Polarized Targets in the BC & AD Eras

Chris Keith
JLab Target Group

Polarized Targets in the BC & AD Eras

(Before Crabb & After Don)

Chris Keith
JLab Target Group

Outline of my talk*

1. The earliest polarized targets
2. A better way to polarize
3. Better materials, instruments, and theories
4. Ammonia takes over
5. The Don Crabb type target

*In the interest of time, several important results and individuals will, regrettably, be overlooked. My apologies.

1950s: The first polarized targets used with particle beams were built in *Oak Ridge*

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length and should be submitted in duplicate.

"Brute Force" Polarization of In^{115} Nuclei; Angular Momentum of 1.458-ev Neutron Resonance

J. W. T. Dabbs, L. D. Roberts, and S. Bernstein
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received March 25, 1955)

GORTER[1] and Kürti and Simon[2] have suggested the possibility of polarizing nuclei by the direct application of a large external magnetic field to the nuclear spin system at a very low temperature. The magnitude of the polarization f_N has been given by Simon[3] and Rose[4] as

$$f_N = \frac{1}{3}\frac{I+1}{I}\frac{\mu H}{kT} \quad (1)$$

for the case $\mu H \ll kT$, where I is the nuclear spin quantum number, μ is the nuclear magnetic moment, k is the Boltzmann constant, H is the applied magnetic field, and T is the absolute temperature. Even in the most favorable cases, values of $H/T \sim 10^5$ gauss/deg are necessary to obtain polarizations of ~1 percent. Thus, to achieve useful polarizations by this method, it is necessary to use the method of adiabatic demagnetization to obtain sufficiently large H/T values. Rose[4] has also pointed out that the absorption of polarized s neutrons by polarized nuclei forms a basis for determining the angular momentum J of levels of the compound nucleus. When the absorption is due to a single level (as near a resonance), the value of J for this level is obtained from the *direction* of the change in absorption cross section with changes in relative spin orientation. The expressions for the neutron cross section σ are

$$\sigma = \sigma_0[1 + f_n f_N I/(I+1)] \quad \text{if} \quad J = I + \tfrac{1}{2}, \quad (2a)$$

and

$$\sigma = \sigma_0(1 - f_n f_N) \quad \text{if} \quad J = I - \tfrac{1}{2}. \quad (2b)$$

Here σ_0 is the cross section in the absence of polarization, and f_n is the neutron polarization. In such an experiment the fractional change in the transmitted neutron intensity, $\Delta C/\bar{C}$, is given by

$$\Delta C/\bar{C} = 2 \tanh(Nt\sigma_0 f_n f_N f_I) \quad (3)$$

for reversal of the relative spin orientations. In (3), $Nt\sigma_0$ is the macroscopic absorption cross section of the sample, and f_I is $I/(I+1)$ if $J = I + \frac{1}{2}$ and unity if $J = I - \frac{1}{2}$. For small polarizations, $\Delta C/\bar{C}$ is proportional to $Nt\sigma_0$ as well as to the product of the two polarizations $f_n f_N$. It is therefore advantageous to make the nuclear sample as thick as possible consistent with intensity requirements.

Experiments have been carried out on the polarization of In^{115} nuclei. Indium was selected because of its large nuclear magnetic moment, and because the thermal neutron cross section is almost entirely due to the 1.458-ev resonance.[5] The metal was used to obtain a short nuclear spin-lattice relaxation time[6] and a high thermal conductivity.[7] The metal, in the form of 20 thin plates 0.025×1.5×3.5 cm, was thermally connected to a cooling salt some 12 cm away by means of silver wires. Each indium plate was soldered to the upper end of a wire and the coolant salt was crystallized around the lower ends of the wires to provide thermal contact to the salt. This unit was in turn mounted on rigid insulators in a silver cage which was cooled by another demagnetized salt and suspended on nylon strings. Both salt samples were $Fe(NH_4)(SO_4)_2 \cdot 12H_2O$. This assembly was mounted in a cryostat described previously.[8] The design of the sample assembly was based on minimization of eddy current heating and reduction of the possibility of heating due to vibration. The salts were cooled by adiabatic demagnetization from 0.99°K and 16 400 gauss to a final temperature near 0.035°K.[9] The sample assembly was then slowly lowered[8] to place the cooling salts within a magnetic shield and to bring the In plates into the gap of the Weiss magnet in such a manner that the plane of the plates was parallel to the field direction. The magnet was then turned on slowly to 11 150 gauss. These operations were performed slowly to reduce heating; in particular the field was raised very slowly near the In superconducting threshold value.

The source of neutrons was a beam from the ORNL graphite reactor. The nuclear sample was bombarded with polarized thermal neutrons obtained by reflecting this beam from the 220 planes of a magnetized Fe_3O_4 crystal.[10] The energy selected was 0.075 ev in first order, and a subsequent reflection from the 111 planes of a Cu crystal served to reduce the second-order content of the beam to ~1.6 percent.

The relative spin orientation of the neutrons and nuclei could be made either parallel or antiparallel as follows: By adding small magnetic fields produced by Helmholtz type coils to the stray fields already present from the Fe_3O_4 magnet and the low-temperature Weiss magnet, (1) a smooth rotation of a relatively strong field (~30 gauss) or (2) an abrupt reversal of a weak field was produced.[11] In the first case the neutron spins were polarized 87 percent antiparallel to the nuclear spins, and in the second case the polarization was 79

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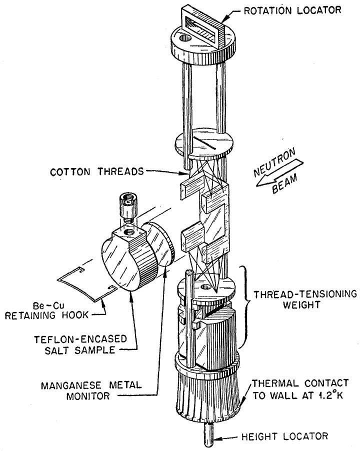


FIG. 2. Sample and monitor assembly.

