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POLARIZED NUCLEAR TARGETS

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ABSTRACT

The static and dynamic methods for producing polarized targets are briefly discussed and compared. Nuclei that have been polarized by these methods are summarized. The equipment necessary for producing a working target is described, as are the capabilities presently available at LAMPF. A short description is presented of a polarized ^{13}C target proposed for use at the LAMPF HRS spectrometer, as an example of a polarized target for use in nuclear physics research.

I. INTRODUCTION

The feasibility of performing intermediate energy nuclear physics scattering experiments with polarized targets of protons and deuterons has been well established for many years. The extension of such an experimental program to include polarized heavier nuclei appears feasible for a certain limited number of nuclei. One possible candidate is ^{13}C . The purpose of this paper is to discuss briefly the methods for polarizing nuclei, to compare the relative advantages and disadvantages of the methods, to summarize the nuclei that have been polarized, and to describe the present experimental capabilities for polarizing at LAMPF.

Consider a nucleus with spin I ($I \neq 0$). I is related to the nuclear magnetic moment μ by the relation $\vec{\mu} = g \left(\frac{e\hbar}{2m_p c} \right) \vec{I}$ where g is the nuclear gyromagnetic ratio, $g = \mu/\mu_N$, $\frac{e\hbar}{2m_p c} = 5.050 \times 10^{-24}$ erg/gauss is the nuclear magneton μ_N , and $\vec{I}$ is the spin angular momentum vector. In a polarized target we require that the magnetic moments be aligned relative to some direction in space. The magnetic moment or, equivalently its associated magnetic field, provides a means to achieve preferential alignment through the use of various techniques. Almost all of the techniques involve subjecting the nuclear magnetic moment to external magnetic fields, which are manipulated to provide the desired polarization. To define polarization quantitatively, consider an ensemble of nuclei, each with spin I . If a magnetic field B is applied to provide an axis of quantization, the nuclei can be in any one of $2I + 1$ energy states, each characterized by a different value of m , the projection of the spin vector on the axis.¹ The values of m range from $-I \leq m \leq I$. If the population of each state is a_m , the polarization P is given by²

$$P = \frac{\sum_m m a_m}{I \sum_m a_m} .$$

When the various energy levels are not equally populated, the assembly is said to be oriented. The alignment A of the assembly is defined by²

$$A = \frac{\sum_m a_m [m^2 - I(I + 1)/3]}{I^2 \sum_m a_m} .$$

For spin $I > 1$, other parameters may be required to completely specify the system.² If $I = 1/2$, $A = 0$, the polarization P describes the system.

To polarize nuclei there are several ways in which magnetic fields are applied. Consider a nucleus in some substance. Each nucleus is subjected to the field of its surrounding electrons, as well as those of neighboring atoms. The net magnetic field is the sum over all other constituents within the sample. In addition, one can apply external fields. The techniques for applying fields fall under the broad category of static methods. We present a summary from Ref. 2.

II. STATIC METHOD FOR POLARIZING NUCLEI

A. General Considerations

The basic technique is to produce splitting by a $\vec{\mu} \cdot \vec{H}$ type interaction where the lowest energy level is appreciably populated. The sample is typically cooled to very low temperature 10 to 100 mK so the depolarizing effects of thermal agitation are minimized. One method is called orientation by magnetic hyperfine structure. This technique makes use of the fact that unfilled electron shells of a paramagnetic ion can produce a field at the nucleus of the order of 100,000 to 1,000,000 gauss. Thus, a technique that will orient the

moments of the electrons in space will orient the magnetic fields acting on the nuclei and hence will orient the nuclei. Using this idea paramagnetic materials in the form of either a powder or single crystal may be polarized by cooling to ~50 mK and simultaneously applying with a magnet an external field of, say, 500 gauss. Under these conditions the electron moments are magnetized to saturation and thus the magnetic fields they produce at the nuclei are polarized. The nuclei themselves, however, may or may not be polarized; this depends on the relative values of the nuclear hyperfine splitting $\frac{\mu B}{k}$, where μ = magnetic moment, B = the total field at the nucleus, and k = Boltzmann constant. If $\mu B/k$ is of the order of, or larger than, the lattice temperature, then polarization and/or alignment can occur.

