CONF-7810119--4

REPORT OF THE WORKSHOP ON POLARIZED TARGET MATERIALS

by

G.R. Court, D.G. Crabb, R.C. Fernow, D.H. Fitzgerald, S.W. Gray,
D.A. Hill, J.J. Jarmer, A.D. Krisch, M. Krumpolic and T.O. Niinikoski

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared for

XIX International Symposium on
High Energy Physics

Argonne National Laboratory,
Argonne, Illinois

October 23, 1978

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated under Contract W-31-109-Eng-38 for the
U. S. DEPARTMENT OF ENERGY

REPORT OF THE WORKSHOP ON POLARIZED TARGET MATERIALS*

Argonne National Laboratory
Argonne, Illinois 60439

October 23-24, 1978

and

October 30-31, 1978

G. R. Court	Liverpool University
D. G. Crabb	University of Michigan
R. C. Fernow	Brookhaven National Laboratory
D. H. Fitzgerald	University of California at Los Angeles
S. W. Gray	Indiana University
D. A. Hill	Argonne National Laboratory
J. J. Jarmer	Los Alamos Scientific Laboratory
A. D. Krisch	University of Michigan
M. Krumpolz	University of Illinois, Circle Campus
T. O. Niinikoski	CERN

* Work supported by the U.S. Department of Energy.

OUTLINE

1. Introduction
 2. Survey of "Clean" Target Materials
 - 2.1 H_2
 - 2.2 HD
 - 2.3 D_2
 - 2.4 He^3
 - 2.5 Li^6D
 - 2.6 B_2H_6 , LiH_4B
 - 2.7 CH_4
 - 2.8 C_2H_6
 - 2.9 NH_3 , NH_2CH_3
 3. Radiation Damage in Polarized Target Materials
 - 3.1 Current Problems
 - 3.2 Damage Mechanisms
 - 3.3 DNP With Radiation Induced Free Radicals
 - 3.4 Optical Bleaching
 - 3.5 Effects on DNP
 4. Dynamic Polarization with Stable Cr^V Complexes
 5. Miscellaneous Topics
 - 5.1 Figure of Merit
 - 5.2 Theoretical Remarks on DNP
 - 5.3 Cooling Power and Heat Transfer
 - 5.4 Choice of Magnetic Field for DNP
 - 5.5 EPR Measurements in a Polarized Target
 6. Summary
- Acknowledgements
- References

1. INTRODUCTION

During the last two decades there has been an increasing interest in spin effects in high energy physics. The polarized proton targets which were developed some 20 years ago allowed the first precise experiments on spin effects. However, the field is now coming to the point where present polarized target materials are no longer totally adequate.

Recently large spin effects in high energy strong interactions have been observed in:

1. Large P_T^2 processes¹
2. Inclusive processes²

It seems clear that better polarizable materials might significantly improve the data in these processes for the following reasons:

1. Large P_T^2 requires high beam intensity which reduces target polarization because of radiation damage
2. Inclusive data is seriously contaminated by events from the heavy C and O atoms in PPT materials

It thus seemed appropriate to reexamine the polarized target materials currently in use. An earlier examination of many of these materials was made by Borghini.³ The workshop concentrated on an examination of

- radiation damage in polarized target materials
- a survey of "clean" target materials
- dynamic polarization results with the new stable Cr(V) complexes

In addition to the normal polarized target experts with backgrounds in high energy physics, low temperature physics and solid state physics, we included scientists with strong backgrounds in various areas of chemistry and radiation damage physics, as these areas were quite crucial to our goals. However, it is clear that much closer collaboration with experts in these areas will be necessary to find polarized target materials that allow the precise experiments on high P_T^2 processes and inclusive processes.

2. SURVEY OF "CLEAN" TARGET MATERIALS

Since the Berkeley Conference⁴ of 1971 there have not been many advances in the polarizable nucleon content of materials used for polarized targets. In fact, the experimental situation with respect to some potential target materials has not changed greatly since

Borghini's review of 1966.³ In part this appears to reflect the inherent difficulty of working with highly hydrogen-rich substances. Also, most of the active groups have been kept busy doing the many scattering experiments which could exploit the hydrocarbon targets that came into wide use around 1970.

There are a number of light molecular species which have a polarizable nucleon content appreciably greater than that of

currently used target materials. In what follows we review previously obtained results for each species and discuss the prospects for improvement, with emphasis on those species that either appear more tractable or are inherently more attractive from the point of view of polarizable nucleon content.

In general materials in which neutrons and protons can be independently polarized are the most useful. However, there are scattering experiments such as π^0 inclusive and jet production, in addition to the obvious ones in which recoils are identified, for which targets containing only polarizable pn pairs are not necessarily as a disadvantage. Thus, species such as D_2 and Li^6 are well worth considering.

2.1 H_2

"Brute force" polarization of the order of 10% may well be possible in H_2 with current magnet and refrigeration technology, although this has not been demonstrated. The attainment of larger polarization is made improbable by fundamental limitations on the heat transfer at the solid-liquid boundary of the ortho-para heat of conversion. In any case, such a target would have severe limitations in the areas of magnet aperture, polarization reversal, and very high field at the target. Dynamic polarization in H_2 is hindered because paramagnetic impurities catalyze the conversion of nearby molecules to the non-magnetic para form.

2.2 HD

"Brute force" polarization in HD is eminently feasible. Bozler and Graf⁵ have obtained 40% proton polarization in a field of 10T with a dilution refrigerator at 23 mK, in a sample doped with a small amount of ortho- H_2 to relax the nuclear spins. However, a target of this sort would again suffer from restricted aperture, difficulty of polarization reversal, and high ambient field. Also, at these temperatures beam heating effects would already be appreciable at a charged particle flux of $10^6/\text{cm}^2\text{sec}$.

Honig⁶ has proposed a method for surmounting most of the above problems by exploiting the ortho-para conversion of the H_2 dopant. Hereafter we refer to this method as the "modified brute force" (MBF) method. New problems arise in this method, to be discussed later.

Dynamic nuclear polarization (DNP) in HD has been a tantalizing possibility for better than a decade, but to date results have been sparse and not highly encouraging. Nevertheless, there are a few hopeful hints, and the stakes are high enough to warrant a vigorous pursuit of this possibility in the near future.

DNP in HD would presumably be based on a "solid effect" acting on a dopant of paramagnetic H-atoms. Other types of center can certainly be induced in HD, but H-atoms are the most straightforward. We consider four different methods for producing H-atoms dispersed in HD.

