Proceedings of Polarized Fusion Fuel Workshop

G.L. Kulcinski, L.W. Anderson, H.H. Barschall, J.D. Callen, and W. Haeberli

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FUSION TECHNOLOGY INSTITUTE

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Held in
Madison, Wisconsin
on
28-30 March 1983

G.L. Kulcinski - Chairman
L.W. Anderson - Organizing Committee
H.H. Barschall - Organizing Committee
J.D. Callen - Organizing Committee
W. Haeberli - Organizing Committee

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I. INTRODUCTION

I. Introduction

In the 25 October 1982 issue of Physical Review Letters, R.M. Kulsrud, H.P. Furth, E.J. Valeo and M. Goldhaber (see Appendix A) made the suggestion that polarization of the reacting particles could be used to change the reaction rates and the angular distributions of the reaction products in the plasma of a fusion reactor. This suggestion was discussed in more detail in two reports of the Princeton Plasma Physics Laboratory (PPPL-1912 and PPPL-1949). Popular accounts of the suggestion also appeared in the August 1982 issue of Physics Today and in the September 1982 issue of Fusion.

Atomic and nuclear physicists have used polarized nuclei for many years, but typically only microscopic quantities or microamperes of charged-particle beams have been involved. For pure hydrogen the maximum degree of polarization has been around 80%. For applications in fusion, beam intensities eight orders of magnitude larger, as well as higher degrees of polarization are needed, hence new methods would have to be developed.

The kind of questions that arise when fusion reactors using polarized fuels are considered are listed in Appendix B. The problems are in atomic physics, nuclear physics, plasma physics, and reactor engineering, and possibly also in surface physics and condensed matter physics.

In December of 1982, members of the Fusion Engineering Program at the University of Wisconsin proposed to the Office of Fusion Energy of the U.S. Department of Energy that a workshop should be held to address some of the questions that had arisen in the past few months concerning the promise of spin polarized fuel in fusion reactors. It was felt that it would be desirable to bring together the scientists who had suggested research and development projects and experts in the various areas of physics many of whom had not previously worked in fusion. In February 1983, after the Office of Fusion Energy had approved the workshop, invitations were distributed, and those who actually participated in the workshop are listed in Appendix C.

The meeting took place on March 28-30, 1983 at the University of Wisconsin-Madison and the program is shown in Appendix D. The first day consisted of presentations on the present state of knowledge in the pertinent areas of atomic and nuclear physics, as well as papers on the basic ideas of the proposed use of polarized fuels. In the morning of the second day the participants met in four groups for informal discussions on what is known and what data should be obtained as soon as possible. The nuclear physics and reactor panels finished their discussions at noon. After a brief general meeting of all participants in the early afternoon, all the participants joined either the plasma panel or the sources panel. The secretaries of each of the four panels presented a summary of the work of their panels on Wednesday morning; each report was followed by a lively discussion. On Wednesday afternoon, an overview of the workshop was given.

The abstracts of the papers that were presented are reproduced in the following pages, followed by the reports of the panel secretaries and the workshop summary. No formal papers were required because of the short notice before the workshop.

We should like to thank the Office of Fusion Energy for providing financial support for the workshop and all the visitors, especially those who were willing to make long trips on short notice, for their contributions to the workshop.

II. ABSTRACTS OF INVITED PAPERS

POLARIZED NUCLEI

Maurice Goldhaber

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Nuclear physicists are used to treating different isotopes of an element as if they were different species. All the known forces, strong, electromagnetic, weak and gravitational, interact differently with different isotopes of an element. Since a nucleus with a non-zero nuclear spin can be polarized, we can think of each direction of polarization as representing a (temporarily) different species, because the interactions which are important, the strong, electromagnetic and weak, are different for different spin directions. Under special conditions we can keep each "species" essentially isolated. Many fundamental insights have come from the production and interaction of polarized particles and nuclei; and the possibility of important applications is now being considered.

My interest in the role of nuclear spin in nuclear reactions began about 50 years ago, when I became a research student at the Cavendish Laboratory. Cockcroft and Walton were then studying the reactions of Li isotopes with hydrogen isotopes. I tried to understand why they found a much better yield for the reaction $^{6}Li(d,\alpha)\alpha$, than for the reaction $^{7}Li(p,\alpha)\alpha$. At that time the spin of ^{6}Li was believed to be zero, because no hyperfine structure had been seen in its atomic spectra. Assuming that the deuteron ($I = 1$) interacts with ^{6}Li predominantly in an S wave, I drew the simple conclusion that this reaction would be "spin forbidden", unless the spin of ^{6}Li was $I = 1$, because two α-particles could not have relative angular momentum $\ell = 1$. Soon Fox and Rabi, using an atomic beam method, showed explicitly that the spin of ^{6}Li was indeed larger than zero.

After Fermi and his collaborators had demonstrated the existence of slow neutrons in October of 1934, one could expect that the reaction $^{6}Li(n_{slow},{}^{3}H)\alpha$ was not only exothermic but also "spin allowed", and immediately Chadwick and I were able to establish this reaction. For polarized slow neutrons one should obtain polarized ^{3}H. I believe this has not been tested.