In some single-crystal materials the direction of the crystalline electric field is fixed relative to the crystal axes. The interaction of this electric field with magnetic ions can restrain the direction of the magnetic field at the nucleus. At low temperatures an alignment occurs along or in a plane perpendicular to the axis of the electric field. A polarization can be produced by applying an additional external magnetic field. In Table I we list the nuclei that have been polarized by these techniques,² which is called the static method. The degree of polarization that can be obtained is a compromise among several factors. In general the lower the temperature the higher the polarization; however, from an experimental point of view the higher the temperature the easier the problem of handling heat loads. As a rough guide, at 0.35 K, ²⁷Co59 will have a polarization of 0.25 and an alignment of 0.2; ⁶⁷H0165 will have a polarization of 0.75.² To make more definite statements, one would have to consider details of the desired polarized nuclei in conjunction with the specific requirements of the proposed experiment.

TABLE I
NUCLEI POLARIZED BY STATIC METHODS

23V	51Sb	62Sm	70Yb
25Mn	58Ce	65Tb	92U
27Co	59Pr	66Dy	93Np
29Cu	60Nd	67Ho	94Pu
33As	61Pm	68Er	95Am

Polarization can be obtained by applying with a magnet a strong external magnetic field which acts directly on the nuclei. In addition, the material is cooled to low temperature, the technique is called the brute-force method. It is in principle applicable to all substances but in practice is restricted to materials (such as metals) where the nuclear-spin-lattice relaxation time is short enough to permit reasonable polarization times. We consider the case of hydrogen and evaluate the brute-force polarization at 10 T and 0.01 K. For protons $\mu = g\mu_N$, where $g = 2.79$ and μ_N is as was given previously,

$$P = \tanh \left(\frac{\mu B}{kT} \right)$$

$$\frac{\mu}{k} = \frac{(2.79)(5.050 \times 10^{-24} \text{ erg/gauss})}{1.380 \times 10^{-16} \text{ erg/K}} = 1.02 \times 10^{-3} \frac{\text{K}}{\text{T}}$$

$$\frac{B}{T} = \frac{10\text{T}}{0.01\text{K}} = 10^3 \frac{\text{T}}{\text{K}}$$

$$P = \tanh [(1.021 \times 10^{-3})(10^3)] = \tanh (1.021)$$

$$P = 0.77 \text{ or } 77\%$$

If the temperature is increased to 0.02 K,

$$P = \tanh (.51) = .47 \text{ or } 47\% .$$

We see that very low temperatures and strong fields are required for reasonable polarization.

There are presently at least two groups, one at Karlsruhe and another at Duke University, who have active programs of nuclear research using the brute-force technique. Both groups are conducting experiments with neutron beams incident on the polarized target. In Table II below we indicate the types of nuclei and polarization (at 10 T, and 0.01 K) to be expected with this method.^{3,4} There are other methods for polarizing nuclei, at least three of which should be mentioned. The optical-pumping method has been used to polarize ³He gas to about 50% at a density of 10¹⁸ atoms/ml. The rotating sample method has polarized hydrogen in a sample of yttrium ethyl sulfate (YES). A relatively new method called microwave-induced optical-nuclear polarization (MIONP) was used to polarize hydrogen to 42% in fluorene. These methods all have potential application in producing polarized nuclear targets, but at this time their utilization has been very limited.

TABLE II
NUCLEI POLARIZED OR PROPOSED TO BE POLARIZED
BY THE BRUTE FORCE TECHNIQUE

3He3(1/2+), [50%]	23V51(7/2-), [63%]	55Cs133(7/2+), [27%]
3Li6(1+), [15%]	25Mn55(5/2-), [51%]	57La139(7/2+), [30%]
3Li7(3/2-), [57%]	29Cu63(3/2-), [42%]	59Pr141(5/2+), [45%]
4Be9(3/2-), [23%]	29Cu65(3/2-), [44%]	73Ta181(7/2+), [35%]
5B11(3/2-), [49%]	33As75(3/2-), [20%]	75Re185(5/2+), [48%]
		75Re187(5/2+), [48%]
11Na23(3/2+), [30%]	41Nb93(9/2+), [63%]	81Tl203(1/2+), [53%]
12Al27(5/2+), [53%]	49In113(9/2+), [63%]	81Tl205(1/2+), [53%]
21Sc45(7/2-), [60%]	49In115(9/2+), [63%]	83Bi209(9/2-), [54%]