A. IRRADIATION

Rebka and Solem⁷ have obtained a proton polarization of 3.7% and a deuteron polarization of $\sim 0.4\%$ in HD at 1.2T and 1.2K, by the "solid effect" on one of the two EPR transitions of H-atom impurities. The H-atoms were induced by irradiation of solid HD in a bremsstrahlung beam of 60 MeV maximum energy. Total dose was $\sim 10^4$ R which resulted in $\sim 10^{-4}$ H-atoms per HD molecule. By raising the field to 2.5T, lowering the temperature to 0.4K, and saturating both "forbidden" EPR transitions, one (naively) might expect to attain $P_H \sim 2 \times 3 \times 2 \times 3.7 = 44\%$.

Experiments of this sort are difficult and tedious. They require access to an electron accelerator and work in a high-radiation area. Worse, irradiation, probably inevitably, produces "foreign" paramagnetic species and H_2 , D_2 recombination products, which are depolarizing and complicate the physics. One can wait for the H_2 to convert to para- H_2 , but this requires a long wait after irradiation, ~ 10 days for Rebka and Solem.

B. TRITIUM SPECIES DOPING

Here one mixes HT or T_2 with HD, freezes the mixture and waits for decay and ionization products to build up. One has good control over initial concentrations, and requirements for special apparatus are minimal. However, the physics is again rather complicated. This technique has been used in D_2 , with limited success.⁸

C. ATOMIC BEAM DOPING

Rebka⁹ has proposed that a relatively clean and controllable method of doping HD would be to mix an RF discharge-produced atomic-H beam with a molecular beam or gas stream of HD, and then freeze the mixture. This method has the advantage that H_2 and unwanted paramagnetic species could be minimized.

D. SPARK DISCHARGE DOPING

Here HD gas passes through a spark discharge, or, H_2 gas passes through the discharge and is added to a stream of HD gas, before freezing. This is similar to method C, perhaps somewhat simpler but less controllable.

Any target utilizing HD, polarized by whatever means, will have certain advantages and disadvantages relative to current targets, inherent in the material.

Advantages

1. The NMR linewidths are fairly small:

$$\Delta f_H \sim 19 \text{ kHz}, \Delta f_D \sim 1.3 \text{ kHz}.$$

This makes thermal equilibrium (TE) calibrations easier and more reliable.

2. Target insertion and removal can in principle be quite rapid, at cryostat temperatures which never have to exceed 30K.

Disadvantages

1. Spatial density of H is only $\sim 1/2$ that of current targets.
2. The target is destroyed whenever the cryostat temperature rises much above 5K. Since currently visualized HD targets would have lengthy "maturation" periods, this is a serious reliability problem. However, this period could be usefully used for unpolarized "dummy" running.
3. The density of the target may be difficult to determine and reproduce accurately.
4. In order to take full advantage of the low background of HD, cryostats with less material intercepting the beam must be used.
5. So far, high purity ($>> 99\%$) HD is not readily available, from commercial sources.

The following are lists of advantages and disadvantages peculiar to MBF or DNP, listed roughly in order of decreasing importance.

HD-MBF Advantages

1. Simpler physics than HD-DNP.
2. Target preparation method is already fairly clear.
3. No homogeneous field is required, except for dynamically polarized D.
4. No microwaves are required. But strong RF is needed for polarized D.

HD-MBF Disadvantages and Problems

1. Magnet failure destroys target.
2. Have to hold stable low temperature for ≈ 2 weeks.
3. Target not available during this period.
4. Probably much more radiation-sensitive than HD-DNP. ²The maximum tolerable flux of charged particles is $\sim 10^7/\text{cm}^2\text{-sec.}$
5. Target or polarizing magnet must be movable.
6. Homogeneous field required for D-DNP.
7. Polarization reversal: adiabatic passage or reversal of the holding field are the only possibilities.
8. Need high-field magnet, $\approx 10\text{T.}$
9. TE calibration unavailable for long periods.

HD-DNP Advantages

1. Some DNP attainable immediately following target preparation. In Solem's experiments, pol. $\sim 1/3$ of maximum, immediately after irradiation, rising to maximum with ~ 5 day time constant.

2. Magnet failure does not destroy target.
3. Probably much less radiation-sensitive than HD-MBF.
4. Continuous very low temperatures are not required.
5. Pol. reversal dynamically.
6. Does not require high-field magnet.
7. No need to move either target or magnet.

HD-DNP Disadvantages and Problems

1. How to prepare target without use of bremsstrahlung radiation.
2. Physics more complicated than HD-MBF.
3. The EPR linewidth went from $\sim 10G$ to $\sim 20G$ in going from 4.2 to 1.2K, in Solem's case.
4. D and H polarizations occur at different microwave frequencies. (This could also be an advantage if H and D polarization is wanted separately.)
5. The apparent necessity of O_2 -impurity means another parameter to control, and complicates the radiation chemistry.
6. Requires two sources or a modulator for two microwave transitions? Separation is ~ 1.4 GHz.

It is clear that the problems with the MBF method are relatively greater and that a DNP approach would be far more flexible. However, the MBF method has one big advantage in that the essential features have all been proven.

2.3 D_2

Rebka and Waine¹⁰ achieved $\sim 1\%$ polarization at 0.8T and 1.2K in solid D_2 containing D-atoms. Procedures for doping similar to those for HD may be possible.

2.4 He^3

He^3 would make an attractive neutron target. Optical pumping has yielded polarizations in excess of 50% in low pressure He^3 gas.¹¹ Although it is possible to preserve polarization while compressing the gas into the NTP range,¹² attempts to liquify the polarized gas meet with severe difficulties.¹³ Attempts to polarize solid He^3 by the use of Pomeranchuk cooling have met with more success, yielding polarization of at least 47% at 5.4T at temperatures of less than 5mK.¹⁴ In addition to a few other problems with this method, beam heating would probably cause the overall figure of merit of such a target to be less than that of conventional deuterated targets.¹⁵ The beam flux would be limited to $\sim 10^5/cm^2$ -sec.

2.5 Li^6D

Abragam and co-workers¹⁶ have demonstrated polarizations of $P_H \sim 95\%$, $P_{Li} \sim 80\%$ in Li^7H . The sample was a crystal $5 \times 5 \times .5mm$

which was irradiated by $\sim 10^{18}/\text{cm}^2$ of $\sim 3\text{MeV}$ electrons. Dynamic cooling on the resulting centers was carried out in a dilution refrigerator at $\sim .5\text{K}$ in a 5T field. Equal spin temperatures of H and Li^7 were attained, with a polarizing time constant of ~ 2 days.