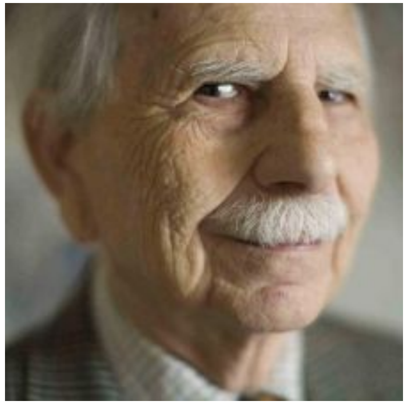
S. Berstein et al., Phys Rev. 94 (1954) 1243

These experiments measured the transmission or capture of polarized neutrons with polarized nuclei such as ^{55}Mn, ^{149}Sm, ^{115}In etc

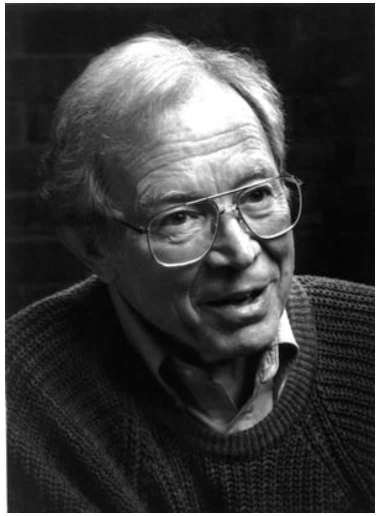
The samples were brute-forced polarized at temperatures ~0.04 K, either in external fields of 1 – 2 T or using the large hyperfine fields of the sample nuclei

1960s: Abragam (Saclay) and Jeffries (Berkeley) invent Dynamic Nuclear Polarization, a better way to polarize nuclei.

Both gentlemen were immediately recruited to build polarized proton targets at their respective institutions.

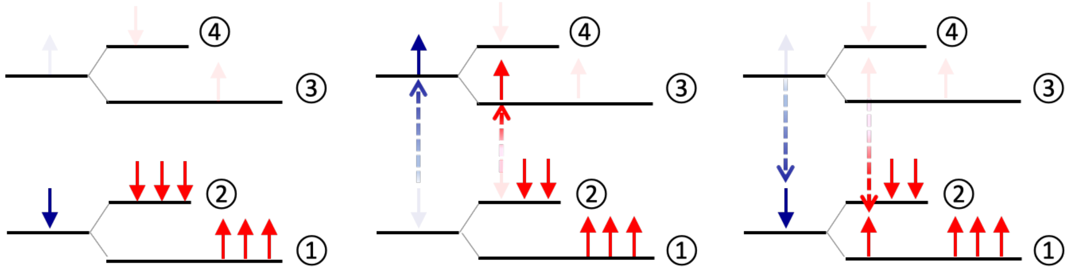


Anatole Abragam, 1914 -2011



Carson Jeffries, 1922 - 1995

Dynamic polarization is the transfer of polarization from unpaired electron spins in the sample to nuclear spins.



At low T and high B: only states ① & ② are populated. Electrons are polarized. Protons are not.

Use RF to drive transition ②→③

Both spins flip.

Electron flips back to its equilibrium state very quickly. *Proton stays in its new spin state.*

➔ Repeated spin flips lead to *Positive Proton Polarization*

1960s: Earliest DNP target material was LMN polarized at ~1.5 K and 1 T

$La_2Mg_3(NO_3)_{12}\bullet 24H_2O$ doped w/ Nd^+ or Ce^{3+} ions

→ low concentration of polarized protons (~3%)

→ badly affected by radiation damage

The Berkeley team (LtoR): Owen Chamberlain, Gil Shapiro, Claude Schultz, & Carson Jefferies

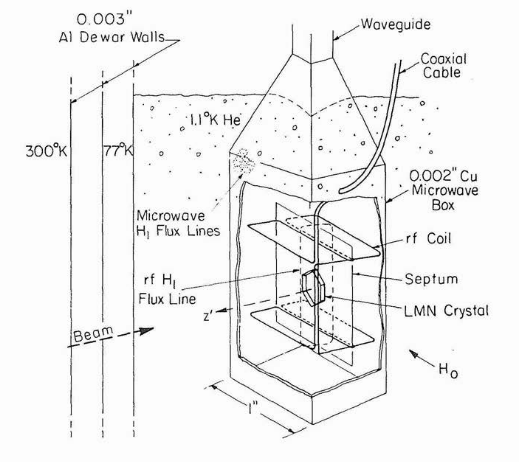


FIG. 7. DETAILS OF THE FIRST LARGE POLARIZED TARGET (Berkeley), reference 22. Only one of four large Nd:LMN crystals is shown.

O. Chamberlain et al., Phys. Lett. 7 (1963) 293.

DIFFUSION DE PROTONS POLARISES DE 20 MeV PAR UNE CIBLE DE PROTONS POLARISES ET MESURE PRELIMINAIRE DU PARAMETRE C_{nn}

A. ABRAGAM, M. BORGHINI, P. CATILLON, J. COUSTHAM, P. ROUBEAU et J. THIRION
Centre d'Etudes Nucléaires de Saclay, France

Reçu le 15 Octobre 1962

L'étude expérimentale de la réaction proton-proton nécessite la mesure d'au moins un des paramètres de corrélation de spin. Jusqu'ici cette mesure était tentée par une expérience de triple diffusion. Cette méthode a été appliquée à quelques centaines de MeV 1) mais se révèle trop délicate à moyenne énergie. Il est pourtant possible d'atteindre ces paramètres par diffusion de protons polarisés par une cible de protons polarisés 2). Une telle expérience a été réalisée au Cyclotron de Saclay pour mesurer C_{nn} à 20 MeV (lab). Le schéma de principe en est montré sur fig. 1.

