POLARIZED PARTICLES IN CYCLOTRONS

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Most experiments on polarization phenomena with cyclotron beams have been made along two lines :

1) Analysis, with available polarization analyzers, of particles emitted in reactions, so far only in the proton case.

2) Use of polarized beams obtained by scattering, e.g. polarized protons from α-p scattering, as developed at Los Alamos by L. Rosen. These methods suffer from the disadvantage of low counting rates and, in the latter case, from the limited energy resolution of the polarized beam.

The advantage of polarized sources is that they provide very clean beams with large intensities, for cyclotrons in the worst case 2×10^8/s on the targets. Also, with polarized sources the spin orientation can be changed at will to provide complete independence from geometric effects such as left - right (or up - down) measurements. Also, vector or tensor polarized beams of deuterons can be achieved at will.

There are certainly cases where the analysis of the polarization of the emitted particles cannot be replaced by measurements with polarized incident beams. But often, as for example, in (p,d) experiments with polarized protons and obviously in elastic scattering experiments, the same information can be obtained.

Part I - Polarized Sources

Many proposals for making polarized beams have been described[1]. Three methods which have been successful are :

1) Selection of one component corresponding to one orientation of the nuclear spin (maximum polarization 1). This needs both high and low magnetic field gradient separation. It is the CERN method[2], which will be described in the last paper of this session.

2) Selection of the components belonging to one electron spin orientation of the atoms, followed by ionization in a very low magnetic field. This is the method used by Fleischmann and collaborators at Erlangen. It has been adopted at Harwell[3] (linear accelerator) and at Minnesota[3]. The maximum polarization value of the nuclear spin I is $1/(2I + 1)$.

3) Separation of the components belonging to one electron spin orientation coupled with the frequency transitions for reorienting the nuclear spins. Ionization must then be made in a relatively high field. Maximum vector polarization value is $\pm$ for protons, $\pm$ 2/3 for deuterons.

As the possible intensity depends on the flux left after a first magnetic-gradient

separation of the atomic beam, methods 2 and 3 should have the same limits. HF transitions are the keys to high polarization values and to high versatility (e.g., flipping of the spins at will).

Formation of an Atomic Beam

Most experiments use adaptations of the procedure developed by Keller[2] ar CERN. Hydrogen is dissociated by an RF discharge at pressures up to 3 mm Hg. The pyrex tube which is used supports a 1 kW discharge (20 Mc/s). Dickson and Craddock at Harwell are dissociating at a lower pressure (300 microns), and use a large number of capillaries for the exit of the atoms to provide good geometric collimation of the jet. Although this device makes the pumping requirements easier, the intensity obtained is considerably lower. Dissociation at high pressures[1] has been tried with limited success; it seems that volume recombination can only be avoided by reaching high temperatures, which then make deflection in magnetic field gradients difficult.

The pressure is limited by volume recombination effects; surface recombination is usually negligible if the pyrex is clean (e.g. cleaned with hydrofluoric acid and if the surface is subsequently kept wet). Essentially 100% dissociation can be obtained.

The atoms leave the tube through a hole and should enter a good vacuum over as short a distance as possible. Most apparatus have adopted the suggestion of Clausnitzer[3] which is an adaptation of experiments on supersonic flow by Becker. Although the term supersonic flow would be wrong here for the range of pressure used, nevertheless an increase in beam intensity is observed. A conical pealer with sharp edges is placed about 5 mm from the hole in the pyrex tube. Pumping in between is usually done by a Roots pump which is insensitive to atomic hydrogen. Otherwise, mercury pumps should be used; oil would loose its properties in a short time.

Clausnitzer has recently proposed to recombine the atoms on the pealer with heated platinum; this technique would allow pumping with oil diffusion pumps. A complete study of this part of the apparatus is not available yet, and improvements can perhaps be expected in the future.

Magnetic Separation

The atomic states are separated according to the electron spin orientation. Half of the beam is made convergent, the other half diverges and is pumped out. Usually, either a quadrupole or a sextupole lens is used. In the latter case the field gradient is directed towards the axis, and is proportional to the distance from the axis. These characteristics would provide point focusing if the velocities were constant. Unfortunately the velocity distribution is complex with a mean higher than a Maxwellian one, due partly to the velocity of the gas when it leaves the pyrex tube. One has, then, large chromatic aberrations. The choice of a magnetic lens depends on the geometry (i.e. the distance at which ionization is made) but the characteristics are not

critical. The gradient is limited by the saturation of the pole pieces; in the sextupole case the maximum field close to the pole pieces is about 9000 gauss. Only a little could be gained by using special magnetic alloys. Permanent magnets can be used, but coils are very convenient for testing purposes. The profile of the pole pieces along the distance traveled by the atomic beam is designed for maximum solid angle; other separating magnets have been used by Hughes at Yale, but they provide considerably lower intensities.