B. Static Method Hardware Requirements

As a general statement, static methods require very low temperature $T \lesssim 0.02$ K. The lower the temperature, the better the polarization. To obtain very low temperature a dilution refrigerator is used. An external magnet may or may not be required, depending on the material being polarized. For materials that are polarized by the brute-force method, very strong, 7 to 10 tesla, external fields are required. Fields of this strength can be obtained with superconducting magnets. The polarization of the sample can be calculated provided one knows the temperature.

III. DYNAMIC METHOD FOR POLARIZING NUCLEI

A. General Considerations

Dynamic nuclear polarization (DNP) techniques^{5,6} have been developed within the last twenty years. There are four basic requirements for DNP that are listed in Table III.

TABLE III

EXPERIMENTAL REQUIREMENTS FOR DYNAMIC NUCLEAR POLARIZATION

1. A suitable material containing the nuclei of interest along with paramagnetic polarizing centers required for spin pumping.
2. Cooling of the material to low temperature $T \lesssim 0.5$ K.
3. Exposing the material to a strong and uniform (10^{-4}) 2.5T magnetic field.
4. Irradiating the material with microwaves at a frequency near 70 GHz.

The main features of DNP are that at low temperature and strong field the electrons associated with the paramagnetic centers are almost completely polarized. The electron polarization is then transferred to the nuclei by applying microwave energy at the correct frequency to induce electron-nuclear spin flips. A key feature is that the electron-spin-lattice relaxation time is short while the nuclear relaxation time is long. Thus, for example, a nuclear spin that has been flipped parallel to the field will remain there while the corresponding electron will flip back so that it can be used again to flip other nuclei. In this manner microwave-induced spin pumping permits, in some cases, substantial polarization to be produced. Nuclei that have been polarized in this way are listed in Table IV.

TABLE IV
NUCLEI POLARIZED BY DNP

$^2\text{He}3(1/2+)$, [20%]	$^7\text{N}14(1+)$, [12%]
$^3\text{Li}6(1+)$, [70%]	$^7\text{N}15(1/2-)$, [12%]
$^3\text{Li}7(3/2-)$, [80%]	$^9\text{F}19(1/2+)$, [70%]
$^5\text{B}10(3+)$, [37%]	$^{13}\text{Al}27(5/2+)$, [10%]
$^5\text{B}11(3/2-)$, [60%]	$^{20}\text{Ca}43(7/2-)$, [80%]
$^6\text{C}13(1/2+)$, [26%]	$^{57}\text{La}139(7/2+)$, [40%]

