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A POLARIZED PROTON TARGET FOR NIMROD

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(Presented by A.J. Egginton)

1. INTRODUCTION

This paper describes briefly the main characteristics of a polarized proton target built at the Rutherford Laboratory for high energy physics experiments with Nimrod. The target has been used by the resident Counter Group at the Laboratory in a study of πp scattering to determine the parities of the $N^*_{1/2}$ (1688) and $N^*_{3/2}$ (1920) isobars (1).

The target is based on the same physical method as was used by Abragam, Borghini et al. (2) in the first polarized target incorporated in a nuclear physics experiment, and by Jefferies and the Chamberlain group in the Berkeley target (3): namely, the dynamic polarization by the solid effect of the protons in the hydrogen atoms (the 'free' protons) of the water of crystallization in single crystals of lanthanum magnesium nitrate $La_2 Mg_3 (NO_3)_{12} \cdot 24\, H_2O$,' LMN ' containing a dilute paramagnetic impurity.

Although only about 3% of the nucleons in LMN are free protons, in this experiment it was possible to distinguish between scattering from free and bound protons by the kinematics of the scattering process (1).

2. THE TARGET

The target consists basically of four single crystals of LMN tied together to form a cube of side 2.5 cm. Each crystal was grown* (from a seed) to the required thickness of about 6 mm over a period of several months by gradually lowering the temperature of a solution of LMN in which the paramagnetic impurity was introduced by replacing $^1/_2$ of the La atoms by Nd^{144}. The crystals were then each cut to the dimensions 25 mm × 25 mm × about 6 mm, one long side being parallel to one of the natural hexagonal sides of the crystal so that when mounted together to form the final target cube, all the crystals had the same crystallographic orientation (to within about $^1/_2{}^0$).

This crystal block is mounted in a microwave cavity of copper (Fig. 1), similar to that used at

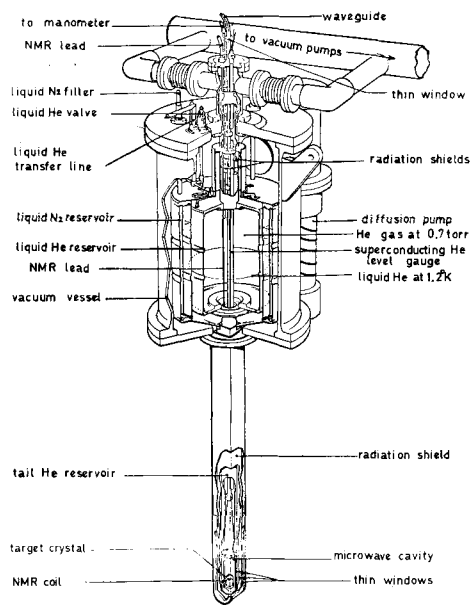


Fig. 1 - The cryostat.

* By J. C. H. Waldron, AERE, Harwell.

Berkeley, which is pierced with some small holes to allow entry of liquid helium from the tail of a conventional reservoir of capacity about 24 litres. The temperature of the liquid is reduced by mechanical pumps of capacity 500 litres/sec. The heat leak to the helium, in the absence of microwaves, is about 0,25 watts. The initial cooling of the crystal from 300 °K to 77 °K was always carried out very slowly (~ 10 hours) to avoid differential contractions within the crystal which could result in substantial increases in its thermal conductivity (4).

The cryostat (Fig. 1) is provided with thin windows to allow entry of the incident beam, and exit of the scattered mesons and recoil protons over an unobstructed angle of 315° in a vertical plane and ± 10° in a horizontal direction. The window in the main vacuum tail il of 0.25 mm stainless steel; that in the radiation shield is of copper, thickness 0.05 mm. The tail of the helium reservoir is a cylinder with an integral semi-spherical end, electroformed of copper of thickness 0.12 mm. The cavity is also of copper, thickness 0.05 mm.

The cryostat is mounted in the 10 cm gap between the poles of an electromagnet (Fig. 2) which provides a horizontal field of 18.2 kG with a uniformity of ± 1 G over the crystal volume and less than ± ½ G in time. The magnet power supply is stabilized using series transistors and consumes about 35 kW. The diameter of the pole pieces is 46 cm and of the coils 122 cm.