Large fluxes of atoms can be obtained, even at large distance. We have measured a flux of $2 \times 10^{15}/cm^2$- s at a distance of 2 meters from the sextupole magnet. Because the focusing properties are rather crude, the flux varies roughly as the inverse of the square of the distance.

It is not yet clear what the limitation of the intensity is, e.g. whether the pumping speed inside the sextupole is or is not the limiting factor. If not, substantially higher intensities should be obtained by scaling up the size (and the cost) of the system.

It is established that intensities of the order of $10^{16}/cm^2$- s can be obtained with actual apparatus at distances of the order of 50 cm from the sextupole magnet. If one can ionize at that distance, beam intensities of the order of 1 μA or more, before acceleration, can be obtained.

Ionization

Electron bombardment has been reported by many authors for ionizing the atomic beam. We first attempted to use an Oak Ridge type source where the atoms crossed the plasma at the center of the cyclotron. An external beam of the order of $2 \times 10^{10}/s$ was obtained, but the polarization had disappeared. The ionized atoms probably stayed in the source itself for a long time, moved up and down the magnetic field, and eventually hit the cathode or reflector. Another simple way to ionize is to use a magnetron type ion source[4]. The kind we have used thus far has a poor efficiency but does not depolarize. It will be discussed later.

Residual Vacuum Problems

In the case of deuterons, the residual beam due to cyclotron vacuum contamination can be small (< 10%) and, in fact, is not a problem in our experiments. The proton case is different; the residual pressure of H_2O or hydrogen compounds should be smaller than 10^{-7} mm Hg in the ionization region. Even at the center of the cyclotron such pressures can be achieved, as shown by Keller[2] et al., by cooling the dees to liquid nitrogen temperature. Of course the problem is easier if the atoms are ionized outside of the cyclotron.

High Frequency Transitions

Two types of transitions based on principles proposed by Abragam and Winter[5] have been tried at Saclay. Both use the adiabatic transition method but are different

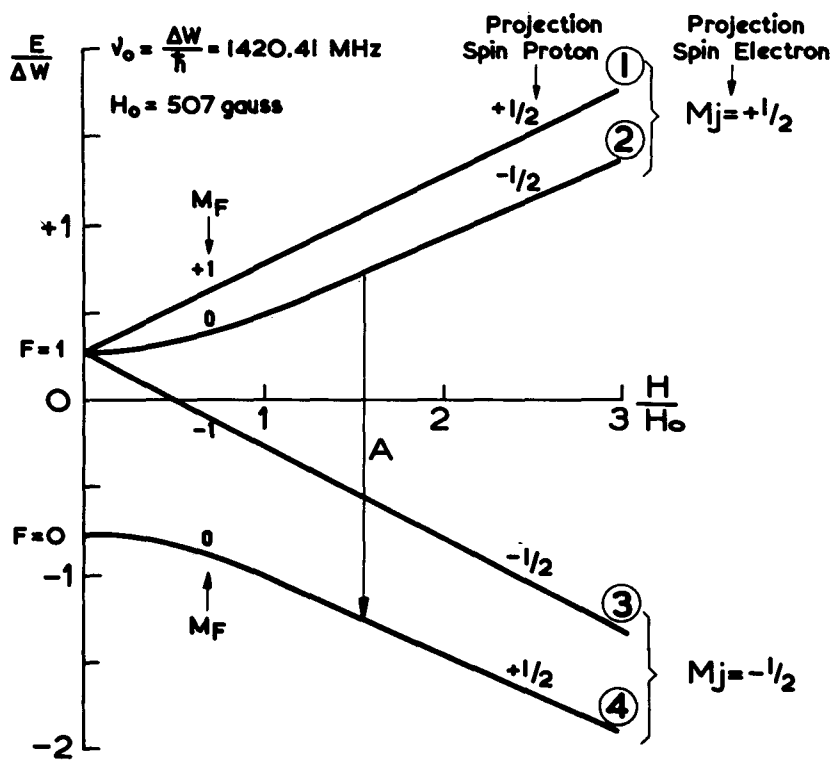

Fig. 1 Rabi diagram for protons.

in theory. The first is the high field, one-transition type. The second is the interchange of populations in low fields. Combination of the two provide a large number of possibilities.