We know many methods to polarize nuclei on a small scale. Can we do it on a large scale? New ideas, to be given a chance, should be approached with courage, optimism and a critical attitude — preferably in descending proportions. Let me take the liberty to raise some questions which this workshop may either dismiss immediately or find worth a closer look. Generally speaking, whenever we want to polarize nuclei, we must somehow introduce net angular momentum in such a way that it is transferred to the nuclei.

We can impart angular momentum in many ways. The most obvious is to start a macroscopic body spinning. In the gyromagnetic effect studied by Barnett macroscopic angular momentum is transferred to the spin of electrons. Under suitable conditions this will also happen for nuclear spin. Could we learn something interesting from such studies?

The angular momentum carried by circularly polarized photons can be used to polarize bound electrons and their spin transferred to nuclear spin. We shall hear about this later. Could this perhaps be done on a large scale with the high intensity lasers developed for inertial fusion? Could we transfer a large amount of angular momentum to a drop of liquid hydrogen, etc., by using circularly polarized laser light not only to polarize electrons but also to polarize protons, etc?

Recently intense beams of polarized electrons have been produced by transferring angular momentum from photons to photo-electrons from gallium arsenide. Could these electron beams be used to transfer spin efficiently to nuclei either in a gas where they stop or, e.g., by sending them along proton beams with which they will have ample time to interact?

Clearly, if and when intense sources of polarized nuclei become easily available, we shall see a big impact on both research and applications, perhaps in some respects comparable with the effect of the easy availability of separated isotopes during the last forty years. Besides polarized plasma fusion there could be other applications, e.g., polarized nuclei like ^{3}He, ^{6}Li and ^{10}B might permit improved methods of producing and detecting polarized neutrons, thermal as well as epithermal.

We are clearly at a time of widespread interest in the field of nuclear polarization, and this workshop may help us to focus our ideas.

POLARIZATION OF NUCLEI IN NUCLEAR FUSION -- REVIEW

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Abstract

The normal D-T fusion reaction is actually a combination of different nuclear reaction channels depending on the particular relative orientation of the D and T nuclei. These channels have different strengths and angular distributions of the reaction products. These channels can be separated out by properly polarizing the nuclear fuel prior to its injection into a hypothetical fusion reactor. It will be shown that this polarized fuel should stay polarized to a high degree. The various depolarization mechanisms will be discussed and it will be shown that their rates are very likely so small that the plasma in the fusion reactor should stay polarized to a high degree.

CROSS SECTIONS FOR POLARIZED FUSION REACTIONS

G. M. Hale, Theoretical Division, Los Alamos National Laboratory

The work of Kulsrud et al.[1] has strongly revived interest in cross sections for fusion reactions induced by polarized particles. Here, we review briefly the formalism nuclear physicists use to describe such cross sections, survey the polarized beam-polarized target data available for the d-t, d-^{3}He, and d-d reactions, and give results from Los Alamos R-matrix analyses of these and other data for polarized cross sections of interest in fusion reactors.

The center-of-mass differential cross section for a nuclear reaction can be expressed as

$$\sigma(\underline{k}',\underline{k},\hat{s}) = \mathrm{Tr}[M(\underline{k}',\underline{k})\rho(\hat{s})M^{\dagger}(\underline{k}',\underline{k})] \quad , \tag{1}$$

where $\underline{k}$ and $\underline{k}'$ are the initial and final momenta, respectively, and $\hat{s}$ is the spin quantization axis direction (i.e., the $\underline{B}$-field direction) for specifying the spin states of the initial particles through the density matrix ρ. The transition matrix M contains all the nuclear dynamics of the reaction. The rotationally invariant cross section (1) depends only on the relative angles of $\underline{k}'$, $\underline{k}$, $\hat{s}$, as for instance, the set (θ,β,ϕ), shown in Fig. 1.

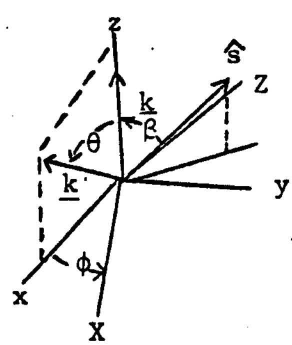

Fig. 1. Scattering coordinate system.