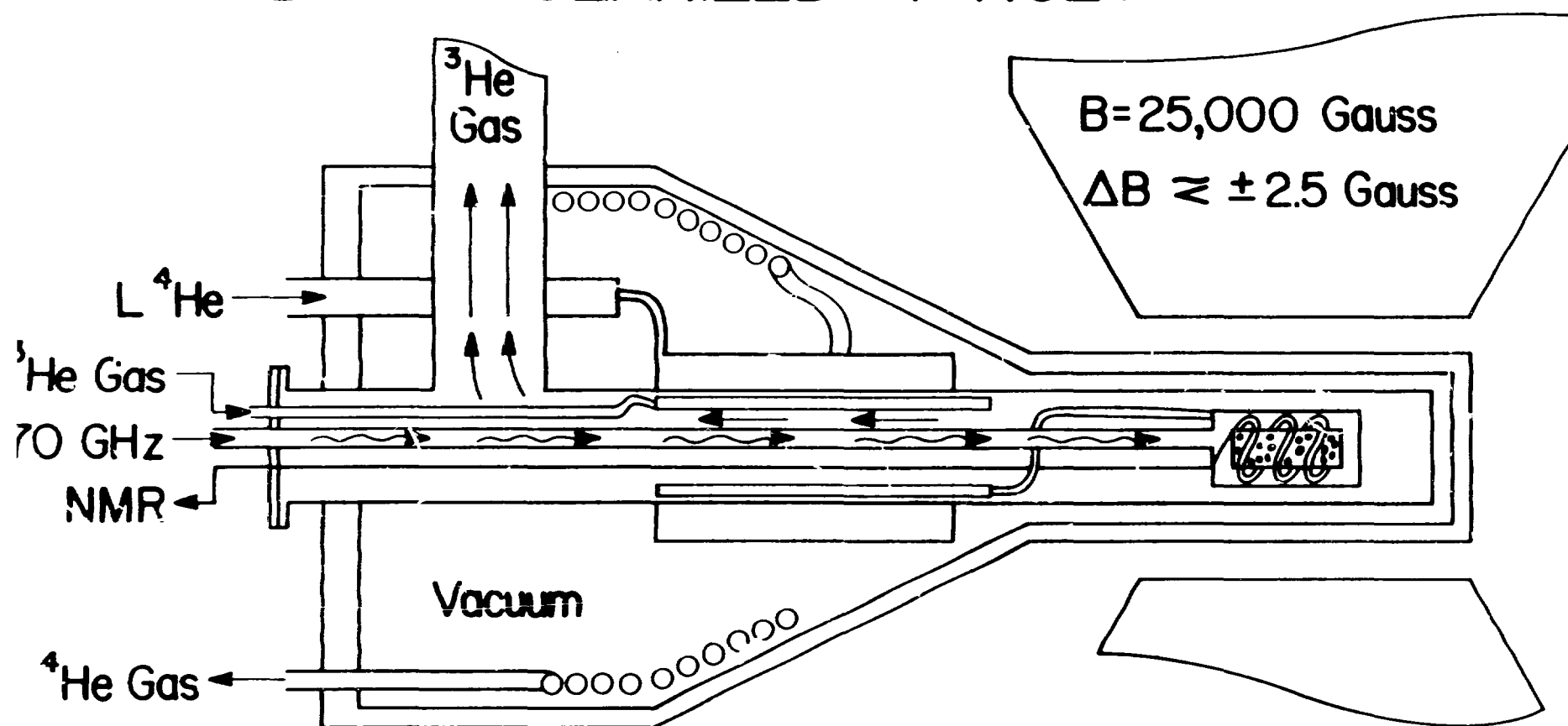
B. DNP Hardware Requirements

There are four main hardware requirements for DNP as follows:

1. A polarizing magnet capable of providing a 2.5-T field with uniformity $\lesssim 10^{-4}$ throughout the target volume.
2. A cryogenic refrigerator capable of cooling the target material to < 0.5 K.
3. A 70-GHz microwave system.
4. A system for measuring the degree of polarization, usually by nuclear magnetic resonance (NMR) techniques.

The apparatus is shown in schematic form in Fig. 1. The magnet can be either a conventional electromagnet with resistive windings or superconducting. Which type is used depends on details of the experiment requirements. Of paramount importance is field uniformity throughout the target volume, which must typically be of the order of ± 2.5 gauss out of 25,000 gauss. The uniformity requirement ensures a well-defined spin-transition frequency; a substantial field deviation could result in a nonuniform polarization of the sample. To achieve the low polarizing temperature of 0.5 K, two types of refrigerator have been used, a ^3He evaporation type and a powerful dilution cryostat. A ^3He refrigerator is shown in Fig. 1. With this system, liquid ^4He

DNP POLARIZED TARGET



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DNP Requirements:

1. Strong and uniform magnetic field - 2.5 T
2. Low temperature $T < 0.5\text{ K}$
3. Microwaves
4. Target material with paramagnetic polarizing centers

Fig. 1. Schematic diagram of a DNP Polarized Target.

is used to cool the radiation shields and inner heat exchangers. To obtain 0.5 K, ^3He is used in a closed-loop cryogenic mode. The room-temperature ^3He gas is delivered to the cryostat where it is cooled down and condensed to liquid at about 2 K under a pressure of 200-400 torr. The liquid ^3He then passes through a heat exchanger (not shown) which cools it to less than 1 K, then it is expanded directly in the target cell to a low pressure of about 0.1 torr. Liquid ^3He at 0.1 torr has a temperature less than 0.5 K. Powerful roots-type pumps maintain this low pressure. Refrigeration is needed because of the heat load generated by the polarizing microwaves, which is typically 1-2 mW per gram of material, and to a lesser extent that caused by a charged particle beam. Refrigeration is accomplished because it takes energy, the latent heat of vaporization (about 30 joules/mole at 0.5 K), to cause atoms of ^3He to change phase from liquid to gas. After being pumped, the ^3He gas is routed through a special handling and purification system and then directed back to the refrigerator. When the experiment is complete, the gas is pumped into sealed tanks for storage.