To specify the transitions, we use the Rabi diagrams for protons (Fig. 1) and deuterons (Fig. 2), which give the energy of the levels of an atom as a function of the magnetic field; the levels are labelled by numbers which will be used later on. In the low magnetic field region, the interaction between electron and nucleus is large, compared with the effect of the magnetic field, and the right description has to be given for the different F values, F being the total spin. For the high magnetic field region, electron and nucleus are almost completely decoupled.

The well known high frequency transitions in a homogeneous field[6] will not be discussed here as their performance is not as interesting for polarized sources.

High Field Transition. The type of transition can be chosen at will, but a few are forbidden. In the proton case the transition used is from the level $m_o = +1/2$, $m_p = -1/2$ to the level $m_e = -1/2$, $m_p = +1/2$. One should note that the adiabatic method insures the exchange of the population of the levels and not the equalization. The efficiency of the exchange can be close to 100%. The conditions are as follows for a magnetic field of 885 g and a frequency of 2860 Mc/s : the oscillating HF field should be of the order of 1 G, which is easily obtained with a cavity and a magnetron with about 20 W power. The magnetic field should be shaped, a difference of about 10 gauss is needed between entrance and exit of the cavity. The net result is a polarization of +1 for the protons.

In the deuterium case, Fig. 2, electronic flipping is easily obtained for the transitions 1 → 6, 2 → 5, 3 → 4. For the other transitions like 2 → 6 a higher power

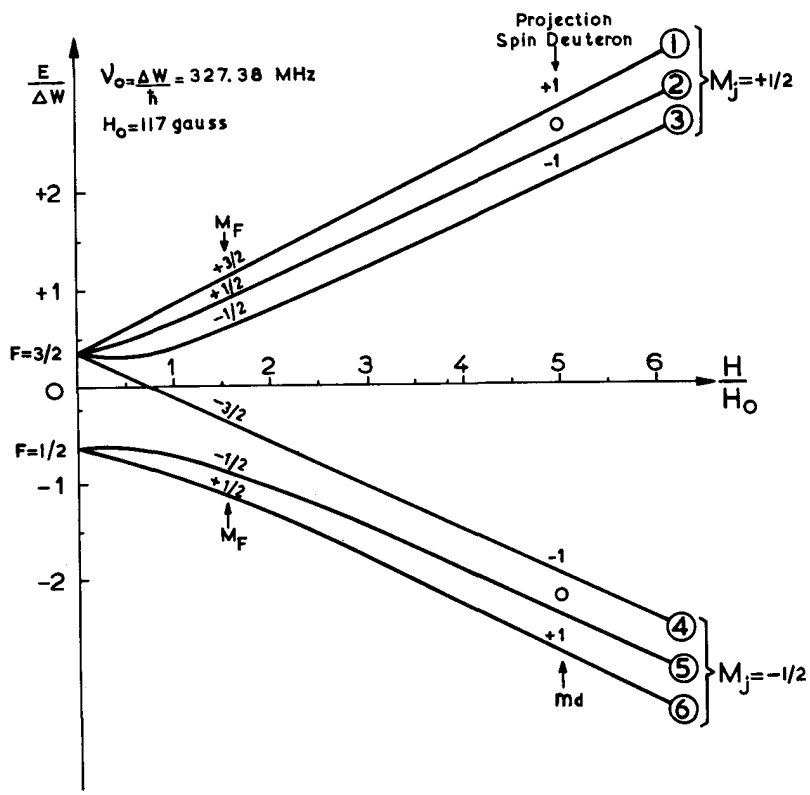

Fig. 2 Rabi diagram for deuterons.

is needed, but 400 watt gives a good efficiency. One should note that 3 → 6 is forbidden. The use of the transitions will be described after the discussion of the low field transitions.

Low Field Transitions. In low magnetic fields (a few gauss), for a given F the energy levels corresponding to different m_F are equidistant. The RF transition completely exchanges the populations corresponding to $+m_F$ with the ones corresponding to $-m_F$. This is obtained by using a high frequency corresponding to the difference in energy between two equidistant levels. The oscillating field should be of the order of 1 gauss, which is easily obtained with an oscillator of a few watt. The effect on the polarization is the following : for protons -1 polarization, for deuterons -2/3 pure vector polarization.

