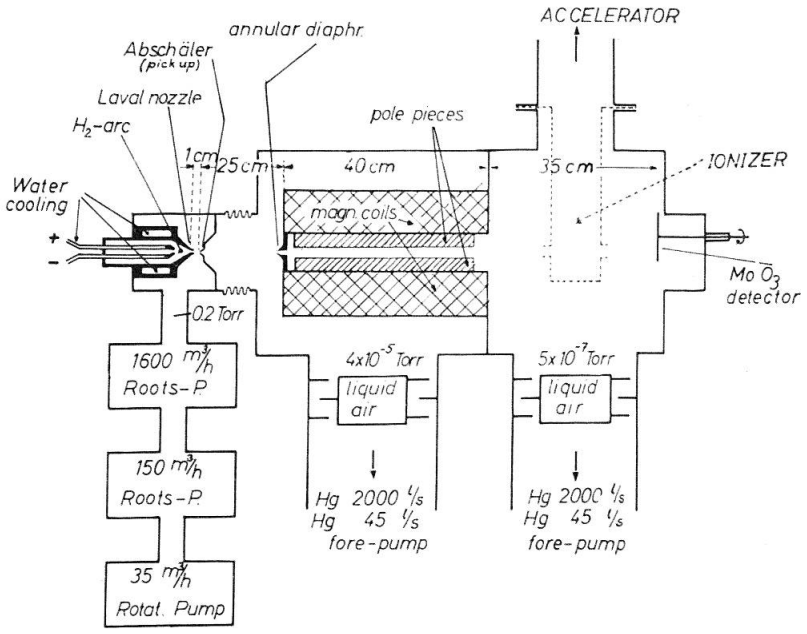


Figure 2

In the arc discharge we have 200 Torr of H_2. The nozzle has a diameter of 0.2 mm and is made of a ceramic. The distance between the Laval nozzle and the Abschäler is evacuated to a vacuum of between 0.2 and 0.4 Torr by two high-speed mechanical Roots pumps in series. The total

pumping speed of this arrangement is 1600 m^3/h or 450 l/s at a pressure of up to 1 Torr.

The length of the path in this section is kept as short as possible. However, the distance between the Laval nozzle and the Abschäler, the shape and the angles of the Abschäler and the adjustment are very sensitive because of possible eddy formation and production of shockwaves. This distance is about 10 mm in our arrangement. In the next section we use a mercury pump of 2000 l/s with a liquid air-trap, which decreases the pumping speed to about 1000 l/s. The pump evacuates this volume down to $5 \cdot 10^{-5}$ Torr. Then follows an annular diaphragm with an outer diameter of 2 mm. Then follows the 4-pole magnet with a length of 30 cm and a magnetic field strength gradient of 40000 Oe/cm at the entrance side and 15000 Oe/cm at the exit. These large gradients necessitates near the entrance the passage of particles through stronger fields. The magnet is so dimensioned that with a particle velocity of 5000 m/s the deflection of the component selected would be about 2 mm. If the velocity corresponded to 300° K, then the deflection of the maximum of the Maxwellian distribution would be about 6 mm. 30 cm further on is a Molybdenum-oxide detector. Figur 3 is a general view of our setup. One can see the Rootspumps, the arc source, the section containing the magnets and the section for the ionizer. There is a very important difference between the detection of an atomic beam by Molybdenum oxide using a Wood's discharge and using an electrical arc. With the latter source, it was noted that the blue colour did not come up before taking the Molybdenum-oxide out of the vacuum into the air. Apparently the presence of some water is important for the forming of the blue Mo-oxide. Therefore one cannot compare the intensities of the atomic beam in the Wood discharge with those in the Laval nozzle arrangement by means of the blue colouring of the Mo-oxide detector. The quantitative comparison will not be possible until we have used the Pirani manometer we have constructed. The process of forming blue Molybdenum oxide is according to a recent research work of chemists

$$Mo\,O_3 + H(\text{reducing}) \rightarrow Mo_4\,O_{10}\,(OH)_2\,.$$

The deflected patterns one gets by quadrupole weak field separation shows figure 4. It is taken using our former apparatus with a circular, not a annular diaphragm.

We want to separate by an opening the component which goes to the centre of the magnetic field, where the magnetic field strength is zero. CLAUSNITZER has checked experimentally in his thesis by using two 4-pole fields in series that this component remains polarized to $90 \pm 10\%$ after it has left the 4-pole field. It is thus shown that the polarization is not disturbed or destroyed by flipping processes under workable conditions.