The polarizing microwaves are generated by either carcinotrons or extended-interaction oscillator-type tubes. The frequency required is near 70 GHz. These tubes are tuned remotely to the optimum frequency for best polarization. The microwave power is directed onto the target material by a special wave guide.

Target polarization is measured by nuclear magnetic resonance (NMR). With the NMR method two separate measurements are required. One measurement is called the thermal equilibrium (TE) calibration. It is done with the microwaves off and at a higher temperature where the spin-system thermal relaxation time is short enough to ensure that thermal equilibrium has been achieved. Under this special condition the degree of target polarization (P) can be calculated. For

spin $1/2$, $P = \tanh(\mu B/kT)$ where the symbols in the argument of the hyperbolic function have the same meaning as previously. The area of the measured TE signal corresponds to the calculated polarization, which in turn calibrates the measuring system. After this measurement is complete the temperature is reduced and the microwaves applied. As the polarization increases so does the measured NMR signal area; one then takes the ratio of the enhanced signal area to the TE signal area times the calculated TE polarization to obtain the enhanced polarization. With this method the hydrogen polarization of targets used at LAMPF can be measured to an accuracy of about $\pm 4\%$.

Of critical importance to DNP is the target material. It must contain the nuclei of interest and paramagnetic polarizing centers. The solid state physics requirements are a short thermal relaxation time for the paramagnetic electrons and a much longer nuclear relaxation so that DNP can be achieved. The chemistry compatibility problems are in many cases difficult; as a result, to date, a very broad application of DNP has not been carried out.

Within the last several years a new and quite powerful technique has been developed in conjunction with DNP; it is called the frozen-spin target.^{7,8} With this method the material is polarized with a dilution refrigerator at 0.5 K and 2.5 T as already described. After polarizing, the microwaves are turned off and the temperature of the material reduced to about 0.05 K. At this very low temperature the nuclear spin lattice relaxation time is long, about 200 to 300 hours, so that the polarization is effectively frozen, hence the term frozen-spin target. At this stage the magnetic field can also be reduced from 2.5 T to about 0.5 T or less. The field can be reduced by either turning the magnet down or physically moving the target to a region of lower field. This provides two important advantages to experiments. First, the magnetic deflection of scattered charged particles is substantially reduced, and second,

the solid-angle access for detection of particles can be increased. This technique has been used quite effectively with polarized proton and deuterium targets.^{8,9,10}

IV. POLARIZED TARGET EQUIPMENT AVAILABLE AT LAMPF

With targets polarized by DNP, the polarizing magnet determines the direction of the target polarization either $\hat{n}$, $\hat{l}$, or $\hat{s}$. Here the unit vector $\hat{n}$ is normal to the horizontal scattering plane and is defined by

$$\hat{n} = \frac{\vec{k}_i \times \vec{k}_o}{|\vec{k}_i \times \vec{k}_o|}$$

where $\vec{k}_i$ is the incident beam momentum and $\vec{k}_o$ the scattered particles momentum.

$$\text{The vector } \hat{l} = \frac{\vec{k}_i}{|\vec{k}_i|} \text{ and } \hat{s} = \hat{l} \times \hat{n}.$$

Several complete magnet systems are available for experiments. By a system we mean the magnet, its associated power supply, and control electronics, as well as a mounting stand. In Table V we present a summary of these systems. Two complete refrigerator systems are available for use with the magnets, there are, however, some compatibility limitations. The available systems are summarized in Table VI. A new very powerful 250 mW dilution refrigerator is under development and should be available for experiments by 1987. Two complete systems are available that provide 70 GHz microwaves with power levels up to several watts. For measuring the target polarization two complete NMR systems are available. These systems were designed to measure proton polarization at

106 MHz and 2.5 T field ($\omega_p = 42.577$ MHz/T). Modifications would be required to measure the polarization of other nuclei. With some nuclei it may not be practical to measure the polarization by NMR, in which case other special techniques or new technology may be required.