Combination of the Two Types. For protons, if the transitions are used alternatively, both signs of polarization are obtained at will. For deuterons, it is known that vector and tensor polarization are needed to describe a beam of spin 1 particles.

Vector polarization. It can be proved[7)] that a pure vector polarization of ±2/3 is the maximum possible for a pure vector case; -2/3 has been shown to be obtained with a low field transition only. For the +2/3 case, we have used three transitions : 1) a low field, 2) a high field operating 2 → 5, and 3) a low field. Both procedures can be used alternatively, furnishing a spin flip of extreme convenience.

Tensor polarization. Tensor polarization of ± sign can be obtained by using 1) high field 1 → 6 and 2) low field, or 1) high field 3 → 4 and 2) low field. These cases bring in a constant vector polarization of -1/3. To eliminate almost any effects of vector polarization one can use the following procedure : Four sets of data can be

taken corresponding to different arrangements of the three transitions. (For each one the high field is tuned to 2 → 6).

These are a) low + high, b) high + low, c) high, and d) low + high + low. The first two have -1/3 vector polarization with tensor polarization of opposite signs. The last two have +1/3 vector polarization with tensor polarization of opposite signs. The measurements can be added in such a way that the vector polarization cancels out.

Efficiency of the Transitions

The efficiency can be measured in the following way for the low field case. If one uses simultaneously the two low fields transitions, the net result is no asymmetry at the limit. The deviation from zero asymmetry gives the information needed. Within statistics, zero is observed, which indicates that the transfer of populations is close to 100%. The efficiency for the high field case for 2 → 5 can be obtained also by comparing one low field transition (-2/3) with the three transitions in cascade. Again a yield close to 100% is observed.

For the high field transition 2 → 6 (400 watt), we do not know the yield yet. It should also be high, but may be slightly lower than in the previous cases.

Part II - The Polarized Deuteron Source at Saclay

The different elements of the Saclay polarized source are shown in Fig. 3. The dissociator is the one Keller developed at CERN. The sextupole is 30 cm long; the distance of the pole pieces to the axis changes from 2 mm (entrance) to 6 mm (from the middle to the exit).

For the low field transition, the shape of the magnetic field is obtained by the profile of the pole pieces. The high frequency field is developed inside a coil wound on a quartz tube. The magnetic shielding is to protect either against the cyclotron field or against the field of the high field transition. Typical values of field and frequency used in the deuterium case are 7 gauss and 7.5 Mc/s.

For the high field transition, the shape of the magnetic field is provided by correcting coils on the pole pieces.

The pumping is as follows : after the pyrex tube a Roots pump 1600; before the sextupole a 2000 l/s diffusion pump; and for the sextupole a 2000 l/s pump. Also between the quartz tubes of each HF transition, all available space is used for pumping.

The atomic beam is directed towards the center of the cyclotron, in the medium plane, between the dees. The atoms are then ionized at the center, after a flight distance as large as about 2.5 meters from the sextupole.

The ionization, which has been described[4], has a poor efficiency. We are studying another type, as developed by Helmer, Jepsen[8]. It has a much better efficiency for fields of the order of a few thousand gauss, but it decreases for higher field values. It has the advantage of providing a narrow beam which can be deflected in the medium plane, either with a Birmingham-type deflector or with shaped electrodes