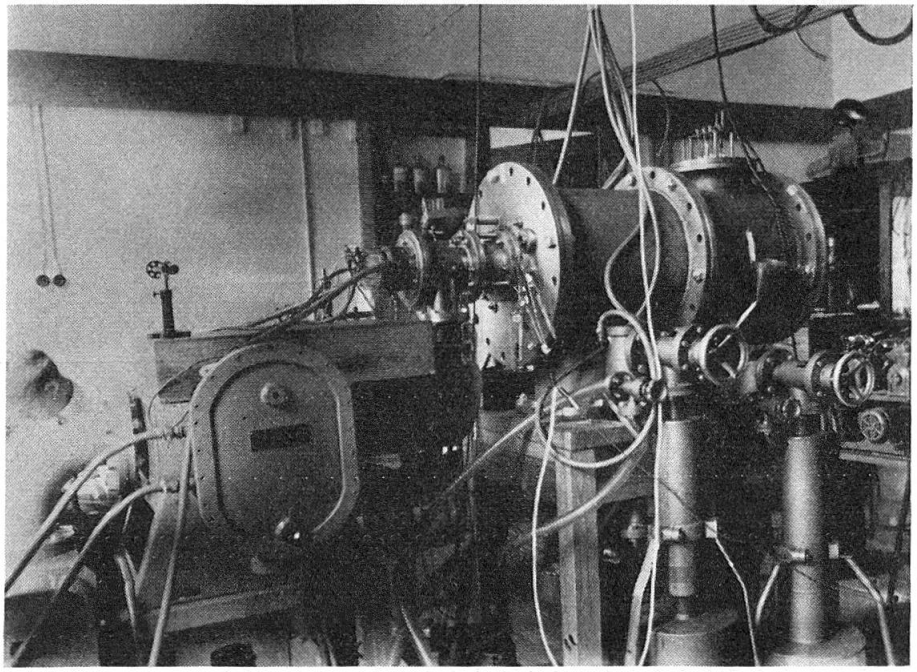


Figure 3

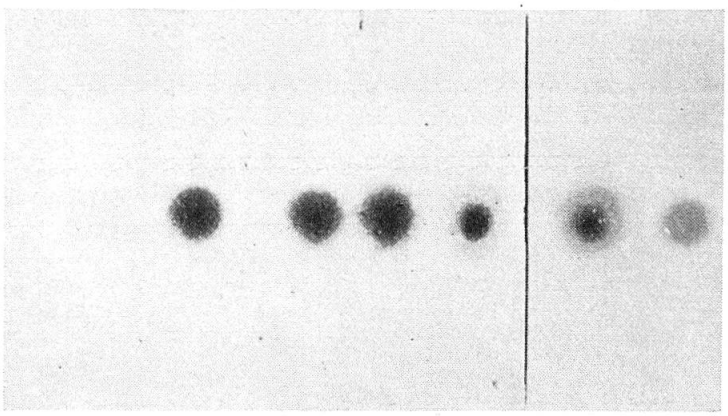


Figure 4

I should like to point to one more fundamental method to separate one hyperfine component which is not impaired by the Maxwellian distribution. BEDERSEN [6] has used superimposed inhomogeneous magnetic and electric fields of equal configuration. This will result in the vanishing of the deflecting force in the region where $\mu \sim \boldsymbol{H}$. In this case the manetic and the electric forces from the magnetic and electric induced dipole moment cancel out. He used this method for alkali atoms. Howerer for hydrogen or deuterium this would need very high electrical fields. If it would work too for hydrogen, it would have the advantage that

the Maxwellian distribution has no more influence, however the focussing would not work.

Figure 5 shows some beam patterns obtained with the Laval beam apparatus and Molybdenum-oxide detector. In one experiment we removed the Abschäler and replaced it by the MoO-detector. A sharply defined area can be seen, the diameter of which is 3 mm (figure 5a). If it is known how many particles pass through the nozzle as well as the percentage of those, which enter the Abschäler we can determine the resulting beam intensity. We have measured the gas intake into the nozzle. This is $2{,}5 \cdot 10^{20}$ particles/s (200 Torr). The diameter of the Abschäler is 0.5 mm. Therefore we have $8 \cdot 10^{18}$ particles/s behind the Abschäler.