While the figure of merit of a Li^7/H target would not be better than existing targets, the above result, along with other considerations, suggests that Li^6D might be highly polarized. The nuclear ground-state of Li^6 is predominantly $^3\text{S}_1$ and the magnetic moment is nearly equal to that of the deuteron, which implies that Li^6D may be thought of as a deuteron plus a "bound deuteron", both polarizable. In other words, four nucleons out of a total of eight may be polarized.

2.6 B_2H_6 , LiH_4B

These materials, while interesting from the point of view of hydrogen content, are considered to be too unstable and reactive to be serious candidates.

2.7 CH_4

Chemical doping of methane might be achieved by mixing it with free radical vapor at room temperature, and then freezing the mixture (see C_2H_6). A more likely possibility would be to create CH_3 -radicals or H atoms in the gas phase before freezing, or to irradiate solid methane. Methane is sufficiently hydrogen-rich as to make these possibilities well worth exploring. A previous doubt about the equilibrium spin-state of solid methane now appears to be clarified.¹⁷⁻¹⁹

2.8 C_2H_6

Methods of doping already discussed might be tried on ethane. Also, Hwang²⁰ has mixed DTBN vapor with ethane and observed the presence of the N^{14} hyperfine structure (hfs) in the EPR of the solid. This at least indicates that a good dispersion of the radical in the solid can probably be achieved by such a method.

2.9 NH_3 , NH_2CH_3

Scheffler²¹ obtained sizeable polarization in solid ammonia doped with glycerol: Cr^{V} , but the time required for polarization reversal was many hours. Scheffler attributed the long time constant to "clustering" of the glycerol: Cr^{V} in the ammonia matrix. When pure Cr^{V} species are used with no third additive such as glycerol, the results are more extreme: very small dynamic polarization and very long nuclear time constant (see Sec. 4). These results seem best explained by the ease with which ammonia tends to crystallize and exclude foreign materials from the crystals. If this is true, there is probably a similar problem with most hydrogen-rich substances, which tend to have small, easily ordered molecules.

It should be noted that crystalline materials may have another difficulty in addition to this reluctance to accept impurities into the lattice. That is, dopants which do manage to become incorporated may themselves show a preferred orientation correlated with the orientation of the crystallite. Dopants such as Cr^{V} which depend on g-anisotropy broadening for much of their polarizing ability will then not be effective.

It might be possible to find some additive which would enable ammonia to form a glassy solid. Or, one may consider the asymmetric molecule of methylamine (CH_3NH_2) to be a more likely candidate for glass formation.

3 RADIATION DAMAGE IN POLARIZED TARGET MATERIALS

3.1 Current Problems

It is well known that radiation damage steadily reduces the polarization in all the currently used polarized target materials.²²⁻²⁵ The proton polarization decays roughly exponentially with accumulated radiation flux ϕ

$$P = P_0 e^{-\phi/\phi_A} \quad (1)$$

where ϕ_A is the characteristic flux for the polarization to decay by 1/e. We use the subscript A to indicate that much of this damage can be repaired by annealing. In general there is a different characteristic flux for positive and negative enhancement signals. The standard butanol- H_2O /porphyrexide (PX) and diol/ $\text{Cr}(\text{V})$ targets have ϕ_A values of $1 - 4 \times 10^{14}$ minimum ionizing particles/ cm^2 . In addition the nuclear spin lattice relaxation time T_{1N} is observed to decrease roughly as one over the dose. This loss of polarization entails additional running time to measure some asymmetry with a fixed error. Still more time is lost since the material must be frequently annealed and changed.

It is also found^{22,25} that the polarization after an anneal slowly declines from the starting polarization. This indicates that there is probably more than one type of damage mechanism occurring in the material. The polarization following annealing appears to follow the empirical relation

$$P_0(\text{ann}) = P_{\text{asym}} + (P_0 - P_{\text{asym}}) e^{-\phi/\phi_{\text{NA}}} \quad (2)$$

where P_{asym} and ϕ_{NA} are material and enhancement dependent parameters. In the diol- $\text{Cr}(\text{V})$ system the plus enhancement state appears to be more resistant to the annealable type of damage but less resistant to the non-annealable type (see Table 3.1). The damaged sample has a higher effective g value with the greatest shift occurring in the negative enhancement peak.

Table 3.1 Properties of Current Polarized Target Materials (.5K, 2.5T)^{25,26}

Material	P_o^+	P_o^-	$T_{ann}[K]$	ϕ_A^+	ϕ_A^-	ϕ_{NA}^+	ϕ_{NA}^-	$\frac{P_a^+}{P_o^+} \quad \frac{P_a^-}{P_o^-}$		(77K)	
								$\frac{P_a^+}{P_o^+}$	$\frac{P_a^-}{P_o^-}$	$G(e_{trap})$	$G(Rad)$
ethanediol-Cr(V)	82	-82	160	$2.3 \pm .3$	$1.8 \pm .2$	$.8 \pm .2$	$.8 \pm .2$	.69	.89	1.5	~4
1,2 propanediol-Cr(V)	82	-82	180	$2.0 \pm .3$	$1.6 \pm .2$	$.8 \pm .3$	$1.0 \pm .3$	.73	.90		
n-butanol/H ₂ O-PX	68	-62	130	$2.2 \pm .5$	4.5 ± 1.0					0.7*	

* In pure butanol.

In the butanol-H₂O-PX system the negative enhancement state is more resistant to the annealable type of damage. The optimum microwave frequency for positive polarization decreases somewhat, while that for negative remains essentially constant.²⁷ When the last point is looked at in more detail by doing a complete plot of polarization against microwave frequency on a heavily damaged sample, it is seen that the line shape is asymmetrically broadened on the lower frequency side compared with the same plot for undamaged material which is essentially symmetric. Thus, both materials suffer an optimum frequency shift in the enhancement closest to $g = 2$. These same enhancements have the most annealable-type radiation damage.

Butanol can be annealed to extend its working life by heating it to approximately 120K. After each anneal the proton relaxation time is typically 5% longer than its previous value and the polarization is slightly smaller. This overall increase in relaxation time, and hence polarization reversal time, and decrease in polarization mean that the practical total life of a target involves typically not more than ten anneals.

3.2 Damage Mechanisms

The mechanisms by which the beam damages the target material are complicated and material dependent. Polarized target materials consist of paramagnetic centers such as prophyrexide or Cr(V) embedded in an irregular lattice of alcohol molecules. Irradiation of the material with high energy beams results in ionization energy being deposited in the material. This energy results in partial disassociation of the solid matrix and creation of new species of free radicals, ion fragments, and molecules.