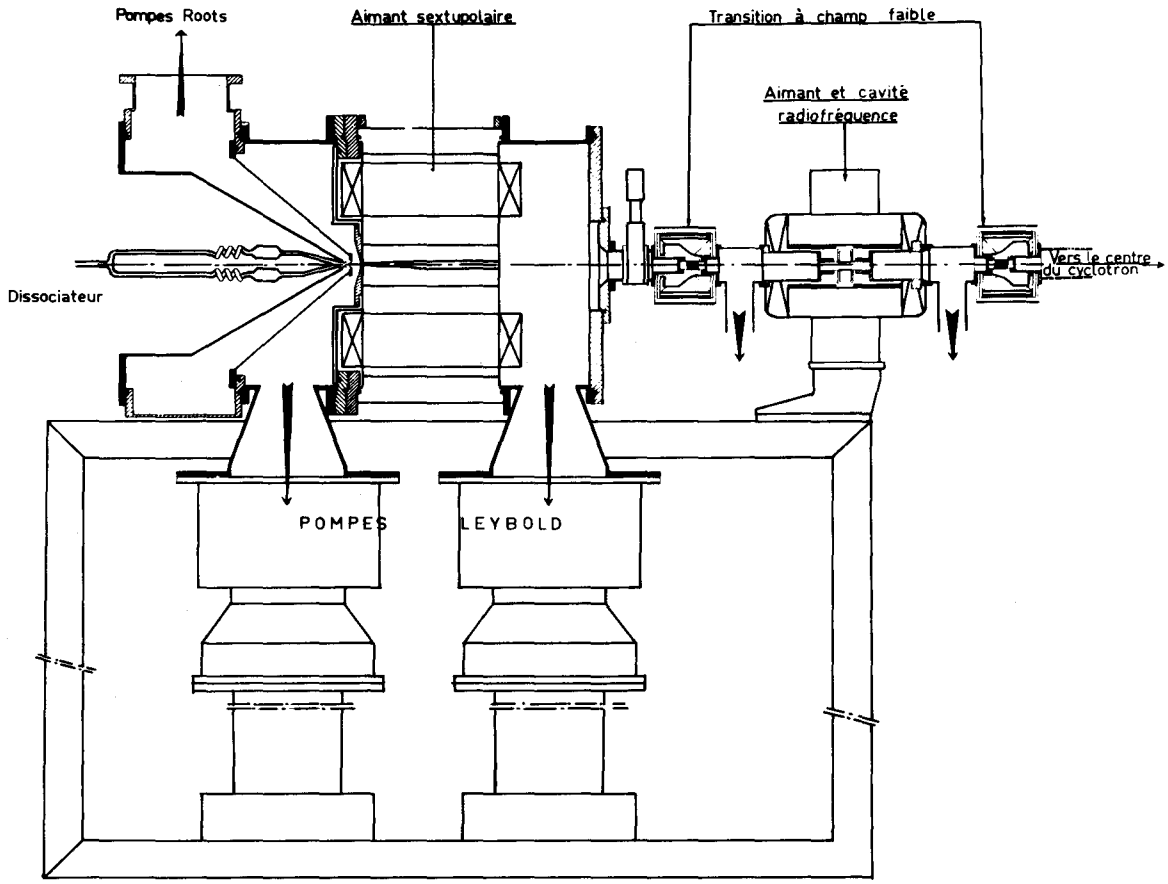

Fig. 3 General view of the Saclay source for polarized deuterons.

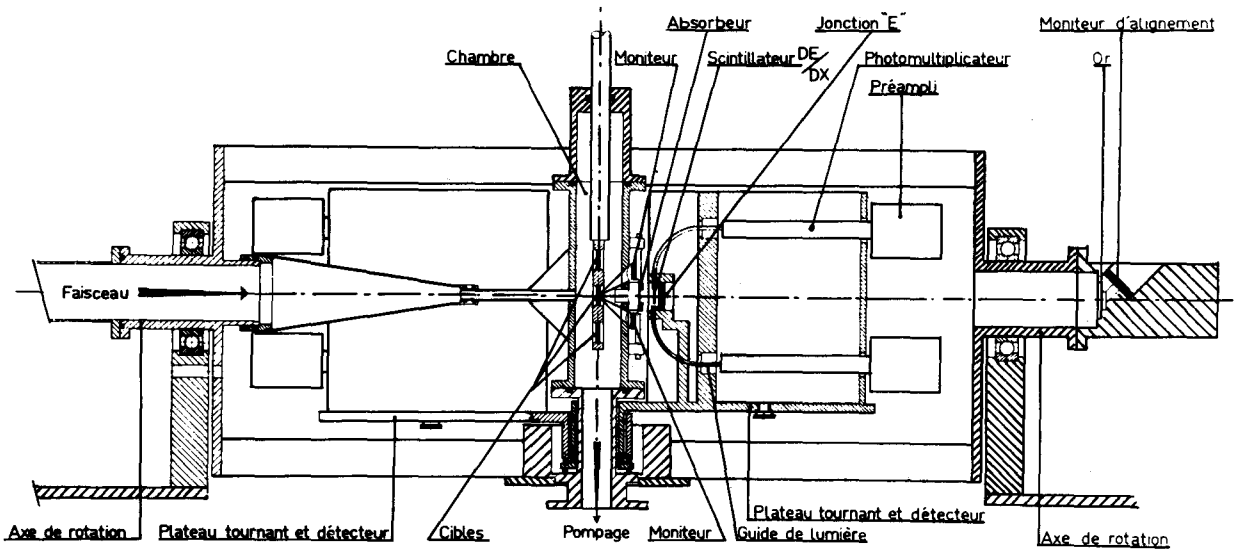

Fig. 4 Chamber for polarized deuterons.