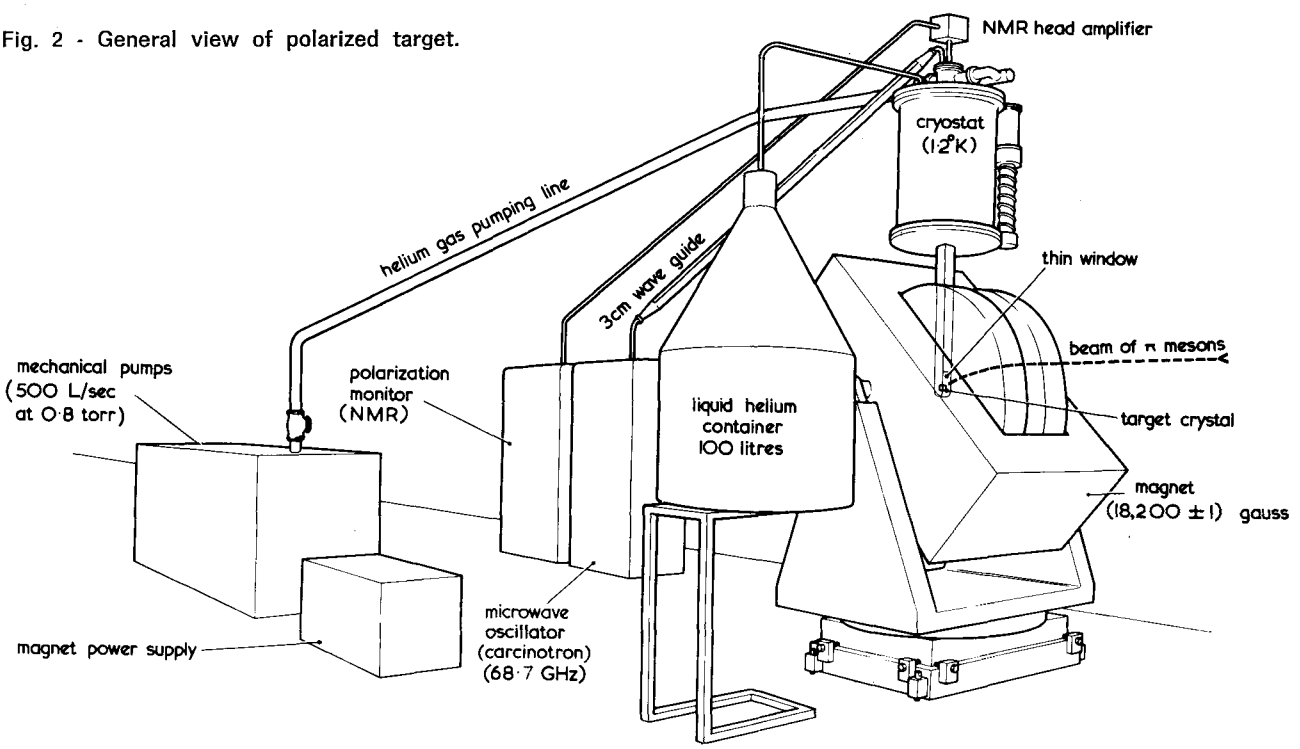
The axis of the target crystals is accurately oriented perpendicular to the magnetic field in a horizontal plane. (This is quickly achieved experimentally by rotating the crystals inside the cryostat at 4.2°K to find the position for which the microwave frequency for maximum polarization is greatest). Under these conditions microwaves of frequency 68.7 GHz (wavelength about 4.4 mm) are required to polarize the protons. The microwaves are generated by a C S F carcinotron and transported by a straight, oversize (3 cm) waveguide, length 3 m, to the top of the cryostat, and thence to the cavity and crystal by 2 m of copper 8 mm guide with a short stainless steel section to act as a heat barrier. The attenuation of microwaves in the transport system between the calorimeter used to measure the absolute power and the cavity is about 6dB.

The microwave power dissipated in the liquid helium is normally about 0.75 watts. The temperature of the target is then 1.2°K giving a theoretical maximum proton polarization of 88%. During continuous operation the cryostat is refilled at intervals of about twelve hours and the daily consumption of liquid helium is 60-70 litres.