Radical formation in aliphatic alcohols RHOH is described in Ref. 26. The major paramagnetic products are the free radicals $\dot{R}OH$, $\dot{R}H$, $\dot{H}$, and trapped electrons, ion fragments such as $RHOH_2^+$ and RHO^- , and molecular H_2 and H_2O . Other species are present at intermediate steps in the reaction. However, EPR spectra show that only a few major radicals are produced in a given material.

One species of radicals $\dot{\text{R}}\text{OH}$ is formed by the elimination of an α hydrogen atom. Thus the hydroxyalkyl radical $(\cdot)\text{CHOHCH}_2\text{OH}$ is formed in ethanediol and $\text{C}_3\text{H}_7\text{C}(\cdot)\text{HOH}$ in n-butanol. The hydrogen atoms in the $-\text{OH}$ group do not appear to be significant in the EPR hyperfine structure. The EPR spectra for these radicals at 77K and 600 MHz are centered near $g = 2$ with a width of 100 gauss for ethanediol and 140 gauss for n-butanol.²⁸ The second major species of free radical is hydrogen atoms. Their EPR spectra show a doublet centered around $g = 2$ and with a separation of 508 gauss. The remaining major radical is trapped electrons. These cause a singlet line near $g = 2$ in the EPR spectrum with widths 8-20 gauss. They have an optical absorption peak at visible wavelengths and cause an intense coloration in the damaged material.

In addition to radical formation the beam may also cause damage to the desired paramagnetic species. For example, paramagnetic Cr(V) may be converted to Cr(IV), Cr(VI), or paramagnetic Cr(III) by reacting with radiation products. There is also evidence that porphyraxide is depleted during the course of irradiation.

Thermal annealing successfully depletes the trapped electron concentration by liberating the electrons and allowing them to recombine with position ions. In addition radical concentrations may be greatly reduced by heating to 0.6 - 0.7 of the melting temperature. Trapped electrons are freed below this temperature.

3.3 DNP With Radiation Induced Free Radicals

In order to better understand the effects of the produced free radicals tests have been made with a sample of undoped butanol by irradiating it in a 4 GeV bremsstrahlung beam.²⁷ The measurements were made at a field of 2.53T and a temperature of 1K. During the irradiation, attempts were made to polarize the sample. It was found that the polarization increased linearly with dose, reaching values of +7 and -6% after a dose equivalent to eight times the dose which would reduce the polarization to 0.75 of its initial value in a normally doped material. The total absorbed dose was $\approx \phi_A$. Over this irradiation period the proton relaxation time fell from an initial value of 1500 secs. to 550 secs. The material was then annealed in the normal way. The proton relaxation time was found to have returned approximately to its initial value while the polarization had not appreciably changed.

A further small irradiation was then made before the experiment had to be terminated because no further beam time was available. The maximum polarization reached was +8% and it still appeared to be rising linearly with dose.

A polarization against microwave frequency plot carried out immediately after the anneal showed a shape and width very similar to that for an undamaged porphyraxide sample but shifted $\approx 0.2\%$ lower in frequency. This shows that the non-annealable centers have a g value approximately 2.001. When the microwave plot from the damaged undoped sample was added to the microwave plot for the

undamaged porphyrin sample the result was in excellent agreement with that obtained for the damaged normally doped sample both with respect to shape and absolute size (see Fig. 3.1).

When the undoped sample was finally removed from the cryostat it was observed carefully while it was allowed to warm up. The beads, which when initially loaded had been completely colorless were seen to have a strong grey-purple color which disappeared quite suddenly just before they melted.

FIGURE 3.1

3.4 Optical Bleaching

We have seen that at least some of the annealing centers are associated with color centers. It should be noted that the formation of red purple color centers in butanol and other alcohols by radiation damage at 77K has been reported elsewhere.²⁸ In these measurements it was generally observed that irradiated material showed a broad absorption spectrum in the range 200 to 500 nm peaked at 500 nm with a second peak in the ultra violet. The visible region absorption could be removed either by annealing the material at temperatures ≈ 110 K or by exposing the material to white or monochromatic light of wavelength 540 nm (optical bleaching). The ultra violet absorption line was unaffected by annealing but could be partially bleached by exposure to radiation of 250 nm wavelength. The EPR singlet line was effectively removed. The presence of other paramagnetic centres associated with the ultra violet absorption was demonstrated by EPR.

This immediately suggests two further developments. Firstly it may be possible to optically bleach a target material. This could have very important operational advantages as the time now employed for heating the material to 120K and cooling it back to operating temperature is a significant part of the running time. It is also quite conceivable that, because the energy input required to bleach the centers is unlikely to be very much higher and could be much less than that required to produce them, a process of continuous optical bleaching would be possible. The technological problems involved do not look too serious as targets have already been used with light guides for scintillators operating close to target temperatures.

Secondly if radiation damage centers are actually used to produce the polarization then once the optimum concentration has been obtained, continuous optical bleaching could be used to maintain this optimum, again possibly giving a very long life time. Alternatively if more than one type of center is produced then the unwanted ones could perhaps be removed by selective bleaching. Again the technology would not appear to present serious problems as high power tunable dye lasers are currently available.

One possible drawback is that in optical bleaching, unlike thermal annealing in damaged alcohols, the freed trapped electron interacts to form a new radical of the ROH type. Thus the total number of induced paramagnetic centers is not reduced. The experiment would be worthwhile however because it isn't clear at this point which radicals are most deleterious to DNP.

3.5 Effects on DNP

In the preceding sections we have described the loss of dynamic polarization with radiation damage and various products formed in the radiolysis of the target material. The results cited there rest on at least some experimental evidence. In this section we become more speculative and consider how the radiation damage may cause the loss of polarization.

The results of section 3.2 show that there are at least 3 species of radiation induced radicals present besides the original paramagnetic dopant. These are the trapped electron, e_{trap} , hydrogen atom H, and hydroxyalkyl radical ROH. The data in section 3.3 show that at least one of the radicals produced in undoped butanol can participate in DNP. When the sample was annealed the polarization remained and T_{1n} increased back to its starting value. Since the e_{trap} are annealed (or bleached) easily and there is no evidence for H at 77K we can probably assume that these are the species that anneal and are responsible for the shortened relaxation time. Since the polarization didn't change after the anneal we assume that the ROH radical is responsible for the DNP, does not anneal at 120K, and that it does not appreciably shorten T_{1n} . Presumably then long-term non-annealable damage results from the build up of the ROH or other radicals and destruction of the original paramagnetic dopant.