In the xyz coordinate system, which is conventionally used to describe scattering processes, M depends only on the scattering angle θ, and the cross section becomes

$$\sigma(\theta,\beta,\phi) = \mathrm{Tr}[M(\theta)\rho(\beta,\phi)M^{\dagger}(\theta)] \quad . \tag{2}$$

Integrated cross sections for fixed β can be defined by

$$\sigma(\beta) = \int_0^{2\pi} d\phi \int_{-1}^{1} d(\cos\theta)\ \mathrm{Tr}[M(\theta)\rho(\beta,\phi)M^{\dagger}(\theta)] \quad . \tag{3}$$

For unpolarized particles having spins s_a and s_b, the density matrix becomes a multiple of the unit matrix and (2) and (3) reduce to the more familiar expressions

$$\sigma_0(\theta) = \frac{1}{(2s_a+1)(2s_b+1)} \mathrm{Tr}[M(\theta)M^\dagger(\theta)] \quad , \tag{4}$$

and

$$\sigma_0 = \frac{4\pi}{k^2} \sum_{Js'\ell's\ell} \frac{(2J+1)}{(2s_a+1)(2s_b+1)} |t^J_{s'\ell',s\ell}|^2 \quad . \tag{5}$$

Expression (5) follows from considering the θ-dependent decomposition of M into reduced matrix elements $t^J_{s'\ell',s\ell}$ of the transition operator for total angular momentum $J = s \oplus \ell = s' \oplus \ell'$.

At low energies, the $T(d,n)^4He$ and $^3He(d,p)^4He$ reactions are almost completely dominated by a resonance having quantum numbers J = 3/2, s = 3/2, ℓ = 0, s' = 1/2, ℓ' = 2. If only this transition $t(3/2^+)$ is taken into account, the elements of M simplify greatly to give the now familiar results for d and t (or d and ^3He) 100% polarized "spin up" along the z axis (β = 0),

$$\sigma_{1,+}(\theta) = 3/2\sigma_0(\theta)\ [1-P_2(\cos\theta)] = 3/2\ \frac{\sigma_0}{4\pi} [1-P_2(\cos\theta)] \quad , \tag{6}$$

$$\sigma_{1,+} = 3/2\sigma_0 \quad . \tag{7}$$

It is important to note for applications in plasmas that, if the transitions are restricted to incident S-waves (ℓ = 0), rotational invariance of the cross section implies the same results (6) and (7) hold for <u>any</u> β, provided θ is always taken to be the angle between $\hat{s}$ and $\underline{k}'$. Thus, the cross section scaling and angular distribution effects induced by polarization are unchanged in this approximation by averaging over incident momentum directions.

Few measurements exist of the type of cross sections of interest here --essentially, spin correlation measurements for both beam and target polarized. At low energies, only $\vec{d}$-$^3\vec{He}$ spin correlations have been measured[2] for the $^3He(d,p)^4He$ reaction near the $3/2^+$ resonance at 430 keV. These measurements were generally consistent with the single $3/2^+$ transition approximation. Most of the polarization measurements for the d-t, d-^3He, and d-d reactions are analyzing powers for first- and second-rank polarized deuterons incident on unpolarized targets.

With relatively few polarized beam-polarized target measurements available for the reactions of interest, one must rely on calculations that take into account the existing measurements. Such calculations are provided by extensive R-matrix analyses[3,4] of reactions in the 4- and 5-nucleon systems done at Los Alamos. The R matrix parameterizes the elements of the transition matrix for all two-body reactions of a given compound system in terms of a simple pole expansion, some terms of which correspond to resonances in the compound system. The analyses for A = 4 and 5 consider data for all the two-body reactions possible at energies below $E_d \sim 8$ MeV, and are generally in good agreement with the measurements included.

Our R-matrix predictions for the 5-nucleon reactions $T(d,n)^4He$ and $^3He(d,p)^4He$ at low energies are very close to the pure $3/2^+$ transition results. We have perhaps a 1% contribution from the J=1/2 S-wave, but perturbing effects from P-waves appear to be more significant. The situation for the d-d reactions is considerably more complex and uncertain. It is apparent from our analysis, and from the work of others[5,6], that no single transition dominates the low-energy d-d reactions as in the 5-nucleon reactions. Both S-waves (quintet and singlet) are present in a somewhat uncertain admixture, and the importance of the J=1, s=1 P-wave ($^3P_1$) increases rapidly with energy.

Integrated cross sections (3) for β=0 calculated from the A=4 analysis for polarized d-d reactions are shown in the table below. The cross sections $\sigma_{m,n}$ are labeled by the projections (m,n) of the deuteron spins on the z axis.

POLARIZED CROSS SECTIONS FOR THE d-d REACTIONS

A. D(d,p)†

E_d(keV)	σ_0(mb)	$\frac{\sigma_{1,1}}{\sigma_0}$	$\frac{\sigma_{1,0}}{\sigma_0}$	$\frac{\sigma_{1,-1}}{\sigma_0}$	$\frac{\sigma_{0,0}}{\sigma_0}$
10	9.657×10^{-3}	1.197	.913	.795	1.363
50	4.780	1.076	1.026	.735	1.272
100	16.05	.949	1.146	.672	1.175
150	25.86	.851	1.247	.610	1.088
200	33.68	.776	1.334	.550	1.011
300	45.14	.672	1.468	.448	.889
400	53.18	.603	1.562	.371	.803
500	59.18	.554	1.626	.320	.749