TABLE V
POLARIZED TARGET MAGNET SYSTEMS AT LAMPF

1. ZOLTAN C-Type Electromagnet
Field: 2.5 T
Uniformity: $< 2 \times 10^{-4}$ throughout ~05 cc
Pole Gap: 3-5/8 in
Field Direction: $\hat{n}$ or $\hat{s}$
2. VARIAN C-Type Electromagnet
Field: 2.5 T
Uniformity: $< 10^{-4}$
Pole Gap: 3 in
Field Direction: $\hat{n}$ or $\hat{s}$
3. HERA Superconducting Split-Coil Solenoid
Field: 2.5 T
Uniformity: $< \times 10^{-4}$ throughout ~64 cc
Warm Bore: 11 in diameter
Field Direction: $\hat{q}$ or $\hat{s}$
4. Superconducting Solenoid
Field: 2.5 T
Uniformity: $< 10^{-4}$ throughout 390 cc
Warm Bore: diameter 7-1/2 in
Field Direction: $\hat{q}$ or $\hat{n}$

TABLE VI

POLARIZED TARGET REFRIGERATOR SYSTEMS AT LAMPF

1. Vertical ^3He (0.5 K) refrigerator;
compatible only with the HERA magnet.
2. Vertical dilution (~ 0.05 K) refrigerator;
compatible only with the HERA magnet.
3. Horizontal or vertical ^3He (0.5 K) refrigerator;
compatible with ZOLTAN, VARIAN, or HERA magnet.

V. COMPARISON OF DNP AND STATIC POLARIZATION METHODS

In Table VII we compare some general features of the DNP and static methods.

TABLE VII

COMPARISON OF DNP AND STATIC POLARIZATION METHODS

	<u>DNP</u>	<u>STATIC</u>
Field	2.5 T 0.5 T (frozen spin)	6 - 10 T or <1T depending on material
Temperature	0.5 K	<0.05 K, for urute force, <0.02 K
Polarization	20 - 90%	20 - 90%
Polarization Reversal	Change Microwave Frequency	Reverse the applied field or rotate the sample

DNP possesses two main advantages over static methods: higher polarizing temperature (~ 0.5 K) and the ability to reverse the polarization without

changing experimental conditions. The higher polarizing temperature is important when the experiment requires the use of a charged-particle incident beam. Detected count rates are directly proportional to the incident beam intensity and beam heating effects are cryogenically easier to handle at higher temperatures. The ability to reverse the polarization without changing experimental conditions is important in the reduction of systematic errors. With DNP this is accomplished by changing the frequency of the polarizing microwaves, all other conditions remain the same. With static methods the polarization is reversed by changing the polarity of the applied field or by rotating the sample. In some cases with the static method, the external field can be much smaller ($<1\text{T}$) than with DNP (2.5 T typical). This feature has important potential advantages for experiments that require low-momentum charged beams or the detection of low-momentum charged particles.

Another important consideration is the chemical composition of the target material. With DNP, paramagnetic polarizing centers are required, which imposes chemical restraints on the form and compatibility of the material. Existing polarized hydrogen or deuterium targets are not pure hydrogen or deuterium. To date the materials used have been of the general form $\text{HO}-\overset{\text{H}}{\underset{\text{H}}{\text{C}}}-$. With these materials hydrogen or deuterium comprises about 10% of the total mass. For most experiments the carbon, oxygen, and other nonhydrogenous nuclei are a source of background which must be taken care of by careful experimental design and corrections made to the acquired scattering data. In some cases the contemplated experiment may not be feasible because of the large background. With the static method various nuclei have been polarized in essentially pure form. An example is holmium where a sample in the form of a single crystal can be polarized by simply cooling it to low temperature. The very low temperature ($<20\text{ mK}$) and strong applied field (6-10 T) required with the brute force method

presents particularly severe problems for experiments considering a brute-force polarized target. The heating caused by charged particle beams will raise the temperature of the sample, which results in lower polarization. For example, an energy loss of 1 MeV per particle with an incident beam intensity of 1 picoamp ($= 6.25 \times 10^6$ particles per second), results in a heat load of 1 μ watt (10 ergs/sec). Dilution refrigerators are available that can absorb heat loads of this amount while maintaining the temperature of the refrigerant liquid at 20 mK or less; however, at these very low temperatures, the Kapitza resistance between the material and refrigerant becomes significant. Herringa¹¹ has estimated that with a heat load of 0.5 μ W at 0.01 K the proton polarization will decrease from 75% to 44% in a sample of TiH_2 . The very large magnetic field of 6-10 T bends the trajectory of scattered charged particles; the amount of bending will limit the lowest-momentum particle that can be detected.