It is not clear at this point precisely how the presence of these new paramagnetic centers affects DNP. The most likely possibilities are (1) increasing the leakage factor by shortening T_{1n} , (2) modification of the EPR line shape, (3) destruction of the original paramagnetic entity and (4) short-circuiting the original spin temperature reservoirs to the lattice. To resolve these questions it would be extremely helpful to have an EPR spectrometer connected to a working (irradiated) polarized target. Then one could observe the growth of new paramagnetic centers with radiation damage. One could also perform careful annealing studies by warming up until specific radicals anneal out and then recooling to see how that radical affected DNP. Unfortunately problems with attenuation in the long waveguides and the lack of a tuned cavity make this direct approach very difficult. However, the same EPR information can be obtained from the NMR signal using the NEDOR¹⁶ technique (see Sec. 5.5). These experiments could be very significant in helping to elucidate the effects of radiation damage on DNP. Coarse information on radical production can also be obtained using a bolometer in the target cavity and sweeping the magnetic field.

Further experiments with radiation induced radicals in undoped materials are clearly desirable. Targets doped in this way would eliminate the Cr(V)/porphyrin oxide destruction problem and at least part of the EPR interference problem. The big questions are how large a P_n can be achieved this way and how much more radiation resistant the target would be. This experiment could be coupled to a test of optical bleaching. In this case trapped electrons would provide even more of the $\dot{R}OH$ radicals which are presumably responsible for the polarization.

Other useful experiments could include a study of the effects of the addition of electron scavengers to the target material to change the annealing properties and an investigation of how ϕ_A depends on T and H . One should investigate the addition of naphthalene and related compounds to butanol to improve its radiation resistance, and DNP in isopropyl-benzene which should freeze to a suitable glass.

Finally we mention the interesting possibility that HD may have superior radiation resistance properties. It has low density, the $D^{\cdot}$ radical decays away at low temperature⁷, and it probably has a low Kapitza resistance and high thermal conductivity. It would be quite remarkable if the same substance simultaneously solved the problems of high hydrogen content and radiation resistance.

4. DYNAMIC POLARIZATION WITH STABLE Cr(V) COMPLEXES

Recently prepared chromium (V) complexes^{29,30} of tertiary α -hydroxy acids possess physical and chemical properties which are of considerable importance for polarized target experiments. They are remarkably stable and soluble in solvents with high hydrogen content (water, alcohols, diols, ammonia), and are easily accessible in pure form.

The chromium (V) complexes of the general structure

(1) $\text{R}_1 = \text{CH}_3, \text{R}_2 = \text{C}_2\text{H}_5$	(5) $\text{R}_1, \text{R}_2 = (\text{CH}_2)_4$
(2) $\text{R}_1 = \text{R}_2 = \text{CH}_3$	(6) $\text{R}_1, \text{R}_2 = (\text{CH}_2)_5$
(3) $\text{R}_1 = \text{R}_2 = \text{C}_2\text{H}_5$	(7) $\text{R}_1 = \text{CH}_3, \text{R}_2 = \text{C}_6\text{H}_5$
(4) $\text{R}_1 = \text{R}_2 = \text{C}_4\text{H}_9$	

were prepared in 60-90% yields by the reaction of anhydrous sodium dichromate in acetone with the following hydroxy acids: 2-hydroxy-2-methylbutyric (HMBA), 2-hydroxy-2-methylpropionic (HMPA), 2-ethyl-2-hydroxybutyric (EHBA), 2-butyl-2-hydroxyhexanoic (BHHA), 1-hydroxycyclopentanecarboxylic (HCpCA), 1-hydroxycyclohexane carboxylic (HCCA), and 2-hydroxy-2-phenylpropionic (HPPA) acids. The synthesis is carried out at room temperature and can be accomplished in two to three days. The stoichiometry of the reaction is $\text{Na}_2\text{Cr}_2\text{O}_7 + 5 \text{R}_1\text{R}_2\text{C}(\text{OH})\text{COOH} = 2 \text{Na}[\text{O}(\text{C}(\text{R}_1)\text{R}_2\text{CO}_2\text{C}(\text{R}_1)\text{R}_2)] + \text{R}_1\text{R}_2\text{CO} + \text{CO}_2 + 5 \text{H}_2\text{O}$.

Some physical and chemical properties are summarized in Table 4.1, while a summary of dynamic polarization results achieved to date is given in Table 4.2.

Table 4.1 Solubility and Stability of Chromium(V) Complexes Of Tertiary α -Hydroxy Acids $\text{R}_1\text{R}_2\text{C}(\text{OH})\text{COOH}$ 29,30

Complex	Solubility ^a		Degree of Decomposition ^b (%) In H ₂ O	Thermal Decomposition (°C)
Cr(V)-HMBA (1)	290	103	58	180
Cr(V)-HMPA (2)	270	4.1	81	180
Cr(V)-EHBA (3)	190	203	28	180
Cr(V)-BHHA (4)	16	87	27	180
Cr(V)-HCpCA (5)	204	730	100	170
Cr(V)-HCCA (6)	340	710	100 ^d	170
Cr(V)-HPPA (7)	170	810	100 ^d	140

a - g/L, 25°C

b - 0.01 M solutions of chromium(V) complexes followed over a period of 24 hr at 25°C.

Table 4.2
Summary of Stable Cr(V) Results

Material ¹	Complex	[10 ¹⁹ spins/ml]	P _H	P _D	ν_N [MHz]	$f_{\pm}$ [GHz]	T _{in} at T [N] [K]	τ (70%) at Q at T [M] [mW/g] [K]	Refrig.	Degas ⁶	Ref.
EG	HMBA	10	76 ± 2 -71 ± 2		108	Std Cr(V)	9 .89	8 5 ~.7	He ³	Y	ANL ³¹
EG	HMBA	7	77 ± 2 -78 ± 2		108	Std Cr(V)	12 .89	9 5 ~.7	He ³	Y	ANL ³¹
NH ₃	HMBA	7	~ ± 1.5		108	Std Cr(V)	~160 ⁷ .89	60 ± 30 5 ~.7	He ³		ANL
PeOH	HMBA	2.6	51 ± 3 -59 ± 3		106.8	69.31 69.74	160 ± 30 .48		He ³		MICH ³²
PeOH	HMBA	(sat.)	50 ± 3 -58 ± 3		106.8		103 ± 28 .48		He ³		MICH ³²
PeOH	EHBA	2.7	61 ± 3 -63 ± 3		106.8	69.26 69.68	244 ± 60 .48		He ³	Y	MICH ³²
PD	EHBA	10	±82 ± 4		106		20 .58		He ³		KEK ³³
BuOH	EHBA	3	75 -80		106.45		21 .78	15 3 .48	He ³	Y	CERN ³⁴
PD-d ₆ ²	EHBA	10	(±97) ³	±40 ±2	106.50	69.23 69.71	3.5 .98	10 5 .4	DR	Y	CERN ³⁴
EG-d ₆ ⁴	EHBA	10		24 ± 3	106				He ³		KEK ³³
BuOD-d ₁₀ ⁵	BHHA	10	(±94) ³	±30 ±3	106.50	69.13 69.69	1 .98	5(D) 5 .4	DR	Y	CERN ³⁴

(1) Materials

EG: ethylene glycol
PD: propanediol
BuOH: 1-butanol
PeOH: 1-pentanol

(2) CD₂OHCD₂OH-d₃ Rapid spin-temperature equilibrium (STE) seen between species.