Le faisceau de particules α de 44 MeV (2 μA) tombe sur une cible de 0.1 mm de polyéthylène. Cette cible est un grand disque tournant dans l'air

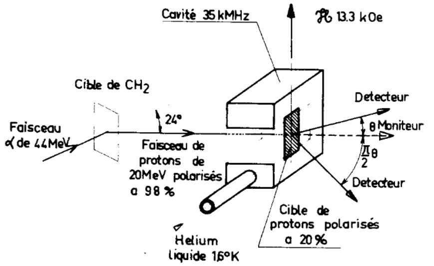


Fig. 1. Schéma général de l'expérience.

afin d'éviter un échauffement local trop important. Les protons de recul de la réaction sont focalisés par un ensemble de deux paires de quadrupôles dont l'axe horizontal commun fait un angle de 24° avec la direction du faisceau initial de particules α. Ce faisceau secondaire de protons a une énergie de 20 MeV, une largeur en énergie de 1.4 MeV, une densité de 1.5×10^6 protons par cm^2, une polarisation verticale de 98% ± 2% (incertitude dont une part est due à la différence entre les analyses de déphasages de la réaction p-He et les mesures expérimentales) 3).

La cible 4) polarisée verticalement est un monocristal de nitrate double de magnésium et de lanthane, $La_2Mg_3(NO_3)_{12} \cdot 24H_2O$ dans lequel 0.2% de La^{3+} a été remplacé par Ce^{3+} paramagnétique. Sa taille est 3 mm × 3 mm, son épaisseur 0.12 mm. Elle est placée près de la paroi d'une cavité de radiofréquence travaillant à 35 kMc/s. Cette cavité est maintenue à la température de 1.6°K par un système de refroidissement 5) n'utilisant que de l'hélium liquide bouillant sous pression réduite après détente dans une vanne à aiguille. Les fluctuations et la dérive de la température restent inférieures à ± 0.01°K pendant la durée de l'expérience. En plus de la cible, le faisceau ne traverse que les fenêtres en cuivre d'entrée et de sortie de la cavité, respectivement de 2.7 mg/cm^2 et 1.3 mg/cm^2 et deux écrans d'aluminium de 0.27 mg/cm^2. L'ensemble de la cavité est placé au

310

A. Abragam eta al., Phys. Lett. 2 (1962) 310

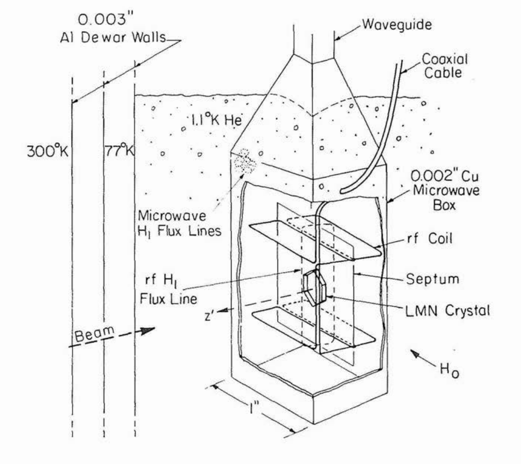
1960s: Earliest DNP target material was LMN polarized at ~1.5 K and 1 T

$La_2Mg_3(NO_3)_{12} \bullet 24H_2O$ doped w/ Nd^+ or Ce^{3+} ions

➞ low concentration of polarized protons (3-4%)

➞ badly affected by radiation damage

The Berkeley team (LtoR): Owen Chamberlain, Gil Shapiro, Claude Schultz, & Carson Jefferies



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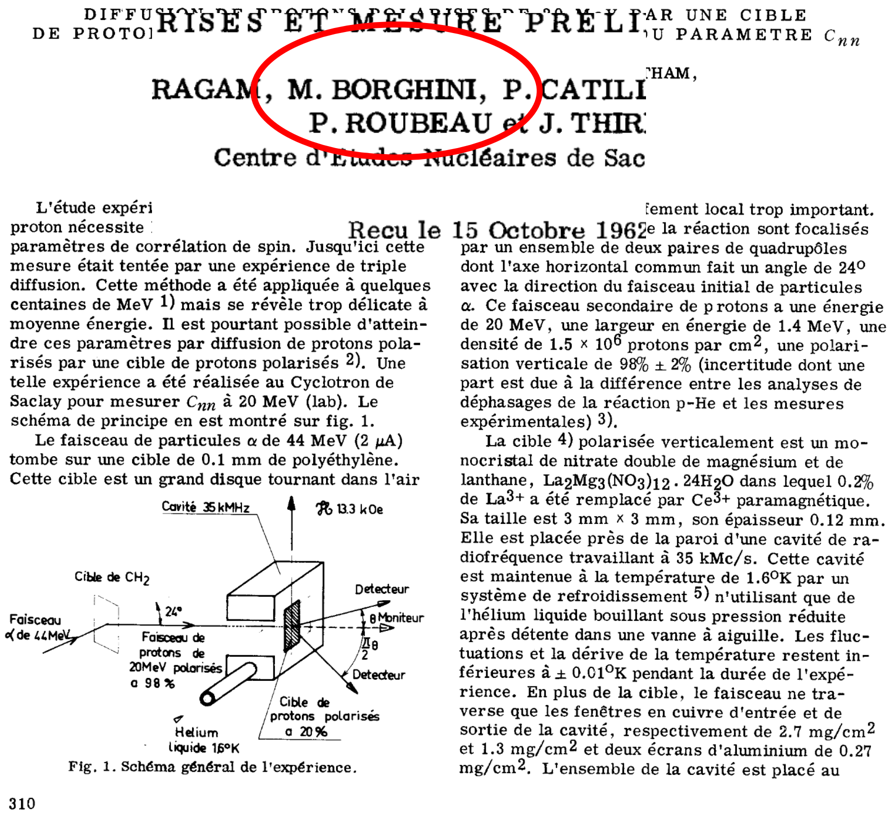

DIFFU[…]RISES ET MESURE PRELI[…]AR UNE CIBLE
DE PROTO[…]U PARAMETRE C_{nn}

RAGAM, M. BORGHINI, P. CATILI[…]HAM,
P. ROUBEAU et J. THIR[…]
Centre d'Etudes Nucléaires de Sac[…]

Recu le 15 Octobre 1962

L'étude expéri[…] proton nécessite […] paramètres de corrélation de spin. Jusqu'ici cette mesure était tentée par une expérience de triple diffusion. Cette méthode a été appliquée à quelques centaines de MeV 1) mais se révèle trop délicate à moyenne énergie. Il est pourtant possible d'atteindre ces paramètres par diffusion de protons polarisés par une cible de protons polarisés 2). Une telle expérience a été réalisée au Cyclotron de Saclay pour mesurer C_{nn} à 20 MeV (lab). Le schéma de principe en est montré sur fig. 1.