VII. POLARIZED ^{13}C TARGET, LAMPF PROPOSAL E955

As an example of a DNP polarized nuclear target, we consider LAMPF proposal E955, "Search for Experimental Proof of the Existence of Lower Components in the Nuclear Wave Function." This experiment requires a polarized ^{13}C target; it is proposed to be done in three stages, each stage corresponding to a different target polarization direction, i.e., $\hat{n}$, $\hat{l}$, and $\hat{s}$. The experiment consists of elastically scattering polarized protons from polarized ^{13}C and measuring the polarization of the scattered proton. The feasibility of polarizing ^{13}C by DNP techniques was established previously at CERN.^{12,13} In the first CERN experiment, the target material used ^{13}C enriched (44%) 1 butanol [$\text{CH}_3(\text{CH}_2)_4^{13}\text{CH}_2\text{OH}$]. The target consisted of a conventional electromagnet with 2.5 T field and a liquid ^4He evaporation refrigerator (0.5 K). A ^{13}C polarization of 21% was obtained, the polarization was measured by NMR. E955

aims to measure $\vec{p} - {}^{13}\vec{C}$ elastic scattering. Excellent momentum resolution as provided by the LAMPF HRS spectrometer is required to separate the ${}^{13}\text{C}$ elastic events from other nuclei in the target. Elastic events from ${}^{12}\text{C}$ are of particular concern because it may not be possible to separate these from ${}^{13}\text{C}$ at all angles where measurements are desired. Because of this concern, the material chosen for the experiment was 99% ${}^{13}\text{C}$ -enriched ethanediol $\text{HO}-{}^{13}\text{C}(\text{H})-{}^{13}\text{C}(\text{H})-\text{OH}$. This enriched material has a minimal amount of ${}^{12}\text{C}$, is available commercially, and the feasibility for polarizing ${}^{13}\text{C}$ in it has been established.¹³

The bending of the elastically scattered protons at 500 MeV is about 15° for an $\hat{n}$ type 2.5 T polarizing field. This amount of bending deflects the protons too much, so they are not detected. Further investigation revealed that by offsetting the center of the polarizing magnet 3/16" upstream and 7/16" beam left of the HRS physical pivot, then for the 10° - 30° angular range desired, the scattered protons can be detected.

The actual experimental resolution that can be obtained is affected by multiple scattering and energy loss in the metal of the target cryostat. In order to reduce these effects as much as possible, special mylar windows were designed and tested vacuum-tight at cryogenic temperatures. Windows of this type will be installed on the refrigerator thereby substantially reducing multiple scattering and energy loss.

The experiment consists of a three spin measurement where the polarization of the scattered proton is analyzed with a polarimeter. To keep running times manageable, beam currents as high as possible are desired. A practical limitation on the beam intensity is radiation damage to the target materials. Beam heating effects at 0.5 K are very small. Experimentally, radiation damage manifests itself in a deterioration of target polarization. With hydrogen

targets, after a flux of about 10^{14} particles/cm² have traversed the sample, polarization is reduced to $1/e$ of the original value.¹⁴ The corresponding flux has not been measured for ¹³C, but we expect it to be similar to that for hydrogen because the radiation damage mechanism should be essentially the same for both nuclei. Polarization can be partially restored by "annealing" the target, which consists of raising the temperature to 120-140 K for a few minutes and then cooling back down. Repolarizing the target yields a maximum polarization a few percent less than what was obtained prior to the 10^{14} particles/cm². The radiation damaging and annealing process can be repeated several times before the damaged material must be replaced. The amount of beam current that can be reasonably tolerated is a question that can only be answered by direct experiment. Systematic effects such as a local depolarization within the sample must be carefully monitored. This requires careful experimental design to ensure that one is able to measure quantities sensitive to this effect.