(3) These large P_H cannot be obtained in undeuterated samples.

(4) (CD₂OD)₂

(5) Sample contained 2% H STE observed.

(6) Dissolved oxygen removal.

(7) Non-exponential.

5. MISCELLANEOUS TOPICS

5.1 Figure of Merit

There are many factors which may enter into the figure of merit of a polarized target. The following list includes factors that are frequently of interest. The relative importance of each factor varies with the type of scattering experiment. Reports concerned with potential target materials should ideally contain enough information to determine these factors.

1. target polarization(s)
2. $\Sigma p_{\uparrow}/\Sigma N$, $\Sigma n_{\uparrow}/\Sigma N$, $\Sigma N_{\uparrow}/\Sigma N$
3. radiation resistance, Φ_A and Φ_{NA}
4. density
5. polarization reversing time
6. independent polarizability of $n_{\uparrow}, p_{\uparrow}$
7. atomic numbers and weights present
8. duty cycle, "dead" times
9. magnet field and homogeneity requirements
10. existence of a suitable dummy
11. susceptibility to beam heating

5.2 Theoretical Remarks on DNP

Many publications cover this subject.^{16,35,36} We only wish to point out here the differences between DNP in LMN (and many other crystalline anisotropic solids) in which the "solid effect" is the dominant mechanism, and isotropic, non-crystalline organic solids doped with paramagnetic impurities, in which the major source of EPR broadening is due to the g-tensor anisotropy (dynamic cooling of nuclear spins).

The main difference is that the "solid effect" can be understood in terms of the response of isolated electron-nuclear spin pairs without any consideration of their interactions among other spins of their species, whereas the response of g-tensor broadened EPR to microwaves can only be handled when these interactions are taken into account. Another important difference is that in the solid effect the transitions induced by microwaves are not "allowed", but in dynamic cooling they are. Two consequent differences follow from these considerations: (1) power absorption in the "solid effect" is very weak but in "dynamic cooling" it is strong (2) response of LMN-type material is "transition probabilistic" whereas in organic targets it is entirely collective and can only be handled by quantum statistics (i.e., thermodynamics). This is why we speak of spin temperature and dynamic cooling in the latter case.

5.3 Comparison of Cooling by Evaporation and Dilution of ³He

Specifying a target's performance by coolant (helium) temperature is all right if a comparison is not being made between

different cooling systems. As is well known, what matters for the end result in DNP is the material temperature, not the coolant temperature. We wish to point out here how evaporation and dilution cooling systems differ from each other and why the heat transfer is more important than the coolant temperature in most practical cases.

The cooling powers and heat transfer characteristics³⁷ are given below for the two systems.

	COOLING POWER	HEAT TRANSFER
Dilution	$\dot{Q}_m \approx 12.5 \sigma S T_m^4$	$\dot{Q}_m \equiv \sigma_t S_t (T_L^4 - T_m^4)$ (Due to Kapitza Resistance)
He^3 Evaporation	$\dot{Q}_m = \frac{\dot{V}_{\text{pump}}}{RT_{\text{pump}}} p L_3^o \approx \exp^{-L_3^o/kT}$	$\Delta T \approx c \cdot \frac{\dot{Q}_m}{\sigma_t}$ (Due to Nucleate Boiling Resistance)

σ, σ_t = heat exchanger and target surface area.

S, S_t = surface boundary conductance in the heat exchanger and target.

$\dot{Q}_m$ = load into the mixing chamber, or He^3 evaporator applied to the target by microwaves.

L_3^o = He^3 latent heat of evaporation.

Using the above we can draw the target temperature T_L as a function of applied load $\dot{Q}_m$:

We conclude that it may well be that the target in a dilution refrigerator is colder at any heat load. The polarization results support this picture.

5.4 Choice of Magnetic Field for DNP

Currently almost every laboratory uses a 2.5T magnetic field for DNP in polarized targets. This is mainly due to the availability of microwave sources from the LMN-era. However, it is by no means clear that 2.5T would give optimum results for the maximum polarization or reversal speed. In fact, it would seem rather natural that there would be an optimum field for DNP in each substance.

To illustrate this, let us consider the spin-temperature model, which gives

$$\max \{P\} = \tanh \left[\max \left\{ \frac{\vec{\mu} \cdot \vec{B}}{kT_S} \right\} \right]$$

for spin $\frac{1}{2}$ (or a corresponding Brillouin function for spin I). The spin temperature can be related to the lattice temperature T_L by

$$T_S = T_L \frac{\Delta_e}{f_e},$$

when the irradiation frequency is at a distance Δ_e from the center f_e of the EPR line. If the EPR line is mainly broadened by g-tensor anisotropy, then Δ_e/f_e is not dependent on magnetic field. The lattice temperature in a dilution refrigerator is given by

$$T_L \approx \dot{Q}_{\text{sat}}^{1/4},$$

where the microwave power $\dot{Q}$ for full saturation is supposed to be proportional to the electron spin lattice relaxation rate T_{1e}^{-1} . This, on the other hand, has a field dependence

$$T_{1e}^{-1} \approx H^{+5},$$

leading to

$$T_L \approx (H^{+5})^{1/4} = H^{5/4}.$$

Therefore

$$\frac{\mu B}{kT_S} \approx \frac{H}{H^{5/4}} = H^{-1/4}$$

and so P probably has a maximum which is determined by the region where one or more of the above relations are not valid. It is suggested that this maximum could possibly be located for some of the well-polarizing materials in a dilution refrigerator.