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Fig. 1. Schéma général de l'expérience.

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A. Abragam eta al., Phys. Lett. 2 (1962) 310

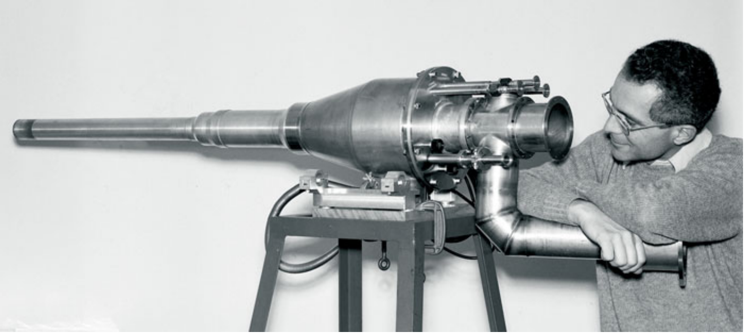
1960-70s: Better target materials & instruments, and new theoretical descriptions

At CERN, Borghini leads an effort to develop target materials of frozen hydrocarbons doped with paramagnetic radicals.

Targets are polarized at even lower temperatures, provided by Pierre Roubeau's ^4He and ^3He evaporation refrigerators. This increases the polarization to ~90% at 0.5 K and 2.5 T.

Borghini also publishes a new description of the polarization process based on quantum statistical methods and the concept of spin-temperature, first introduced by Redfield and Provotorov.

Nevertheless, radiation damage and beam heating severely limited the maximum luminosity of polarized target experiments.



Michel Borghini

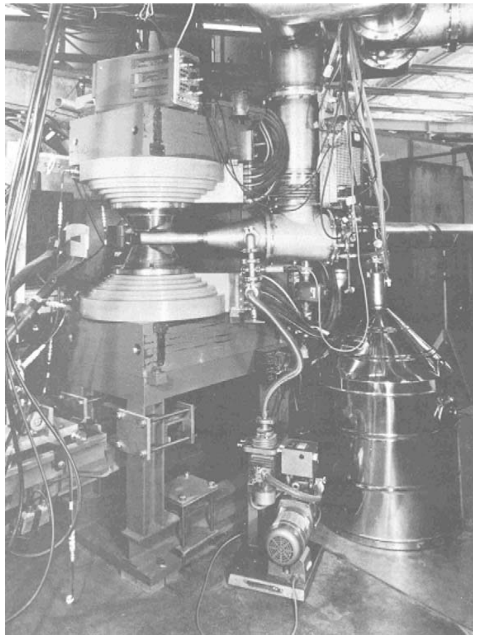
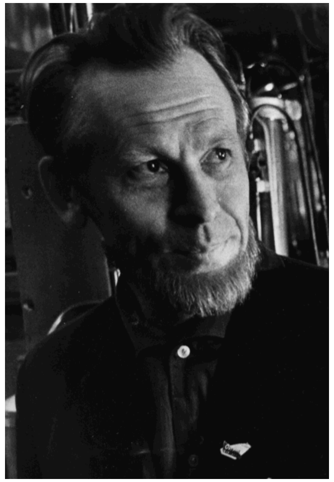


Fig. 1. A CERN polarized target.

1970s: The problem of low luminosity is (partly) solved by higher acceptance

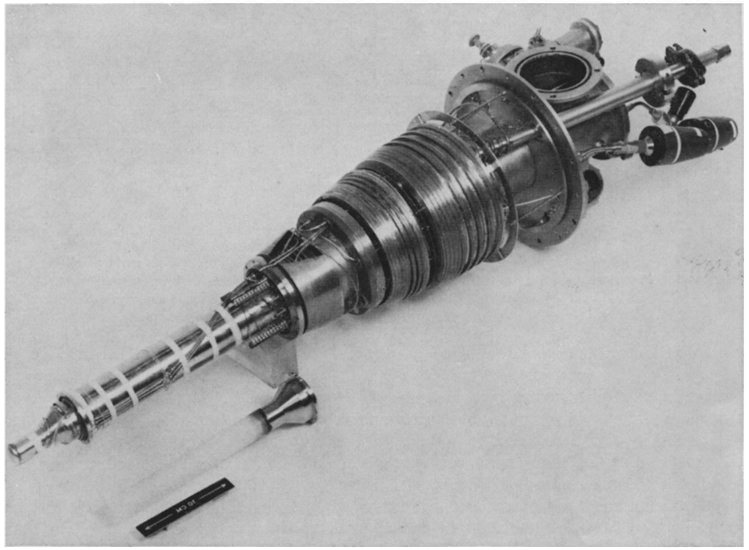
Tapio Niinikoski (CERN) and Boris Neganov (Dubna) invent the *Frozen Spin Target*

These targets operate at *millikelvin temperatures*, so beam heating limits the particle flux even further



Boris Neganov

Tapio Niinikoski



T.O. Niniikoski and F. Udo, NIM 134 (1976) 219

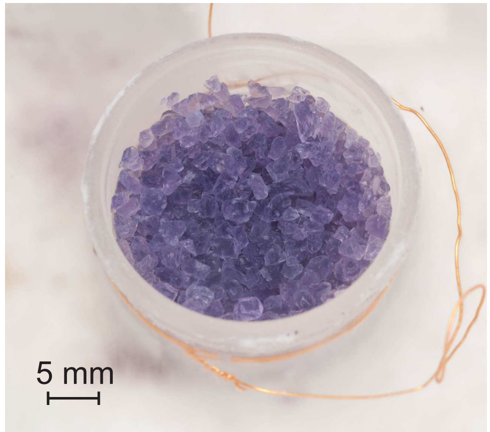
1980s: Ammonia takes over!!