B. D(d,n)†

E_d(keV)	σ_0(mb)	$\frac{\sigma_{1,1}}{\sigma_0}$	$\frac{\sigma_{1,0}}{\sigma_0}$	$\frac{\sigma_{1,-1}}{\sigma_0}$	$\frac{\sigma_{0,0}}{\sigma_0}$
10	8.647×10^{-3}	1.032	.992	.834	1.301
50	4.497	.886	1.143	.749	1.157
100	15.87	.745	1.289	.668	1.020
150	26.55	.645	1.401	.597	.910
200	35.60	.573	1.491	.535	.820
300	49.70	.479	1.621	.436	.687
400	60.08	.421	1.706	.367	.600
500	67.99	.382	1.762	.321	.546

†Sum rule for cross sections

$1/9(2\sigma_{1,1} + 4\sigma_{1,0} + 2\sigma_{1,-1} + \sigma_{0,0}) = \sigma_0$

Apparently, (1,0) is the best configuration for enhancing the cross sections, while (1,-1) is the best one for suppressing it. The maximum enhancement (1.6-1.7) is well below the ideal value (3) that would be realized if only the singlet S-wave transition contributed.

Present knowledge about cross sections for fusion reactions at low energies can be summarized by the following: The dominance of the $3/2^+$ resonance at low energies in the d-t and d-^{3}He reactions allows those polarized cross sections to be predicted with a fairly high degree of confidence, despite the relative scarcity of spin correlation measurements. The increased complexity of the d-d reactions, coupled with a complete lack of spin correlation data, makes predictions of polarized d-d cross sections considerably less reliable. Here, more extensive and more accurate polarization measurements are needed at low energies. The most directly useful, but probably most difficult, measurements would be spin correlations. However, even more accurate second-rank analyzing power measurements would help determine the relative amounts of quintet and singlet S-waves. Polarization transfer experiments, in which the polarization of the outgoing nucleons would be measured for polarized incident deuterons, could provide additional information about the transition amplitudes not contained in the analyzing powers. In any case, a comprehensive analysis that takes into account all the measurements simultaneously would be required to obtain the most reliable predictions of the polarized cross sections.

REFERENCES

1. R. M. Kulsrud, H. P. Furth, E. J. Valeo, and M. Goldhaber, Phys. Rev. Lett. 49, 1248 (1982).

2. Ch. Leemann, H. Bürgisser, P. Huber, U. Rohrer, H. Schieck, and F. Seiler, Helv. Phys. Act. 44, 141 (1971).

3. G. M. Hale and D. C. Dodder, Proc. Int. Conf. on Nuclear Cross Sections for Technology, Knoxville, Tenn., 1979, Johnson, Fowler, and Bowman, Eds. (NBS spec. Pub. 594, 1980), p. 650.

4. G. M. Hale and D. C. Dodder, in Few Body Systems and Nuclear Forces II, Lecture Notes in Physics Vol. 87, Zingl, Haftel, and Zankel, Eds. (Springer-Verlag, New York, 1978), p. 523.

5. B. P. Ad'yasevich and D. E. Fomenko, Yad. Fiz. 9, 283 (1969) [Sov. J. Nucl. Phys. 9, 167 (1969)].

6. W. Grüebler, V. König, P. A. Schmelzbach, B. Jenny, and J. Vybiral, Nucl. Phys. A369, 381 (1981).

Current Status of Polarized Beam Technology

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ABSTRACT

Ion sources for the production of polarized beams of positive and negative hydrogen ions (H,D,T) have been developed over some 20 years for use in nuclear and high-energy acceleration. The operating principle of the sources now in use is based on three steps:

(a) production of hydrogen atoms which are polarized in electron spin
(b) use of the hyperfine interaction to produce various states of nuclear polarization (tensor and vector polarization)
(c) ionization of the polarized atoms to form either positive or negative ions

The talk will review the principles of the three types of sources now in use:

(1) atomic beam sources, based on deflection of atoms in inhomogenous magnetic fields
(2) Lamb-shift sources, based on selective quenching of hydrogen atoms in the $2S_{1/2}$ metastable state
(3) spin-exchange sources, based on optical pumping of an alkali vapor and pick-up of polarized electrons by hydrogen ions.

At present, the best hydrogen ion sources produce about 100 μA positive ions and 6 μA negative ions. The limitations of the present sources and the methods which have been proposed to overcome them will be briefly reviewed.