3. MEASUREMENT OF POLARIZATION

The polarization of the target was determined by observing the nuclear magnetic resonance (NMR) line of the protons in the protons in the crystal: the absolute scale was set by a nuclear

Fig. 2 - General view of polarized target.



physics method, see below. An absolute calibration (3) was also made by measuring the « unenhanced » NMR line for protons (frequency ν_p) in thermal equilibrium with the lattice and bath (temperature T) for which the polarization, given by $\tanh(h\nu_p/2kT)$, is easily calculated.

The principle of the NMR method is as follows. The crystal is coupled to a coil, inductance L, which forms part of a parallel resonant circuit (the NMR ' probe ') tuned to the centre frequency of the proton line. To first order, the effect of the crystal is equivaleht to adding a frequency-dependent resistance $r(\nu)$ in series with L and with the series resistance R of the tuned circuit itself. Since in practice the electrical width of the LC circuit is considerably greater than that of the proton line, the impedance Z of the circuit near resonance at frequency ν may be written:

$$Z = (2\pi\nu L)^2/(R+r)$$

If the value of the main magnetic field is changed somewat so that the protons are no longer in resonance at the probe frequency, Z takes the value $Z_o = (2\pi\nu L)^2/R$.

Now to first order the polarization P is proportional to $\int r d\nu$. Using the above expressions for Z and Z_o, and the fact that R is constant, this integral may be written:

$$P = \text{const.} \int d\nu\, (Z_o - Z)/Z \qquad [1]$$

Hence the relative value of the polarization can be deduced from measurements of the probe

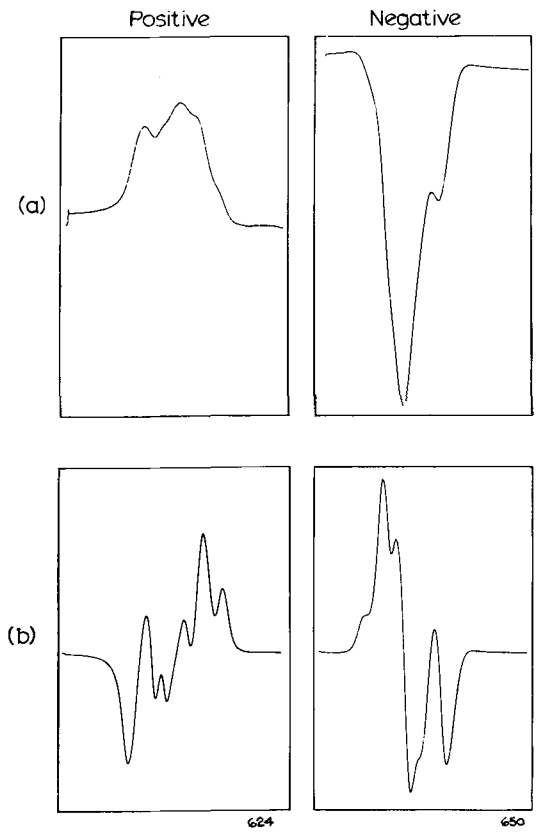


Fig. 3 - Typical proton line shapes for positive and negative polarizations: a) trace of probe impedance « impedance increasing downwards, zero not shown); b) « differential signal ».