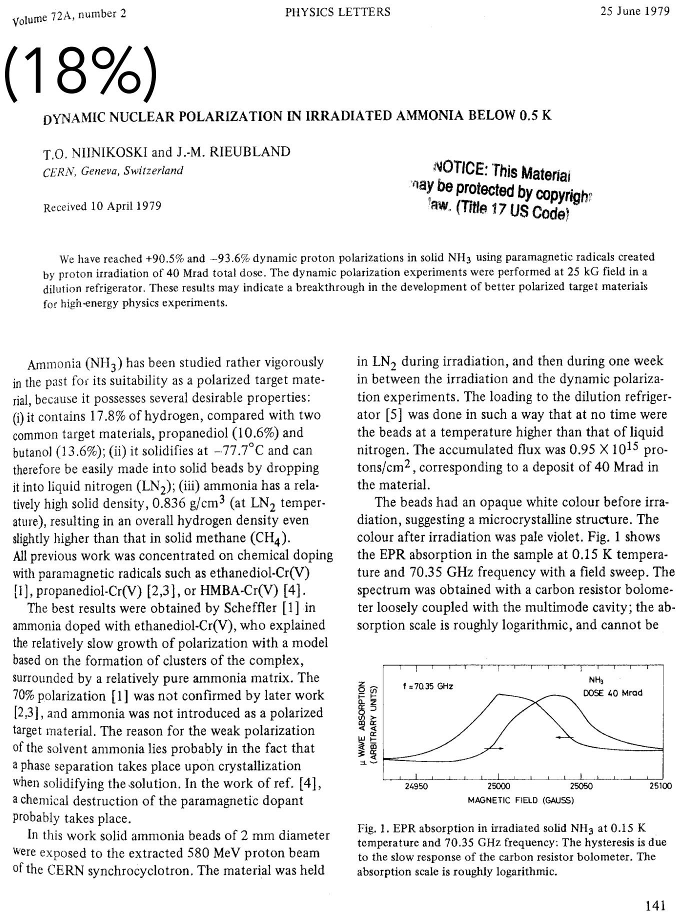
Niinikoski polarizes NH3 to >90% at 2.5 T and < 0.5 K

NH_3 has a higher concentration of polarized protons (18%)

The target sample is *irradiated* to produce the polarized electrons for DNP

"…ammonia might thus bring bring about an improvement of more than one order of magnitude in the radiation resistance of polarized targets."





Volume 72A, number 2 PHYSICS LETTERS 25 June 1979

DYNAMIC NUCLEAR POLARIZATION IN IRRADIATED AMMONIA BELOW 0.5 K

T.O. NIINIKOSKI and J.-M. RIEUBLAND
CERN, Geneva, Switzerland

Received 10 April 1979

We have reached +90.5% and −93.6% dynamic proton polarizations in solid NH_3 using paramagnetic radicals created by proton irradiation of 40 Mrad total dose. The dynamic polarization experiments were performed at 25 kG field in a dilution refrigerator. These results may indicate a breakthrough in the development of better polarized target materials for high-energy physics experiments.

Ammonia (NH_3) has been studied rather vigorously in the past for its suitability as a polarized target material, because it possesses several desirable properties: (i) it contains 17.8% of hydrogen, compared with two common target materials, propanediol (10.6%) and butanol (13.6%); (ii) it solidifies at −77.7°C and can therefore be easily made into solid beads by dropping it into liquid nitrogen (LN_2); (iii) ammonia has a relatively high solid density, 0.836 g/cm^3 (at LN_2 temperature), resulting in an overall hydrogen density even slightly higher than that in solid methane (CH_4). All previous work was concentrated on chemical doping with paramagnetic radicals such as ethanediol-Cr(V) [1], propanediol-Cr(V) [2,3], or HMBA-Cr(V) [4].

The best results were obtained by Scheffler [1] in ammonia doped with ethanediol-Cr(V), who explained the relatively slow growth of polarization with a model based on the formation of clusters of the complex, surrounded by a relatively pure ammonia matrix. The 70% polarization [1] was not confirmed by later work [2,3], and ammonia was not introduced as a polarized target material. The reason for the weak polarization of the solvent ammonia lies probably in the fact that a phase separation takes place upon crystallization when solidifying the solution. In the work of ref. [4], a chemical destruction of the paramagnetic dopant probably takes place.

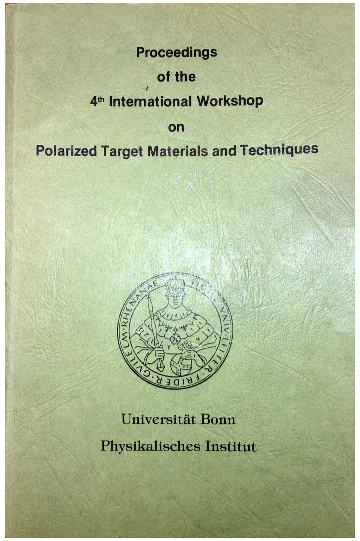
In this work solid ammonia beads of 2 mm diameter were exposed to the extracted 580 MeV proton beam of the CERN synchrocyclotron. The material was held in LN_2 during irradiation, and then during one week in between the irradiation and the dynamic polarization experiments. The loading to the dilution refrigerator [5] was done in such a way that at no time were the beads at a temperature higher than that of liquid nitrogen. The accumulated flux was 0.95×10^{15} protons/cm^2, corresponding to a deposit of 40 Mrad in the material.

The beads had an opaque white colour before irradiation, suggesting a microcrystalline structure. The colour after irradiation was pale violet. Fig. 1 shows the EPR absorption in the sample at 0.15 K temperature and 70.35 GHz frequency with a field sweep. The spectrum was obtained with a carbon resistor bolometer loosely coupled with the multimode cavity; the absorption scale is roughly logarithmic, and cannot be

Fig. 1. EPR absorption in irradiated solid NH_3 at 0.15 K temperature and 70.35 GHz frequency: The hysteresis is due to the slow response of the carbon resistor bolometer. The absorption scale is roughly logarithmic.

1980s: Numerous target groups begin to produce and study irradiated ammonia. The work highlights the 1984 Workshop on Polarized Targets, Bonn (ed. W. Meyer).