SOME DATA ON TRITIUM AND DEUTERIUM

RELEVANT TO THE PRODUCTION OF POLARIZED BEAMS

(from)

W. Haeberli, *Ann. Rev. Nucl. Sci.* 17, 373 (1967). See also

W. Haeberli, *Nuclear Spectroscopy and Reactions, Part A* (Academic Press 1974) p. 151

I. Energy Level Diagrams

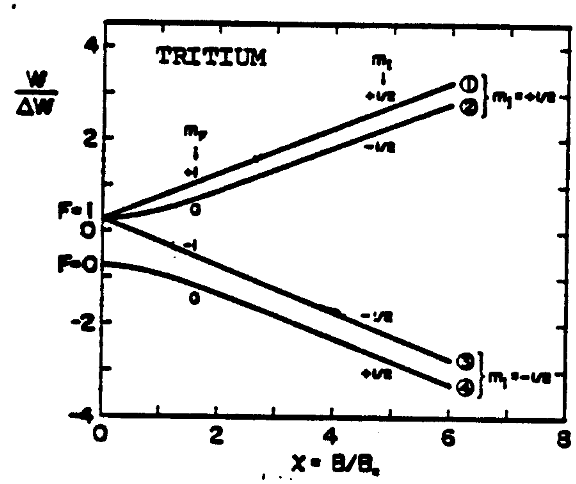

FIG. 1. Energy-level diagram of the tritium atom in a magnetic field. The energy is measured in units of $\Delta W = h \times 1515.0$ MHz ($= 6.2 \times 10^{-6}$ eV). The magnetic field is measured in units of $B_c = \Delta W(g_I - g_j)\mu B$. For the ground state of tritium, $B_c = 541$ G, and for the $2S_{1/2}$ excited state $B_c = 67.6$ G. The diagram is drawn to scale.

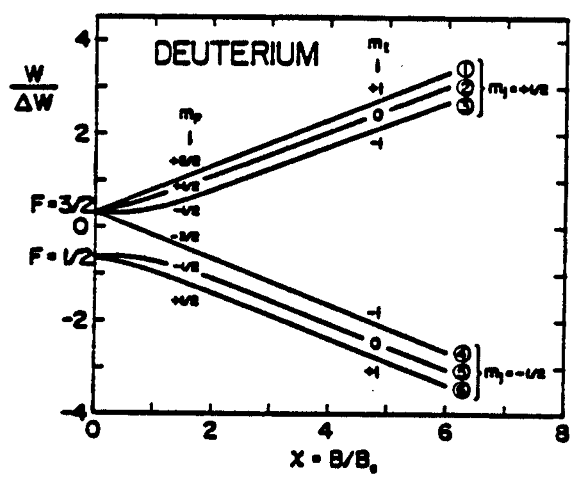

FIG. 2. Energy-level diagram of the deuterium atom in a magnetic field. The energy is measured in units of $\Delta W = h \times 327.4$ MHz ($= 1.4 \times 10^{-6}$ eV). The magnetic field is measured in units of $B_c = \Delta W/(g_I - g_J)\mu_B$. For the ground state of deuterium, $B_c = 117$ G, and for the $2S_{1/2}$ excited state, $B_c = 14.6$ G. The diagram is drawn to scale.

II. Nuclear Polarization:

1. Deuterons, spin 1.

Spin state is completely described by 8 independent parameters [3 components of vector polarization

$p_i = \langle S_i \rangle$, 5 components of tensor polarization

$p_{ij} = \frac{3}{2} \langle S_i S_j + S_j S_i \rangle - 2\delta_{ij}$ (i,j = x,y,z)].

For special case of spin system which has axial symmetry about z, the spin system is described by two parameters:

vector polarization $p_z = N_+ - N_-$

tensor polarization $p_{zz} = 1 - 3\, N_o$,

where N_+, N_o, N_- are the relative populations of the three magnetic substates with respect to the symmetry axis z.