without a grid. Another advantage has to do with the residual vacuum, which is so important for the proton case. Such a source can be closed and made a vacuum pump in itself by using titanium cathodes. The vacuum in the ionization region would then depend only on the molecules entering through the openings, which are very small except for the entrance and exit of the atomic beam. For these, tubes can be used which, if necessary, can be cooled to liquid nitrogen temperature. It remains to be seen if this procedure can be adequate for reducing the residual pressure to low enough values.

Measurements of the polarization of the beam

Experiments of double scattering can give the same tensor parameters as those obtained with a tensor polarized beam. It is a possibility. The same statement is not valid for the vector polarization case. Before data become available one has to estimate the measured efficiencies and measured residual background, assuming no depolarization effects, especially during acceleration. In our case, the estimated polarization for deuterons is 55 ± 5% (the theoretical maximum is 66%); and the sign can be changed at will.

Experiments with 22 MeV Polarized Deuterons

The final beam intensity on the targets is about 2×10^8 over a spot 1 x 4 mm. To provide large counting rates multi-angle detection is used, the solid angles being as large as compatible with either available detectors or useful angular resolution.

The chamber (Fig. 4) has a diameter of 60 mm and the detectors are placed in the air at a distance of 60 mm from the center. Absorbers and anti-scattering baffles are placed between the chamber window and the detectors.

The spin-flip procedure (±2/3 maximum polarization) makes it possible to use only one set of counters, thus avoiding any geometric effect. The detectors (Fig. 5) are four 1 mm thick lithium-drifted silicon squares. Each is divided in two by plastic scintillators (1 mm x 2 mm x 10 mm). The corresponding light is piped by 4 mm dia. lucite rods. The angular resolution is about 3°. The total energy resolution depends on the target thickness and on the particles detected, but is typically of the order of 2%.

A 4096 channel analyzer is used. For each of the 8 angles, spectra are directed towards different parts of the analyzer according to the spin orientation. Observed asymmetries are more exactly the difference between the number of counts for spin up and spin down divided by the sum.

The results for elastic scattering of vector polarized deuterons is shown in Fig. 6. The measurements were taken at an early stage where the polarization was low, i.e. most probably 30-35%. Analysis with a potential model including spin-orbit and tensor interactions is under way by Raynal[7].

The results for $C^{12}(d,p)\,C^{13}$ (ground state) are shown on Fig. 7. In that

experiment, beam polarization was 55 ± 5%. The curves illustrate that cyclotrons are convenient for experiments using polarized sources.