Advantages of lower field

1. Magnet is less expensive and simpler to construct.
2. Microwave sources more powerful.
3. Less cooling required per gram of material.
4. A lower magnetic field permits detection of lower momentum charged particles. Some experiments may not be possible or at best extremely difficult because of the severe bending in the 2.5T field.
5. A lower field on the target may allow spectrometer magnets to be placed closer resulting in an increase in solid angle acceptance and access to the target.
6. Polarization reversal times might be made shorter. The technique of rapidly reversing the target polarization by rapid reversal of the target field would be simpler for reduced fields.

Some experience with low field targets has been gained with the CERN "frozen spin" targets.³⁸ The experimental method involves cooling the target sample by means of a dilution refrigerator. The target is dynamically polarized at about 0.5K and 2.5T. Then the microwave power is turned off and the temperature reduced. At the lower temperature the nuclear spin lattice relaxation time is longer and the polarization is frozen in. At this point the magnetic field can be reduced to 1T or less. In this configuration the target can be operated for several hours with only a relatively small loss in polarization.

A recent development³⁹ along these lines is the proposed Saclay frozen spin polarized target being designed for nucleon nucleon scattering experiments at SATURNE II. The polarizing solenoid and correction coils can achieve a relative uniformity of $\pm 5 \cdot 10^{-5}$ over the volume of the target at 2.5T. Experiments are performed in much smaller holding fields of 0.5 or 1T provided by freely orientable superconducting solenoids.

5.5 EPR Measurements in a Polarized Target

Large polarized targets are rather unsuitable for conventional EPR measurements because of the multimode cavities used and because of the very strong absorption of the good target materials. However, useful and relevant information can be obtained of the electron spin system by simply placing a resistance thermometer in contact with the microwave field of the cavity and deducing the microwave field strength from the resistance as a function of magnetic field at constant frequency. The bolometer shows clearly the transition of the target material from the non-absorbing state to complete absorption. This transition in a uniform field is rather sharp and has been used⁴⁰ successfully for determining the best polarizing frequencies in propanediol-Cr(V) and in butanol-PX at CERN. The same information could also be obtained by measuring the reflected power from the cavity, but one is then bound to use rather high microwave power, in contrast to the bolometric method whose sensitivity increases at low power (in a dilution refrigerator).

The Nucleon Electron Double Resonance (NEDOR) method¹⁶ operates on the principle that the NMR line changes its shape and position, when the EPR is saturated. In particular, when the EPR is fully saturated (whole line), then the shift of the NMR line is given by $\Delta H = H_S$, where

$$H_S = \frac{4\pi}{3} M_S \xi ;$$

H_S is the internal field caused by the electron magnetization M_S and ξ is a factor of the order of unity depending on lattice symmetry. The magnetization M_S can be related to the number N_S of electron spins in the system

$$M_S = N_S \gamma_S \hbar P_S .$$

If the microwaves are rapidly switched off, then the time constant of the recovery of the NMR frequency can be related to the various electronic relaxation times, mainly with T_{1S} when it is slow. Complicated cases may be obtained when T_{1S} is rather fast.

We might speculate that NEDOR could be used, in addition to measurements of spin concentration and shape of EPR, for distinguishing between different electron spin species, such as free radicals produced by radiation damage. This is clearly straightforward in the case of resolved EPR lines, but might also be applied to overlapping EPR lines whose spin lattice relaxation times differ significantly and which do not couple strongly with each other. For example, the H atom doublet line probably can be resolved, but trapped electrons may overlap with some broad radical lines; however, trapped electrons relax slowly.

We propose to study both of these in-situ methods in order to see their potential in trying to understand radiation damage in polarized targets.

Abragam and his coworkers have already used NEDOR in irradiated LiH.¹⁶ At CERN the changes in proton NMR lineshape have been observed but frequency shifts have not yet been measured.

6. SUMMARY

It was apparent at this workshop that polarized target physics is still an active and fertile field. Stable Cr(V) complexes have been developed. In particular, n-butanol-EHBA-Cr(V) targets with their fast polarization time, high polarization in He³ cryostats, higher hydrogen content than the diols, and increased stability compared to PX should become the standard target material once people gain experience in preparing the compound. Further experiments with the "dream" materials HD and CH₄ are being contemplated with some optimism and Li⁶D appears to have some promise. Further understanding of the radiation damage problem could come from incorporating NEDOR techniques into working polarized targets. Radiation induced DNP in undoped material offers a promising approach to a radiation resistant target especially when used in conjunction with optical bleaching.

In order to have a continuing program for investigating new polarized target materials and doping agents and their performance when exposed to ionizing radiation, it is necessary to have a dedicated polarized target facility near a high intensity source of radiation. Such a facility should also have a NEDOR or ESR capability to look for radicals which are produced during irradiation to try to better understand the processes which lead to depolarization.

Two institutions which currently have facilities for the study of DNP in the laboratory are Saclay and CERN though, at present, neither facility is located near an intense radiation source. It might be possible to install these systems in a beam at SATURNE or the CERN SC. Another possibility would be to obtain a small betatron or linac to use as a dedicated source of particles.

Such a facility would make possible a much more systematic investigation of target material than hitherto. Several groups with polarized target systems at various accelerators have made studies in a piecemeal way, but generally such measurements have been in accord with the physics program being conducted and existing accelerator schedules. This situation is not likely to change significantly and only specific measurements which can be fit into a particular schedule are likely to be made in the near future. Possible measurements are discussed below and could be made with PPT V at Argonne which routinely operates in a beam of greater than 10^{10} protons per pulse.

6.1 Irradiate Undoped Samples

G. Court et al.²⁷ have shown that it is possible to obtain a build-up of DNP in undoped butanol irradiated by photons. This work should be continued with butanol and other materials to measure what levels of polarization are possible with this method. The effect of annealing at various temperatures should also be studied. Such measurements could be done in a period when the physics experiment is being tuned up and when there is no need for the target to be polarized. After the cryostat measurements the sample could be removed for conventional ESR analysis. Doped samples could also be tested for comparison.

6.2 Study of New Complexes

Recent measurements of DNP at CERN³⁴ using butanol doped with EHBA show that polarizations of 75-80% are obtainable. This is to be compared with ~ 65% normally obtained with butanol doped with porphyraxide. On the other hand the butanol-porphyraxide mixture is more resistant (by a factor of ~ 3) to radiation damage when compared with ethanediol or propanediol doped with the more conventional Cr^{V} complexes. It is important to establish whether the butanol-EHBA mixture retains this resistance to radiation damage and what the annealing properties are. These measurements can easily be done during a normal physics run using the material as a target and polarizing it.