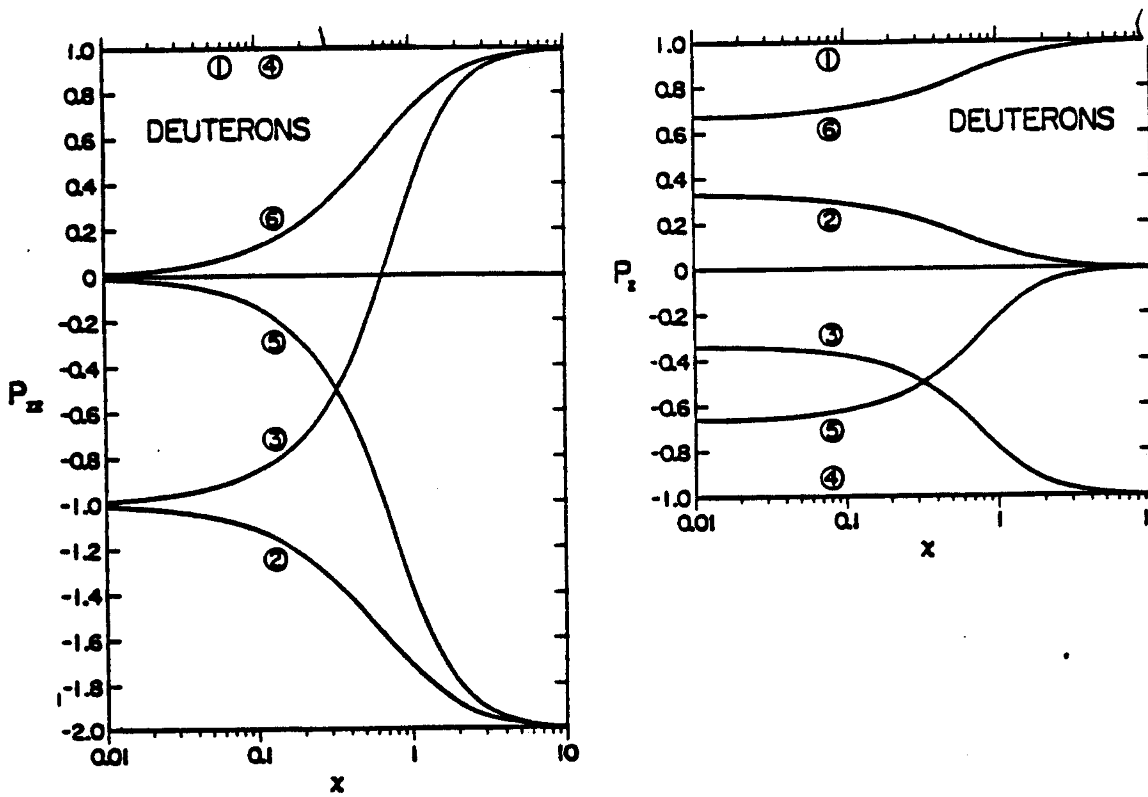

FIG. 5. Vector polarization P_z and tensor polarization P_{zz} of deuterons in the deuterium atom as a function of external magnetic field if any one of the six hyperfine components of Fig. 2 is occupied. The numbers refer to the six hyperfine components of Fig. 2. The field is measured in units of $B_c = 117$ G for the ground state and in units of $B_c = 14.6$ G for the $2S_{1/2}$ excited state of deuterium. If more than one state is occupied, the polarization is obtained by taking the weighted mean.

2. <u>Tritons, spin $\frac{1}{2}$</u>.

Spin system completely described by three independent parameters [3 components of the vector polarization $p_i = \langle S_i \rangle$].

If the polarization vector is along z, the spin system is described by <u>one</u> parameter

$$\underline{\text{vector polarization}} \quad p_z = N_+ - N_-,$$

where N_+, N_- are the relative populations of the magnetic substates along z.

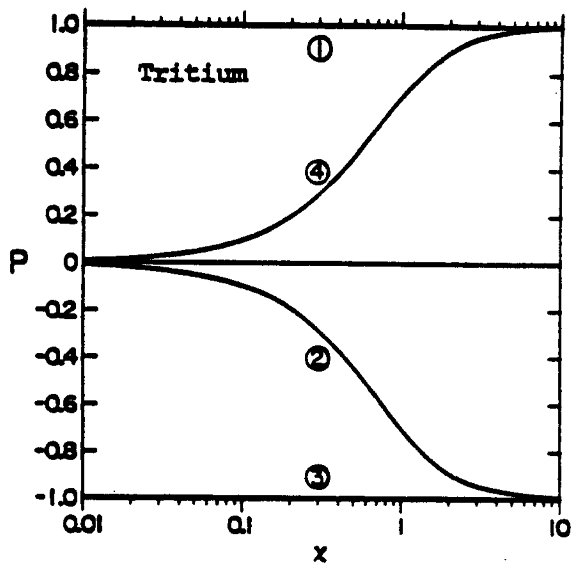

FIG. 3. Polarization P of tritons in the tritium atom as a function of external magnetic field if any one of the four hyperfine components of Fig. 1 is occupied. The numbers refer to the four hyperfine components of Fig. 1. The field is measured in units of 541 G for the ground state and in units of 67.6 G for the $2S_{1/2}$ excited state of tritium. If more than one state is occupied, the polarization is obtained by taking the weighted mean.

III. Hydrogen Atom in the $2S_{1/2}$ Metastable State:

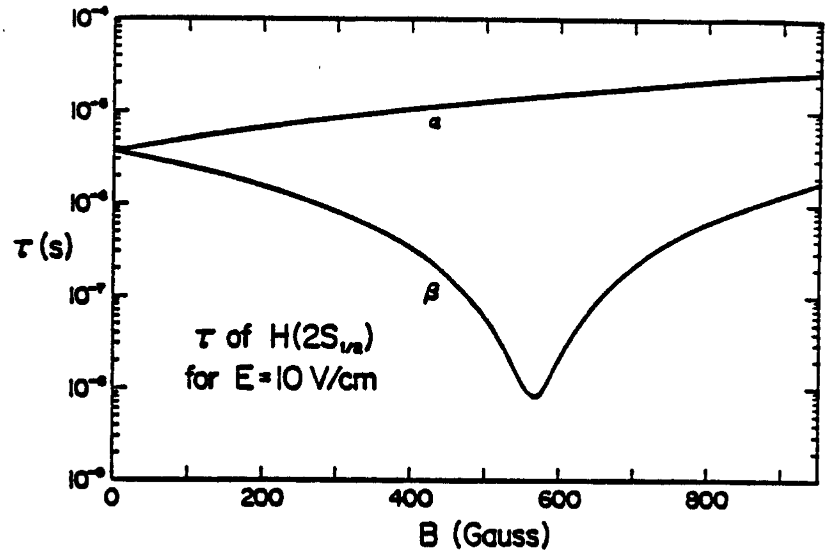

FIG. 14. Lifetime of the $m_j=+\frac{1}{2}$ component (α) and of the $m_j=-\frac{1}{2}$ component (β) of the $2S_{1/2}$ metastable state of hydrogen. An electric field 10 V/cm transverse to the magnetic field is assumed. The hyperfine interaction is neglected.