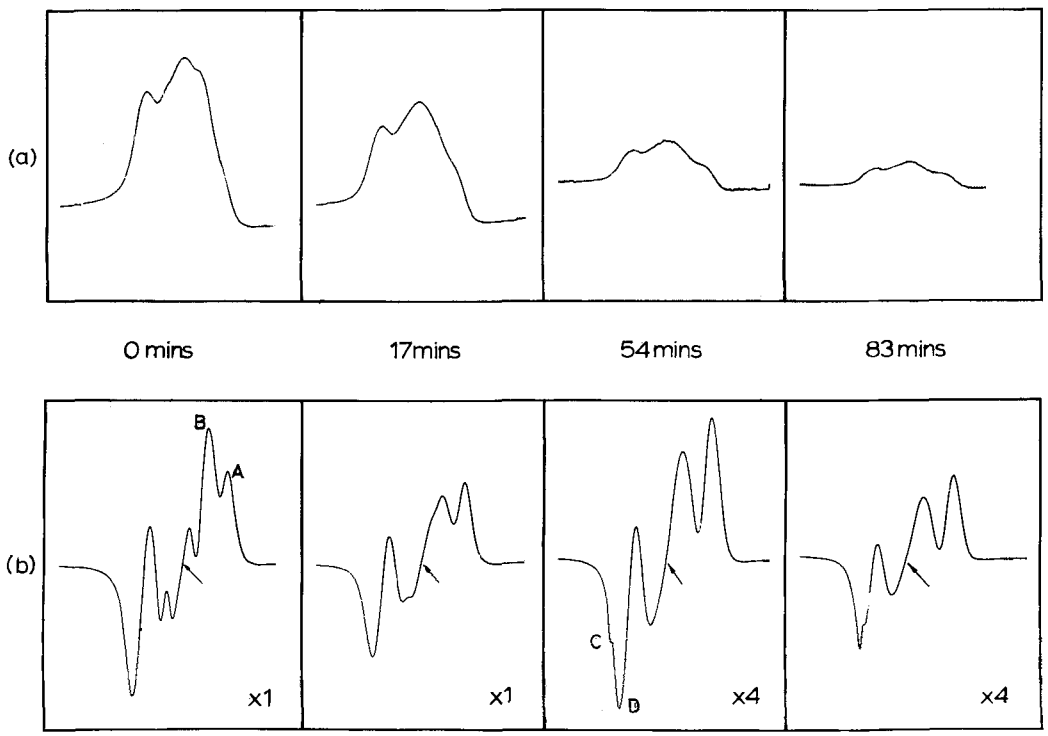


Fig. 4 - Decay of polarization, microwaves off at time zero: a) impedance trace; b) « differential signal ». Arrows show « cross-over frequency ».

impedance as a function of frequency. It is impractical to calculate the value of the constant.

Practical details if the NMR system are now given. The probe coil has three turns of copper foil of thickness 0.05 mm, one turn being placed between each crystal and its neighbour. The coil, together with small PTFE spacers, thickness 0.05 mm, allows circulation of liquid helium between the crystals to improve cooling efficiency. The capacitative element, placed outside the cryostat and connected to the coil by a coaxial cable, is adjusted to tune the probe to 77.3 MHz, the proton frequency at 18.2 kG.

The probe impedance is measured by observing the voltage across the probe when an r.f. current of constant amplitude is passed through it from an oscillator in series with a high resistance. A linear ramp generator is used to sweep the oscillator frequency through the proton line, covering a total range of about 200 kHz every 5 minutes. The voltage across the probe is amplified, rectified and displayed on a chart recorder. The polarization is deduced from this trace using equation [1].

Typical chart recorder traces of impedance for high positive and negative polarizations are shown in Fig. 3a. In these examples the impedance varies across the line by at least a factor of two.

The NMR coil used was very closed coupled to the crystal. It was found that when the complete probe had a high Q (~ 50), a relaxation instability occurred at high negative (but not at positive) polarizations: the polarization would slowly rise to a very high apparent value, then drop quite suddenly by an order of magnitude. This process repeated itself with a period, of order 3-30 minutes, roughly proportional to the microwave power applied. The effect, which was cured only by reducing considerably the Q of the probe, may be due to a type of maser action at 77.3 MHz in which energy stored in the protons lying against the main magnetic field is suddenly released. This effect is being investigated further.

With the method and apparatus described above, the noise level is too high to observe the very weak " unenhanced " polarization of the protons when in thermal equilibrium. Such measurements have been made by frequency-modulating the oscillator (at 177.5 Hz to a depth of a few kHz) and using a phase sensitive detector. The output of this detector, displayed on a second chart recorder when the centre frequency of the oscillator is slowly swept as before, is roughly proportional to the differential of the proton line, and is called the « differential signal », y. The polarization is then given by the double integral (5).

$$P = \text{const} \int d\nu \int (y/Z^2)\, d\nu \qquad [2]$$

where Z, the probe impedance, is obtained from the trace on the first chart recorder described above. The constant is determined experimentally by evaluating this expression fo ran unenhanced line, for which the polarization is known, thus enabling the NMR system to be calibrated absolutely.