Werner Meyer



Best results are obtained after irradiating ammonia at 80 K with 10^9 Rad

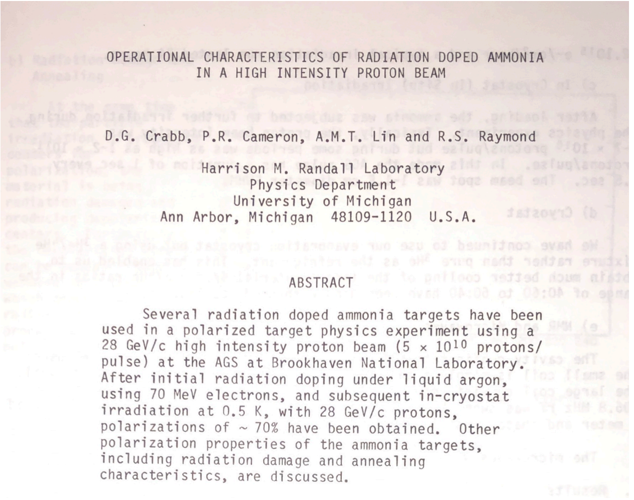
Very high polarizations are obtained at 2.5 or 5 T and temperature below ½ K.

Ammonia is much more radiation resistant than hydrocarbon target materials like butanol and propanediol.

The radiation damage can be repaired by warming the sample to ~90K for a few minutes.

Beam heating remains a problem, however.

1980s: Liquid ^{3}He (or a mixture w/ ^{4}He) is used to cool the target below 1/2 K
Heat transfer is limited by pool boiling



OPERATIONAL CHARACTERISTICS OF RADIATION DOPED AMMONIA IN A HIGH INTENSITY PROTON BEAM

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Physics Department
University of Michigan
Ann Arbor, Michigan 48109-1120 U.S.A.

ABSTRACT

Several radiation doped ammonia targets have been used in a polarized target physics experiment using a 28 GeV/c high intensity proton beam (5×10^{10} protons/pulse) at the AGS at Brookhaven National Laboratory. After initial radiation doping under liquid argon, using 70 MeV electrons, and subsequent in-cryostat irradiation at 0.5 K, with 28 GeV/c protons, polarizations of ~ 70% have been obtained. Other polarization properties of the ammonia targets, including radiation damage and annealing characteristics, are discussed.

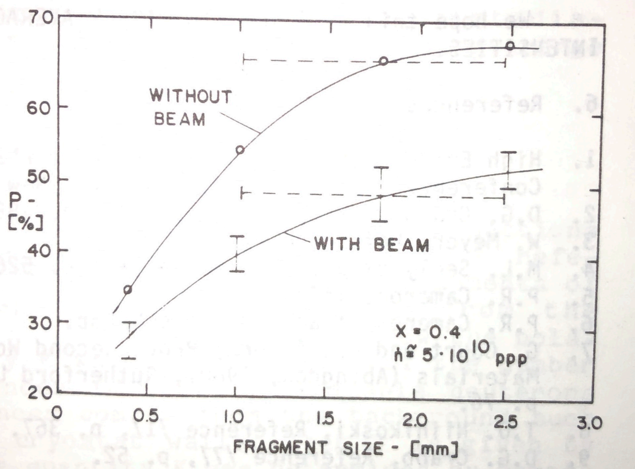


Figure 7
Polarization achieved with target fragments of different sizes.
I polarization with beam on target
● polarization without beam

D.G. Crabb et al., Proc. of 4th Intnl. Workshop on Polarized Target Materials and Techniques, 1984 (ed. W. Meyer)

2.5 T & 0.5 K

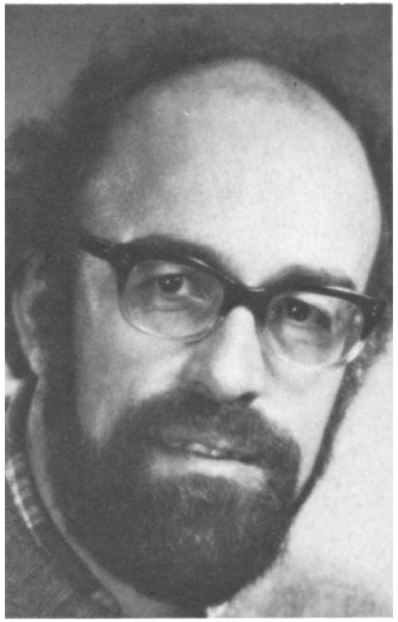
Under an intense beam of protons, the polarization drops by ~30% (rel).

"It is clear from the program at this workshop that indeed it [ammonia] has become a standard material."

"…investigate ways of improving the target fragment cooling."

"We hope this will lead to HIGHER AVERAGE POLARIZATION AT HIGHER BEAM INTENSITIES"

1990: Don Crabb (U. Michigan) demonstrates 96% polarization at 5 T & 1 K



Don Crabb

VOLUME 64, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 1990

Observation of a 96% Proton Polarization in Irradiated Ammonia

D. G. Crabb, C. B. Higley,[a] A. D. Krisch, R. S. Raymond, T. Roser, and J. A. Stewart
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(Received 27 December 1989)