for other values of E: $\tau = \frac{1.13}{E^2}\,[(574\pm B)^2 + 716\,] \times 10^{-9}$ sec

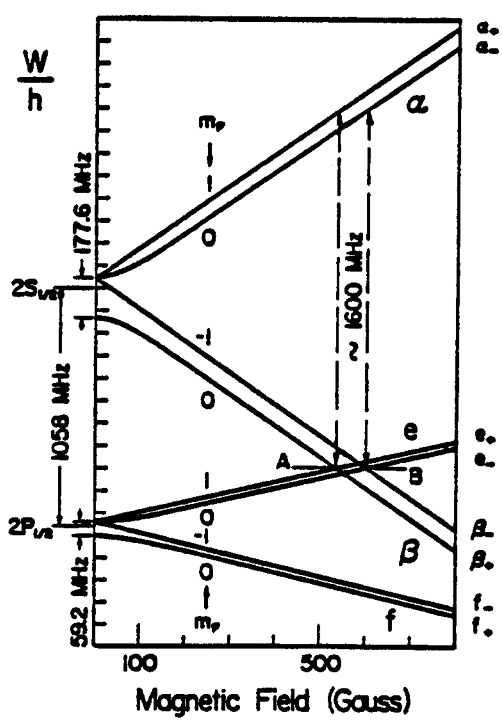

FIG. 13. Energy-level diagram of the hydrogen atom for principal quantum number $n=2$ at an excitation energy of 10.2 eV. The $2S_{1/2}$ and $2P_{1/2}$ states are separated by the Lamb shift 1058.0 MHz($=4.4\times10^{-6}$ eV). The $2P_{3/2}$ state is 19,968 MHz above the $2P_{1/2}$ state and is not shown. The crossings A and B are discussed in the text.

The Production of Polarized Nuclear Spins by Laser Optical Pumping

W. Happer

The ideal reversible work, kT ln(2I+1), required to fully polarize a nucleus of spin I at a temperture T is very small, about 0.018eV for a spin 1/2 nucleus at room temperature. Practical methods for the polarization of nuclei always require more than this ideal expenditure of energy. With optical pumping methods it should be possible to produce large currents of polarized nuclei at an energy expenditure of a few 10's of eV per nucleus.

Because the resonance absorption lines of atomic hydrogen are in the vacuum ultraviolet and because of the small spin-orbit coupling in a hydrogen atom, it will be very difficult to polarize hydrogen atoms by direct optical pumping. However, hydrogen atoms can be polarized with approximately 99% efficiency in spin exchange collisions with alkali atoms. Alkali atoms can be spin polarized with high efficiency by optical pumping with circularly polarized visible or near infrared light. Approximately $\frac{\hbar}{2}$ units of angular momentum are deposited in the alkali atoms for each absorbed photon.

The power requirements are on the order of one watt of optical power per amp of polarized protons. About one hundred amps of polarized nuclei would be required to fuel a fusion reactor with magnetic confinement. Dye lasers capable of delivering the required 100 watts of precisely tuned radiation are already under development for uranium isotopic enrichment. Injection lasers with efficiencies on the order of 50% for conversion of wall plug electrical power into photons are currently available and could be used to optically pump rubidium or cesium beams for spin exchange with atomic hydrogen or tritium. Thus, there would appear to be no technical obstacles in the way of developing efficient, high intensity sources of polarized nuclei based on laser optical pumping.

Spin-Polarized Deuterium for Fusion Applications

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Recently developed techniques for producing spin-polarized hydrogen (H↓) should be applicable to producing polarized protons and deuterons for various applications. A general description of the subject has recently been published[1]. We summarize here the essentials of the method, and comment on some possible applications to providing polarized fuels for plasma fusion.

Production of spin polarized hydrogen rests on the following points:

-Atomic hydrogen can be cooled to very low temperature, $T \sim 0.3K$, in vessels lined with a superfluid helium film.

-If the atoms are allowed to flow into a 5-10 Tesla solenoid, only state a and b can enter (see Fig. 1), while those in states c and d are rejected. The gas of trapped atoms is essentially 100% electron spin-polarized, H↓. Furthermore, the atoms cannot recombine to form molecular hydrogen because H_2 requires that the electron spin of the two atoms be antiparallel.

-By using microwave radiation the transition a → d or b → c can be stimulated. The c or d atoms are immediately ejected from the storage cell, leaving a gas with both the electron and the proton polarized. The ejected atoms form a beam with 100% electron and proton polarization.