At high values of polarization the « differential signal » trace is rich with detail, as can be seen in Figs. 3b and 4b. (The FM depth was chosen for good resolution). Fig. 4 shows how the line shapes change with time after the microwaves are switched off. Note how the relative heights of the peaks marked A and B actually reverse; note also the peaks C and D at lower polarizations. The ratio of the peak heights of A and B gives a useful indication of the magnitude of the polarization.

From analysis of data similar to that shown in Fig. 4, the proton relaxation time for the target cube was found to be about 30 minutes at 1.2°K.

4. ABSOLUTE CALIBRATION

As describes above, the NMR system can be calibrated by observing the unenhanced proton line. Unfortunately, however, this method has several practical disadvantages. Firstly, owing to the long proton relaxation time at 1.2°K the protons take many hours to approach thermal equilibrium; this could be wasteful of accelerator time. (Calibration could be done at higher temperatures, where the relaxation times are much faster, but the probe characteristics may change with temperature). Secondly, difficulties arise due to the dynamic range of many hundreds between unenhanced and enhanced signals; the effect of the reactive component in the probe impedance at high polarizations, neglected in equation [2]; and the double integrations (including base-line fitting) which are required for each measurement due to the variation of line shape with polarization. Finally, and more fundamentally, the polarization determined by the NMR coil is weighted by its r.f. field distribution: thus, if the crystal is not uniformly polarized, the coil will give an average polarization which is different from that seen by the meson beam.

Fortunately in this work it was comparatively easy to calibrate the target by carrying out a proton-proton scattering experiment at energies (~ 725 MeV) for which the polarization of the scattering process had previously been measured accurately without the use of a polarized target, by double scattering experiments (5). The same Nimrod target, beam line and counter array were used, and, as the proton intensity was high, calibration could be carried out in about one hour.

This was the main method used to set the absolute scale of polarization and pp runs were usually made roughly every two days. Only the mean value of the magnitudes of the positive and negative polarizations were measured since this was the only information required for the πp experiment.

Details of the pp scattering calibration will be published elsewhere.

Calibration using the unenhanced line was also carried out occasionally for comparison (see below).

5. OPERATION OF THE TARGET

During πp data-taking the target was operated almost continuously, 24 hours a day, for 3 periods of about 10 days each. Measurements at one meson momentum (one « run ») took several hours and during this time the relative value of the polarization varied bu pu to 5%. It was necessary to monitor the proton line continuously so that the polarization could be kept as high as possible. Due to the long proton relaxation time, peaking the polarization was not easy. It was most important to have a highly stable magnetic field and microwave frequency. Often it was convenient to establish operating fields and frequencies at 4.2°K where all the processes are fast, before pumping to lower temperatures. Reversal of the sign of the polarization took 15-30 minutes.

An average value of polarization was required for each « run », the average being taken with respect to the rate of arrival of mesons. As equipment set up to integrate the proton line automatically was not working reliably during the experiment, the integrations had to be made by hand. To avoid carrying out an excessive number of such integrations, use was made of a reliable graphical relationship found to exist between the " corrected peak height " of the proton line, $(Z_o - Z_{peak})/Z_{peak}$, and the area given by equation [11]. Thus in general, peak heights (and Z_o) were measured and the polarization deduced using the graph.

These relative values of polarization were checked by double integration of the differentiated line, and from the peak height ratios of the differentiated line (see above). The latter proved most useful as the results are independent of many characteristics of the NMR system, including FM depth, stability of oscillator, amplifiers and attenuators, and of phase sensitive detector adjustment. The method is affected, however, by any change in crystal orientation.

The mean relative polarization varied by ± 10% from one run to another. The absolute polarization, determined by pp scattering, had an overall average value for the whole set of experiments of (57 ± 4)%; the maximum observed value was 63%.

Using measurements of the unenhanced proton line to calibrate the system, overall average positive and negative polarizations of 55% and 45%, respectively, were calculated on the basis of the approximate theory expressed in equation [2]. Considering the difficulties and errors in this method as mentioned in the last section, the mean polarization for positive and negative direction, 50%, is probably not in conflict with the more reliable figure determined by pp scattering.