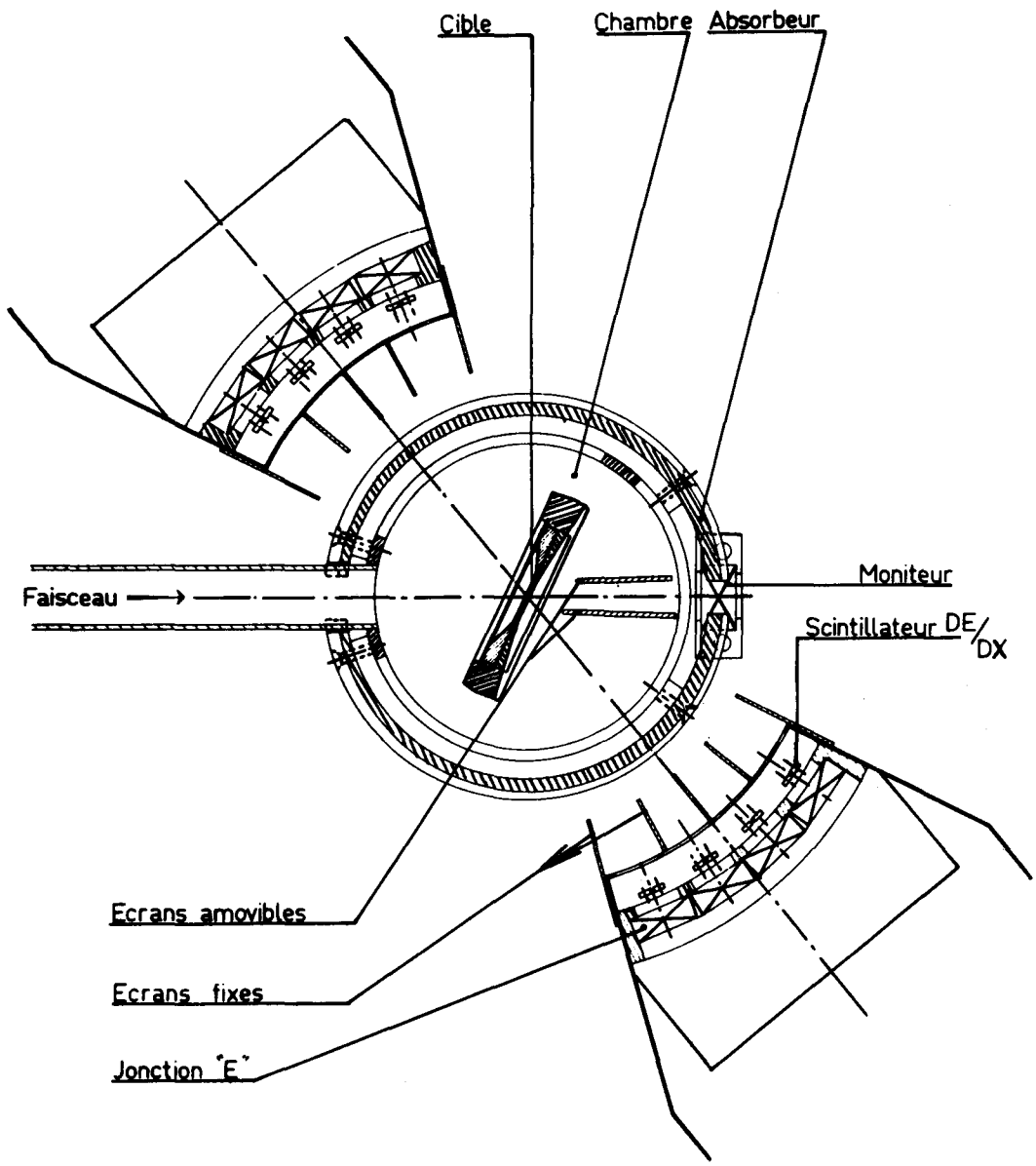

Fig. 5 Detector assembly.

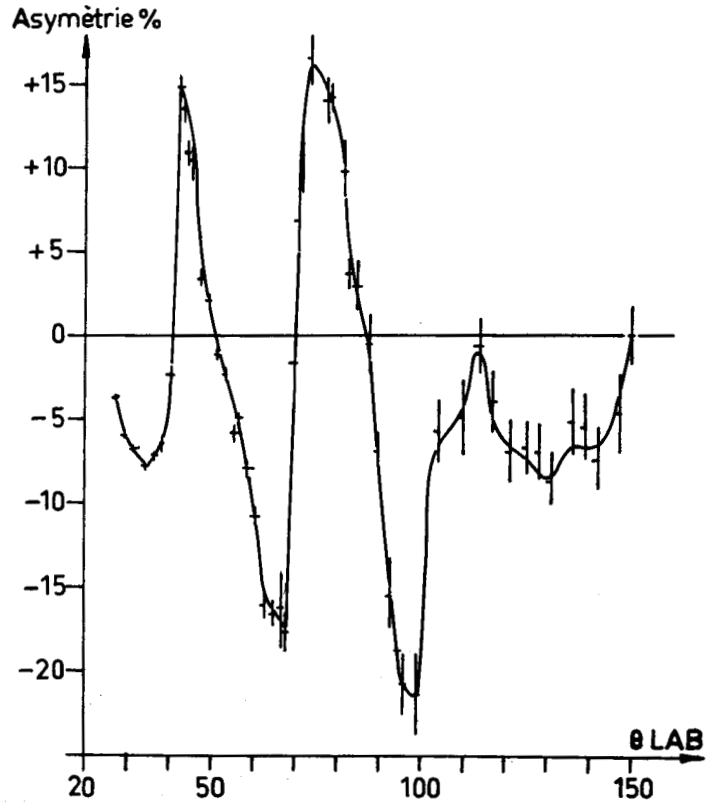

Fig. 6 Asymmetry in scattering from $Ca^{40}(d,d)Ca^{40}$.