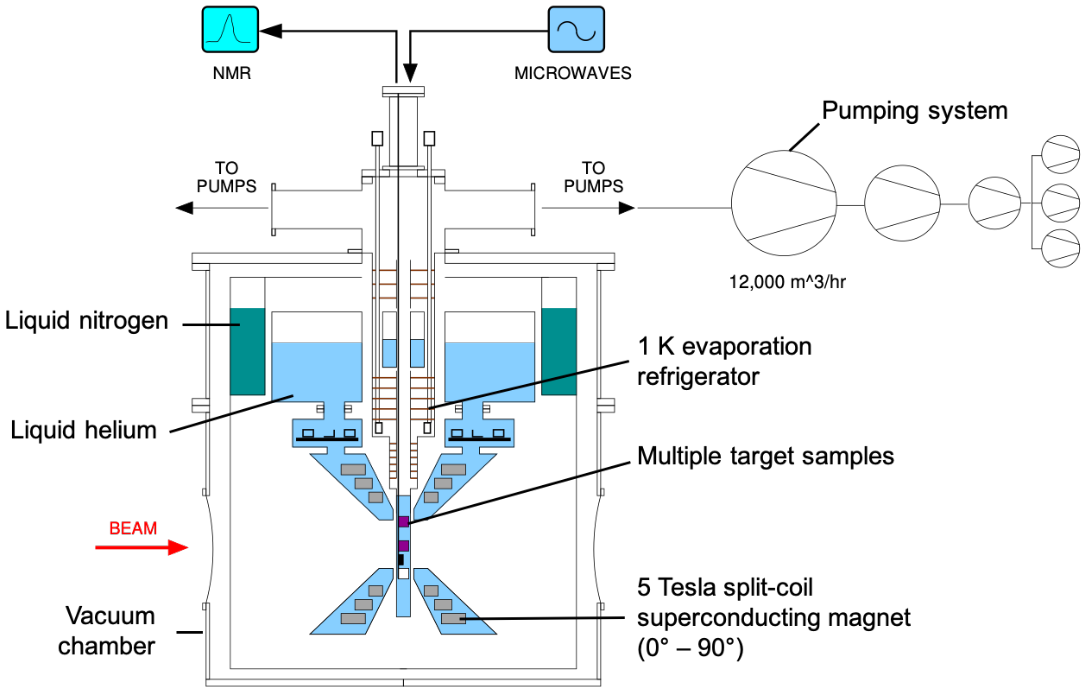
Using dynamic nuclear polarization we obtained proton spin-polarization values of $(+95\pm5)\%$ and $(-97\pm5)\%$ in radiation-doped frozen ammonia. Moreover, the polarization reached 90% in about 25 min. These results were obtained using our new 1-K high cooling power ^{4}He evaporation refrigerator operating in a 5-T magnetic field with 140-GHz microwaves. This unexpectedly large and rapid polarization coupled with about 1 W of cooling power should allow significant improvements in high-energy spin-physics experiments and may have some physics interest in itself.

PACS numbers: 33.25.Hv, 29.25.Kf, 75.25.+z

"This unexpectedly large and rapid polarization coupled with about 1 W of cooling power should allow significant improvements in high-energy spin-physics experiments…"

1990s: Don Crabb moves to U. Virginia and establishes the UVa Polarized Target Group, with Donal Day & Oscar Rondon

The "Don Crabb type target" becomes the *de facto* polarized target for high luminosity experiments



5 T magnet with wide apertures

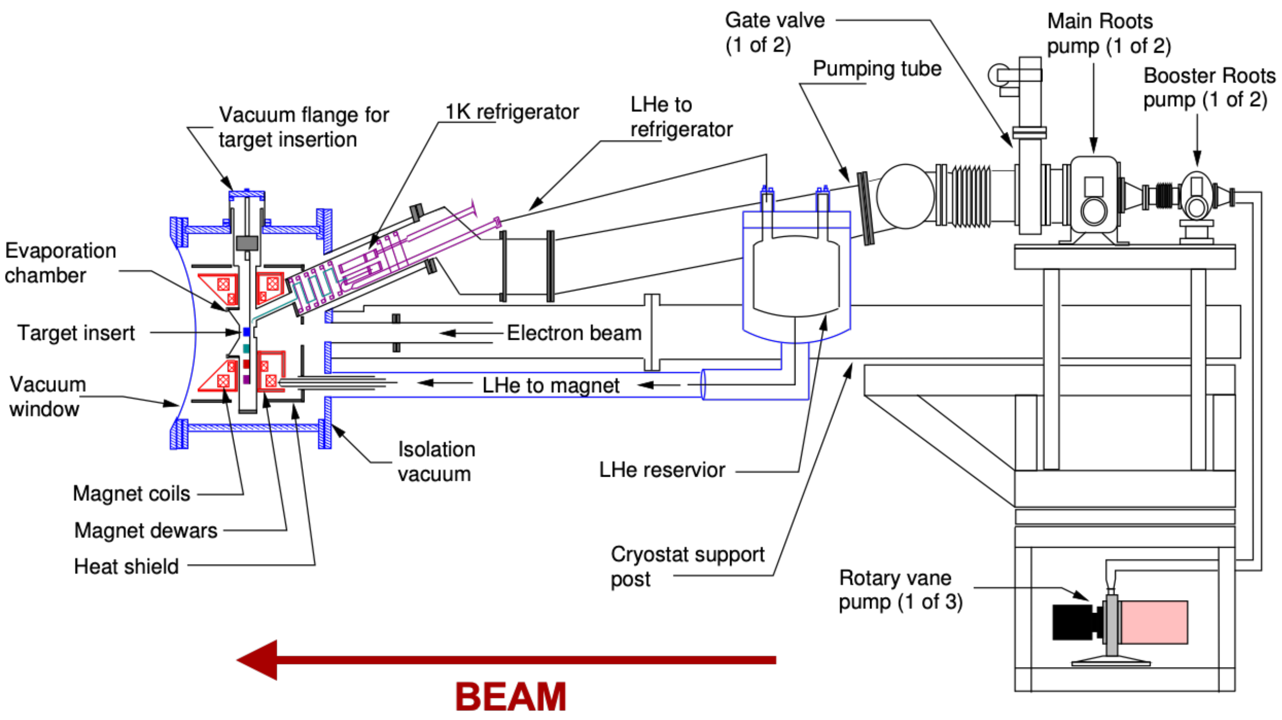
Powerful 1 K ^{4}He evaporation refrigerator