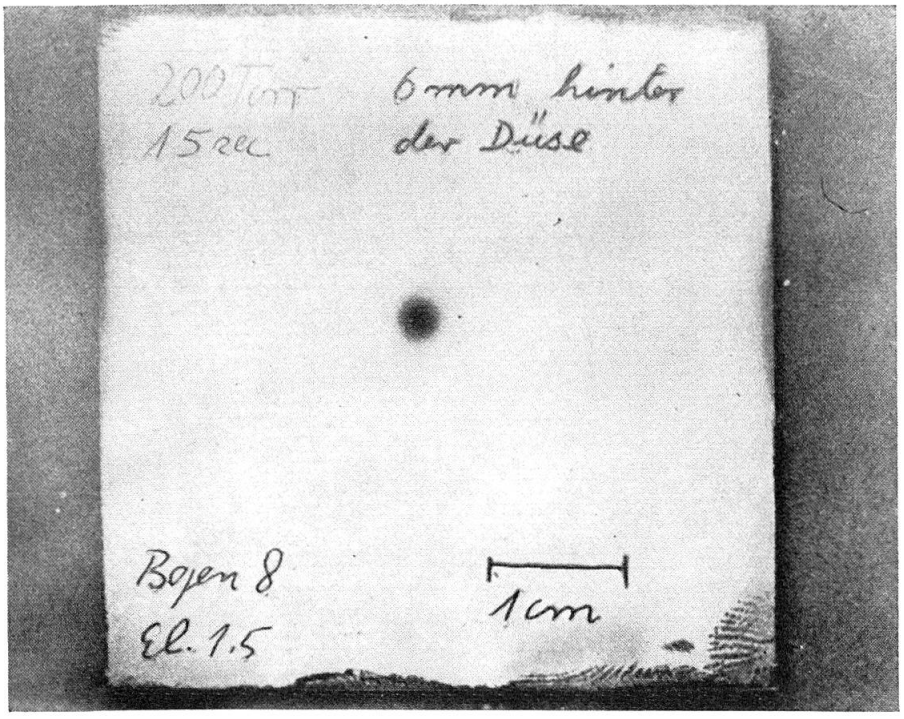


Figure 5a
Well-defined beam leaving the Laval-nozzle (no collimation!)

Of course, a separate measurement must be made to determine which percentage of the beam is dissociated. The degree of dissociation is small until now in our arc source. Figure 5b shows the beam at the end of the apparatus. A wire cross, which is located at the end of the magnets can be clearly seen.

For the ionization we have planned the following arrangement of electrodes in the electron bombardment ionizer which is shown in figure 6. It will be located in the space between the magnet and the Mo O_3 detector

in a can which is separately evacuated by a Vacion pump of 120 l/s for air, which is equivalent to 450 l/s of H_2. A second getter pump is used as a beam catcher.

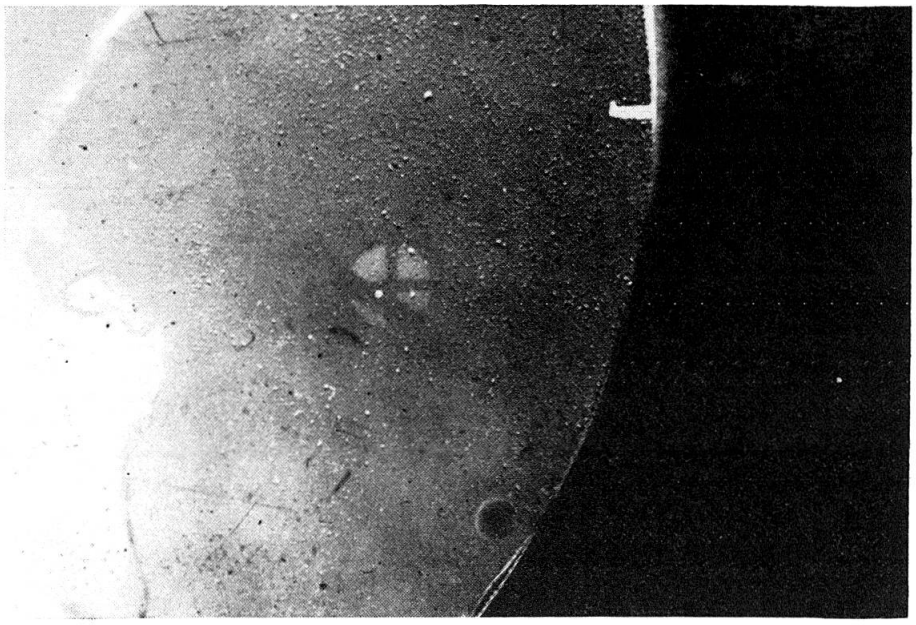


Figure 5b
Atomic beam showing crossed wires and a beam stop wire

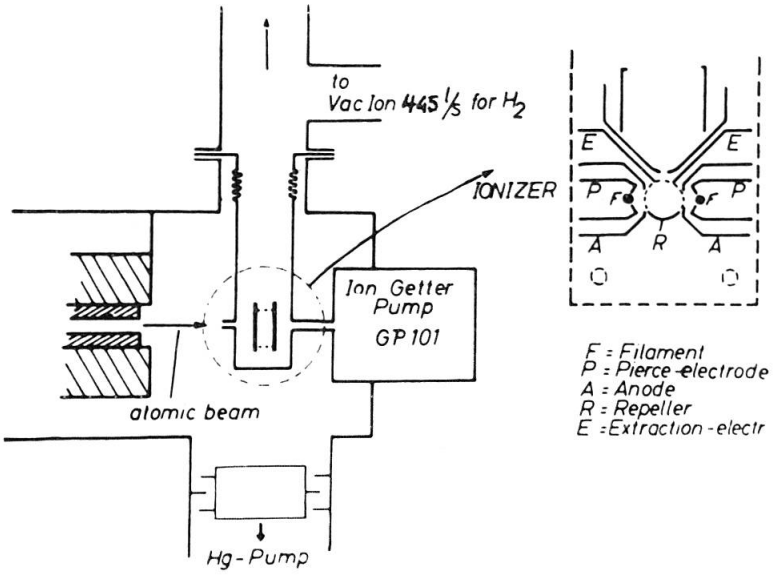


Figure 6

Our next step will be the insertion of the ionizer and especially the increase in the degree fo dissociation.

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