VII. CONCLUSION

Many nuclei have been polarized by either static or dynamic methods. To date only a very few nuclei, primarily hydrogen and deuterium, have been utilized in scattering experiments. This has been due in part to the technical complexity of the targets and in some cases to the rather severe limitations imposed by the various polarizing methods. The development of dynamic nuclear polarization techniques coupled with the frozen-spin concept, which utilizes a powerful dilution refrigerator, offers the hope that several nuclei with $Z > 1$ may be polarized, thereby permitting new and potentially very important nuclear scattering experiments to be carried out. For this to be realized numerous technical problems will have to be solved and a concerted effort made on

developing new target materials. Such an effort requires the effective collaboration of personnel with expertise in nuclear-scattering experiments, low-temperature cryogenics, solid state, and polarized target physics, as well as chemistry.

A somewhat restricted number of experiments can probably be performed utilizing nuclei that have already been polarized with the conventional methods. Because of the very strong magnetic fields associated with the brute-force polarization, utilization of this technique will probably focus on experiments that detect either neutral or relatively high-momentum charged particles.

REFERENCES

1. G. E. Pake, Nuclear Magnetic Resonance, "Solid State Physics Advances in Research and Applications," Volume 2, Academic Press, Inc., New York, 1956, 1.
2. J. M. Daniels and J. Goldenberg, "Nuclear Reactions with Oriented Target Nuclei and Polarized Beams," Reports on Progress in Physics, Volume 25 (1962), 1.
3. R. Aures, W. Herringa, H. O. Klages, R. Maschaw, F. K. Schmidt, and B. Zeitnitz, "A Brute Force Polarized Proton Target as an Application of a Versatile Brute Force Polarization Facility," Nuclear Instruments and Methods in Physics Research, 224, (1984), 347.
4. C. R. Gould, D. G. Haase, K. Nase, N. R. Roberson, and L. W. Seagondollar, "Polarized Target Facility for Neutron Physics Experiments," Sixth International Symposium on Polarization Phenomena in Nuclear Physics, Osaka, Japan, 26-30 August, 1985, 282.
5. C. D. Jeffries, Dynamic Nuclear Orientation, "Interscience Tracts on Physics and Astronomy," Interscience Publishers, John Wiley and Sons, New York, London, and Sidney, 1963.
6. A. Abragam, "Polarized Targets: How?," Proceedings of the International Conference on Polarized Targets and Ion Sources, Saclay, France, December 5-9, 1966, 27.
7. T.O. Niinikoski, Polarized Targets at CERN, "High Energy Physics with Polarized Beams and Targets," Argonne, 1976, AIP Conference Proceedings No. 35, 458.
8. J. Ball, "Improvements of the Polarized Target for Nucleon Nucleon Experiments at Saturne II," Proceedings of the Fourth International

Workshop on Polarized Target Materials and Techniques, Bad Honnet, Federal Republic of Germany, September 3-6, 1984, 112.

9. D. Hill, "A Frozen-Spin Polarized Proton Target for Use at LAMPF," High Energy Spin Physics, 1982, Brookhaven, AIP Conference Proceedings No. 95, 485.
10. T. O. Niinikoski and F. Udo, "Frozen-Spin Polarized Target", Nuclear Instruments and Methods, 134, 1976, 222.
11. W. Heeringa, "A Brute-Force Polarized Proton Target," Proceedings of the Fourth International Workshop on Polarized Target Materials and Techniques, Bonn, Federal Republic of Germany, September 1984, 129.
12. M. Borghini and F. Udo, "Dynamic Polarization of ^{13}C Nuclei In 1-Butanol" Physics Letters 43A, 1973, 93.
13. W. de Boer, et al., "Dynamic Polarization of Protons, Deuterons, and Carbon-13 Nuclei: Thermal Contact Between Nuclear Spins and an Electron Spin-Spin Interaction Reservoir," Journal of Low Temperature Physics 15, 1974, 249.
14. R. Fernow, "Radiation Damage in Polarized Target Materials," Nuclear Instruments and Methods 148, 1978, 311.