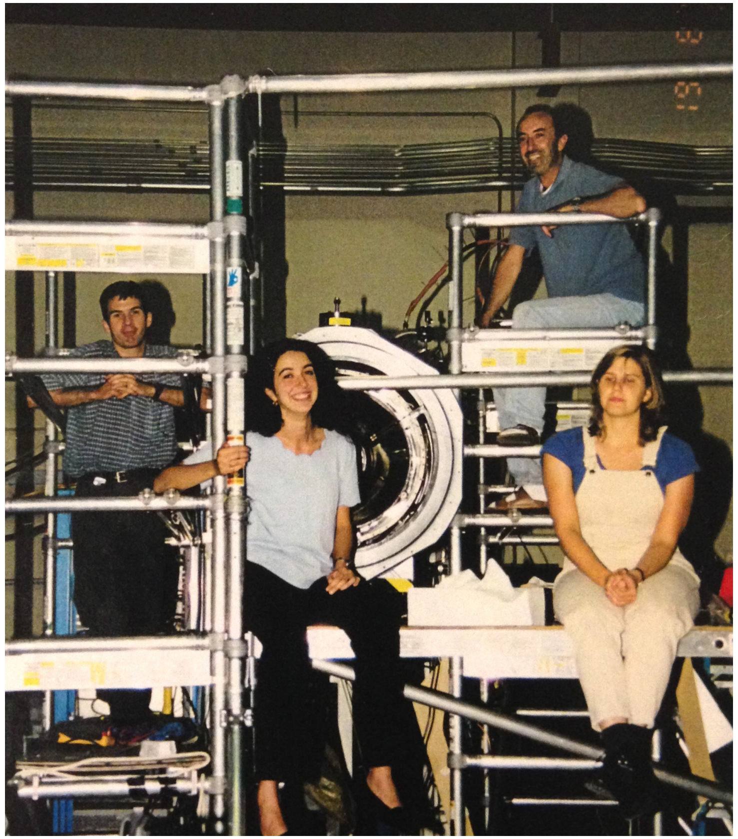
140 GHz microwave tube (EIO)

Liverpool Q-meters for NMR polarimetry

Target insert with multiple samples

1998: A collaboration between UVa, INFN-Genova & Jefferson Lab bring a high-luminosity polarized target into a 4π detector





LtoR: Chris Keith, Raffaella DeVita, Renee Hutchins, Marco Anghinolfi

1990 - 2010s: The UVa Group leads multiple experiments at both SLAC and JLab

- E143 (1993)
- E155 (1997)
- E155X (1999)
- Gen (1998)
- Gen2 & RSS (2000)
- SANE (2008)
- G2p & GeP (2012)
- Eg1 (1999)
- Eg1b (2000)
- Eg4 (2004)
- Eg1-DVCS (2008)

Polarized targets a complicated but rewarding business. . .

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lent of the same physical direction. In so doing, researchers are able to probe otherwise indiscernible quark-to-quark interactions, creating a unique magnifying window into the subatomic realm.

Experimentalist Don Crabb, a research professor of physics at the University of Virginia, says that, with spin alignment, chances increase that subatomic particles will interact in specific ways and that the results of those interactions will be more readily apparent. "Say you have a bale of hay with something buried at its center," he posits. "Shoot a bullet at it, and if it has a hard interior, the shot will ricochet off that interior in a certain way. If you can scatter off individual quarks, you can better understand how a proton or neutron is put together, and how the quarks are interacting to give an individual proton or neutron its properties."

Easier Said Than Done

Not all materials are suitable for polarization. Although experimenters at other facilities have sometimes used frozen alcohols, alignment can be quickly lost through repeated interactions with the Lab's electron beam. JLab's material of choice is ammonia. Once polarized, it tends to remain so, even at high beam current. Target preparation begins with the freezing of gaseous ammonia into a solid block. The block remains immersed in liquid nitrogen and is then crushed into miniature, rock-salt-like granules, which are meticulously spooned into half-inch-deep, dime-size containers. These small receptacles, affixed to a target "stick" and festooned with electronics, are made of a hydrogen-free type of plastic, specifically designed not to interfere with the experimenter's measurement of the target polarization using a technique known as nuclear magnetic resonance, or simply NMR.

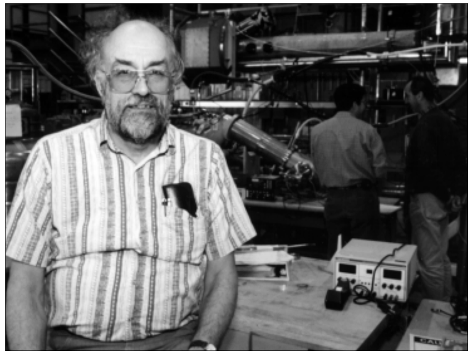
The target stick will eventually be inserted into a canister cooled by liquid helium to just one degree above absolute zero. In turn, the entire array must nestle close to the detectors that will record the quark interplay. Later, experimenters will begin the two-part process of spin alignment, first with a strong magnetic field and then with microwaves, to prepare the target for impact with the beam from the Lab's accelerator, which in turn will generate the subatomic events that will be weighed and analyzed.

If polarized target preparation seems a complex process, it is. The Lab's Polarized Target Group can take up to a year to fabricate and put into place the many pieces that, when fitted together, experimenters use over weeks and months to conduct physics research.

"Ideally the target system comes in completely configured, with refrigeration and magnets," says Mikell Seely, Polarized Target Group manager. "But we usually have to outfit it with polarization detectors, a microwave system, controls and a helium gas supply. We then have to install and maintain it. When these targets are up and running, you have to keep them running at all costs — whether it's weekends or two o' clock in the morning. If something goes wrong, you come in and fix it."

Currently, Seely, Keith, Crabb and co-workers from Genoa, Italy, are preparing a polarized target for a Hall B study slated to begin in September. It will be the third such polarized-target experiment conducted at JLab. The target array is being assembled in the Experimental Equipment Laboratory and is scheduled for a fully integrated test in April and May. The system will be literally wheeled over to Hall B in August to be wedded to the hall's CLAS detector, prior to the start of the experiment's five-month run.

"These are complicated systems," Keith says. "Even though they usually require some kind of care and feeding, we try to make them as robust as we can. Experimenters can't run their experiments if the target is always being repaired."



Don Crabb, research professor of physics at the University of Virginia, sits in front of the Hall B polarized target (module and tube above eye level) and a test apparatus used to check the polarized target's refrigerator (tube at shoulder level). Chris Keith, JLab staff scientist, and Marco Anghinolfi, a user from the University of Genoa, Italy, (background, left & right) discuss results from a refrigeration test.

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1990 - 2010s: In addition to building and operating some of the best polarized targets in the world, the UVa Target Group has been instrumental in producing & training some highly talented physicists

(in no particular order, and I apologize if I forgot you!)

Paul McKee
Renee Hutchins
Christopher Cothran
Hongguo Zhu
Stephen Bueltmann
Yelena Prok
Josh Pierce
Nadia Fomin
Karl Slifer
Nick Kvaltine
Dustin McNulty
Chris Harris
Dustin Keller
Jonathan Mulholland