6.3 Tests of New Complexes

DNP tests of materials such as butanol and pentanol doped with new complexes can be carried out as part of the normal physics program. So long as reasonable polarizations are obtained, samples can be used as targets during the course of a physics experiment and their properties examined.

ACKNOWLEDGEMENTS

The PPT Workshop Committee would like to express our gratitude to the following individuals for valuable suggestions and discussion.

I. P. Auer	Argonne National Laboratory
W. R. Ditzler	Argonne National Laboratory
M. J. Eder	
P. H. Hansen	University of Michigan
P. Kyberd	Oxford University
J. D. Lesikar	Rice University
H. E. Miettinen	Rice University
J. R. Miller	Argonne National Laboratory
A. Penzo	INFN - Trieste
A. Perlmutter	University of Miami
L. Ratner	Argonne National Laboratory
J. Roček	University of Illinois
G. L. Salmon	Oxford University
S. Suwa	KEK
G. Theodosiou	Argonne National Laboratory
A. D. Trifunac	Argonne National Laboratory
D. G. Underwood	Argonne National Laboratory
L. VanRossum	CEN - Saclay

We would like to give special thanks to A. Abragam of the College de France for enlightening and entertaining discussions on many of the topics discussed in this report.

REFERENCES

1. D. G. Crabb et al., Phys. Rev. Lett. 41, 1257 (1978).
2. K. Heller et al., Phys. Rev. Lett. 41, 607 (1978);
K. M. Terwilliger, these Proceedings.
3. M. Borghini, "Choice of Substances for Polarized Proton Targets", CERN 66-3, Jan. 1966.
4. Proc. 2nd Int. Conf. on Polarized Targets (ed. G. Shapiro; LBL 500, UC-34 Physics, Nat. Tech. Inf. Serv., Springfield, Va., 1972).
5. H. M. Bozler et al., Bull. Am. Phys. Soc. 18, 545 (1973).
6. A. Honig, Phys. Rev. Lett. 19, 1009 (1967); H. Mano and A. Honig, Nucl. Instr. and Meth. 124, 1 (1975); A. Honig and H. Mano, Phys. Rev. B14, 1858 (1976); A. Honig, Proceedings of Symp. on Experiments Using Enriched Antiproton, Polarized-Proton, and Polarized-Antiproton Beams (ed. A. Yokosawa; ANL-HEP-CP-77-45, Argonne, Ill., 1977)p. 186.
7. J. C. Solem, thesis, Yale, 1968; J. C. Solem, Nucl. Instr. and Meth. 117, 477 (1974); J. C. Solem and G. A. Rebka, Phys. Rev. Lett. 21, 19 (1968).
8. M. Sharnoff and R. V. Pound, Phys. Rev. 132, 1003 (1963).
9. G. A. Rebka, private communication.
10. G. A. Rebka and M. Waine, Bull. Am. Phys. Soc. 7, 538 (1962).
11. R. L. Gamblin and T. R. Carver, Phys. Rev. 138, A946 (1965).
12. R. S. Timsit et al., Bull. Am. Phys. Soc. 15, 761 (1970).
13. H. H. McAdams and G. K. Walters, Phys. Rev. Lett. 18, 436 (1967).
14. R. T. Johnson et al., J. Low Temp. Phys. 10, 35 (1973).
15. E. Byckling et al., "A Polarized ^3He Target, Proposal for a Feasibility Study", Otaniemi, 1974.
16. Y. Roinel and V. Bouffard, J. Phys. 38, 817 (1977); A. Abragam and M. Goldman, Rep. Prog. Phys. 41, 395 (1978).
17. O. Runolfsson and S. Mango, Phys. Lett. 28A, 254 (1968).
18. P. VanHecke et al., Phys. Lett. 33A, 379 (1970).
19. A. J. Nijman and A. J. Berlinsky, Phys. Rev. Lett. 38, 408 (1977).
20. C. F. Hwang, private communication.
21. K. Scheffler, in ref. 4, p. 271.
22. M. Borghini et al., Nucl. Instr. and Meth. 84, 168 (1970).
23. C. C. Morehouse et al., Phys. Rev. Lett. 25, 835 (1970).
24. H. Petri and G. Abshire, Nucl. Instr. and Meth. 119, 205 (1974).
25. R. C. Fernow, Nucl. Instr. and Meth. 148, 311 (1978), and to be published.
26. S. Pshezetiskii et al., EPR of Free Radicals in Radiation Chemistry (J. Wiley, New York, 1974).
27. B. Craven, Thesis, Univ. of Liverpool (1973).
28. R. Alger et al., J. Chem. Phys. 30, 695 (1959).
29. M. Krumpolc, B. G. DeBoer, and J. Roček, J. Am. Chem. Soc. 100, 145 (1978).

30. M. Krumpolc and J. Roček, to be published.
31. D. A. Hill et al., Nucl. Instr. and Meth. 150, 331 (1978).
32. R. C. Fernow, to be published in Nucl. Instr. Meth.
33. A. Masaike et al., KEK preprint, 1978.
34. T. O. Niinikoski, these proceedings.
35. A. Abragam, Proc. 1st Int. Conf. on Polarized Targets, Saclay, 1966.
36. M. Borghini, in ref. 4, p. 1.
37. T. O. Niinikoski, Proc. 6th Cryogenic Eng. Conf., Grenoble.
38. T. O. Niinikoski and F. Udo, Nucl. Instr. and Meth. 134, 219 (1976).
39. S. Bréhin et al., to be published.
40. T. O. Niinikoski, Proc. Conf. on High Energy Phys. with Polarized Beams and Targets (ed. M. Marshak; AIP Conf. no. 35, Argonne, 1976) p. 458.

30. M. Krumpolc and J. Roček, to be published.
31. D. A. Hill et al., Nucl. Instr. and Meth. 150, 331 (1978).
32. R. C. Fernow, to be published in Nucl. Instr. Meth.
33. A. Masaike et al., KEK preprint, 1978.
34. T. O. Niinikoski, these proceedings.
35. A. Abragam, Proc. 1st Int. Conf. on Polarized Targets, Saclay, 1966.
36. M. Borghini, in ref. 4, p. 1.
37. T. O. Niinikoski, Proc. 6th Cryogenic Eng. Conf., Grenoble.
38. T. O. Niinikoski and F. Udo, Nucl. Instr. and Meth. 134, 219 (1976).
39. S. Bréhin et al., to be published.
40. T. O. Niinikoski, Proc. Conf. on High Energy Phys. with Polarized Beams and Targets (ed. M. Marshak; AIP Conf. no. 35, Argonne, 1976) p. 458.