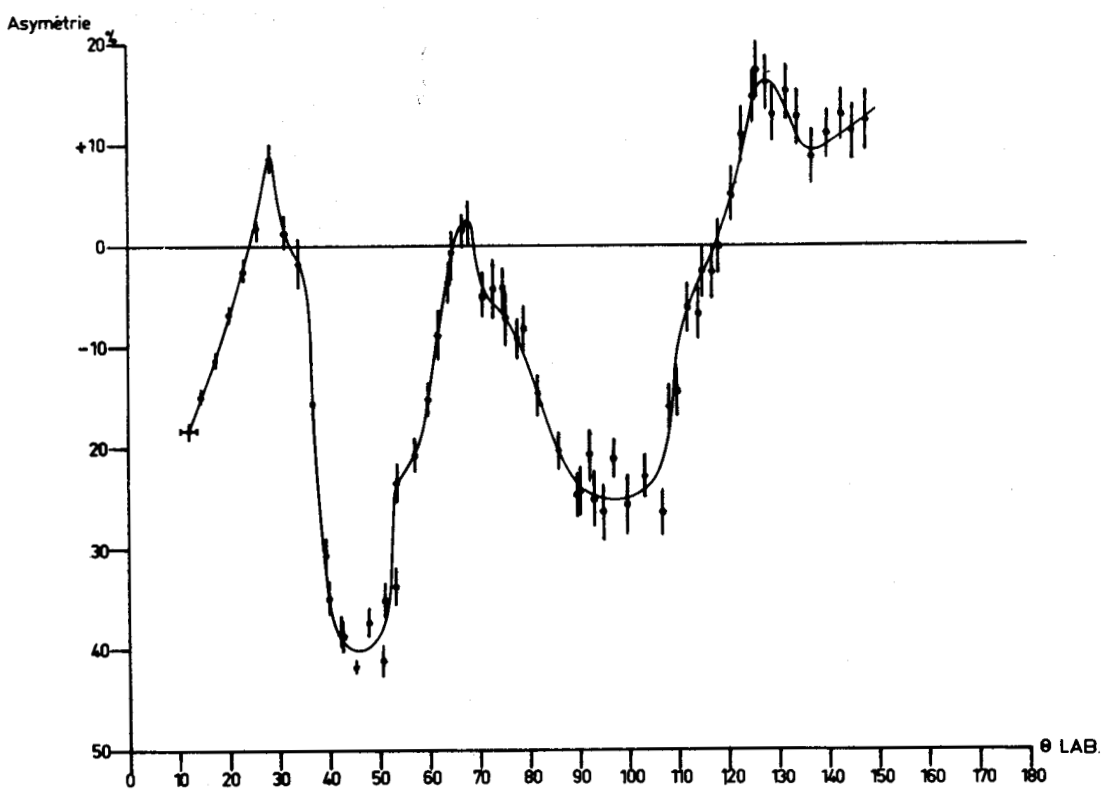

Fig. 7 Asymmetry in scattering from $C^{12}(d,p)C^{13}$ (ground state).

References

1. R. Fleischman, Nucl. Instr. and Meth. 11, 112 (1961); see also, Proceedings Basel Symposium (1960), Helv. Phys. Acta.
2. R. Keller, CERN reports 3141/j and 60-2, Basel Symposium 1960, Helv. Phys. Acta p 48; see also paper III/6.
3. Basel Symposium 1960.
4. D. Garreta et al., Nucl. Instr. and Meth. 17, 123 (1962).
5. A. Abragam and J.M. Winter, Phys. Rev. Letters 1, 375 (1958), Comptes Rendus Ac. Sciences 255, 6, p 1099 (1962).
6. VW. Hughes et al., Proc. Basel Symposium 1960, Helv. Phys. Acta p 89.
7. See e.g. J. Raynal : to be published.
8. J.C. Helmer and R.L. Jepsen, Proc. IRE 49, 1920 (1961).

DISCUSSION

RICHARDSON : In the region where you expect to dissociate these neutrals, presumably there is also a possibility of detachment going on. Have you looked for these negative ions at all?

THIRION : No.