We have observed a shift with polarization of the main peak of the NMR line (or rather of the corresponding " cross-over " frequency of the differentiated signal market with arrows in Fig. 4). This may be interpreted as a change in the internal field seen by the protons (cf. Abragam (7)), although here the effect may be due simply to a change in shape of the line. The shift, whatever its cause (this is currently being investigated), provides a useful indication of the polarization.

No effects due to radiation damage have been observed during these experiments, nor were any effects expected since the total number of fast particles passing through the target ($< 10^{11}$) was comparatively small.

6. A NEW TARGET

A new polarized target is at present being assembled for use in Kp and further πp scattering experiments. The crystals, of LMN, are in the form of a cylinder, diameter 25 mm and length 75 mm. The beam will pass along the axis of the cylinder, which is mounted horizontally in a vertical magnetic field. The cylinder will be closely surrounded by particle counters to determine the position in the target at wich each scattering event occurs. The cryostat will operate continuously, directly from a 100 litre Dewar.

Acknowledgements

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PERFORMANCE OF A POLARIZED PROTON TARGET FOR HIGH ENERGY PHYSICS EXPERIMENTS AT ARGONNE *

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(Presented by R.L. Martin)

INTRODUCTION

A polarized proton target of LMN (~ 1% Nd) has been constructed for use in high energy physics scattering experiments. The target has been used for the measurement of polarization in the π - N elastic scattering at around 2 GeV/c with the Argonne ZGS (1).

A high degree of nuclear polarization can be achieved in paramagnetically dilute crystals by saturating the so-called forbidden transition (2). In this method polarization is achieved by inducing transitions which simultaneously flip the nuclear and electron spins. By the use of this method polarizations as high as 70% have been achieved in crystals of $La_2Mg_3(NO_3)_{12}$. 24 H_2O doped with about 1% Nd.

DESCRIPTION

The blok diagrams for the polarized proton target are shown in Figs. 1 and 2. It consists basically of a Hall-probe field regulated electromagnet with a 3.5 inch gap to supply a uniform 18.5 kOe field, a frequency-stabilized microwave system with sufficient output power to saturate the « forbidden transitions », a nuclear magnetic resonance (NMR) detection system to measure the polarization, and a cryogenic and pumping system to achieve temperatures as low as 1° K.

Th microwave system, Fig. 1, consists of: 1) a backward-wave oscillator, Carcinotron, whic has an operating frequency of around 70 GHz and maximum CW output power of 12 watts; 2) a Y-circulator and matched load to provide 20 db of isolation of the Carcinotron from the rest of microwave circuit; 3) a 0-40 db attenuator; 4) a dual mode 20 db directional coupler, which is used to monitor the power. The reflected power is monitored by a matched crystal detector; this arm also contains a frequency meter which is used to measure the frequency and also provides a signal to stabilize the operating frequency of the Carcinotron; 5) an E-H tuner to match the cavity to output circuit; 6) a multi-mode microwave cavity made out of silver plated 0.13 mm phosphor bronze sheet, which contains the target crystals (see Figs. 3 and 7) a feedback frequency stabilizing system.

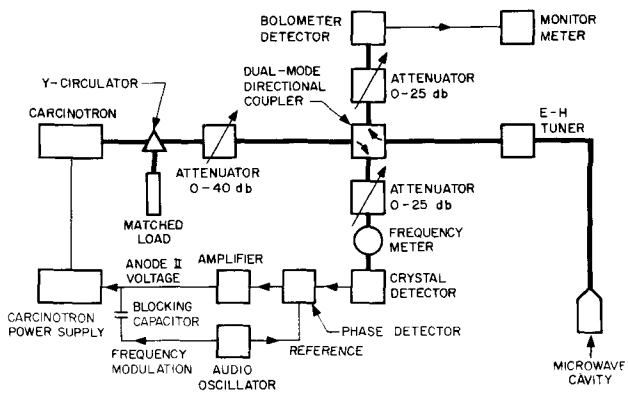

Fig. 1 - Microwave system

* Work performed under the auspices of the U.S. Atomic Energy Commission.