-If the electrons of a selected state are flipped, for instance, by an rf transition, nuclear polarized molecules can be formed. In particular, if atoms with opposite electron spin but parallel proton spins react, highly polarized ortho-H_2 can form a solid. The relaxation time should be sufficiently long to permit useful applications.

-These techniques should be applicable to deuterium and possibly to tritium.

"Gas puffing", and solid pellet injection are two common methods of fueling a reactor. We describe applications of the proposed technique to each, using spin-polarized deuterium.

a) Gas puffing. Fig. 2. shows an "open cell" with a supply of unpolarized D. Atoms in state a, b and c enter, the others are rejected. A microwave field drives the c → d transitions ejecting particles in the $m_I = -1$ state. Other fields drive the transitions a → b and b → c, inside the cell, and all three electron spin transitions are driven in a special external chamber (the "scrambler"). Consequently, all the incoming atoms are eventually ejected in the $m_I = -1$ state. Essentially, the magnet behaves as a "super Stern-Gerlach" spin filter.

For typical design parameters we take the temperature of the cell to 0.6K, and the magnetic field to be 6 T. We assume a flux of 1 particle ampere (1 p-A = 6×10^{18} pps).

Heat load. The major load is on the low temperature refrigerator. Assuming that no atoms recombine in the cell, the heat load is due entirely to need to cool the atom from room temperature to 0.6K. The refrigerator must supply

$$P_r = \text{Flux} \times \frac{3}{2}k\,(T_r - T_{low}) = 6\times10^{18} \times \frac{3}{2} \times 1.4 \times 10^{-23} \times 300 = .04\ \text{W}.$$

The power needed to drive the refrigerator, assuming 100% efficiency, is

$$P_a = P_r\left(\frac{T_{room}}{T_{low}} - 1\right) = 20\ \text{watts}.$$

Additional power is needed to dissociate the atoms at room temperature. The dissociation energy is 2.3 eV/atom and the power needed to dissociate 1 p-A is 2.3 watts.

b) Solid pellet injection. The nuclear-polarized deuterium is allowed to react to form polarized para-D_2. ($J = 0$, $I = 2$). The reaction energy of 4.5 eV/molecule must be carried away, but it can be dissipated at a higher temperature than the storage cell. Assuming a reaction temperature of 6K, the power burden (at room temperature) is

$$P_b = \text{Flux x } 4.5 \text{ eV x } \left(\frac{T(\text{room})}{T(\text{reaction})} - 1\right) = 115 \text{ W per p-A of atoms.}$$

Although these estimates represent thermodynamic limits, they indicate that the basic power requirements are not excessive. In our laboratory at MIT we have created approximately 10^{18} atom of H$\downarrow$ at a rate of about 3 p-mA using a very modest dilution refrigerator (3 mW at 0.3K) and a system which was not designed for high throughput. Much higher quantities look feasible.

1. D. Kleppner and T.J. Greytak, Proceedings of the 5th International Conference on High Energy Spin Physics, Brookhaven 1982, G.M. Bunce, Ed., American Institute of Physics Conference Proceedings, No. 95, (1983), p. 546.

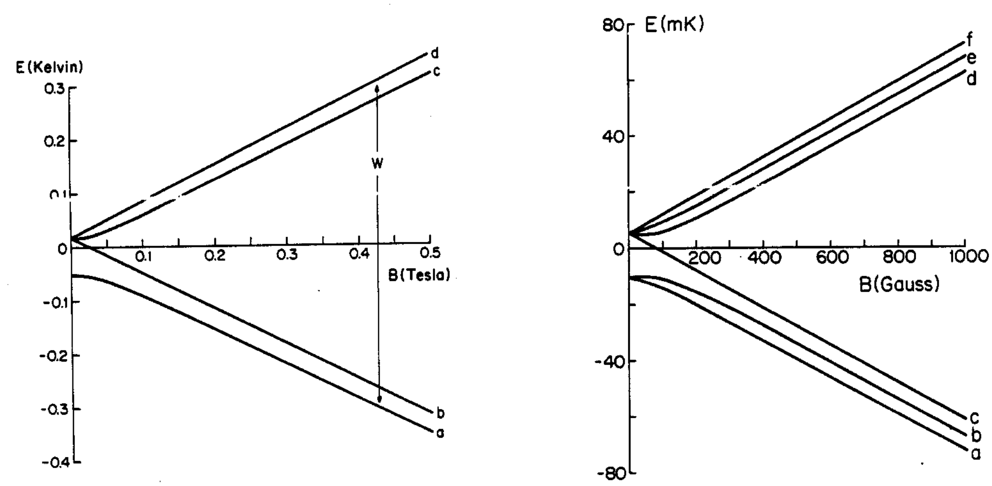

Figure 1 Hyperfine energy level diagrams for hydrogen (left) and deuterium (right). For either isotope, w = 13.5K in a field of 10T.

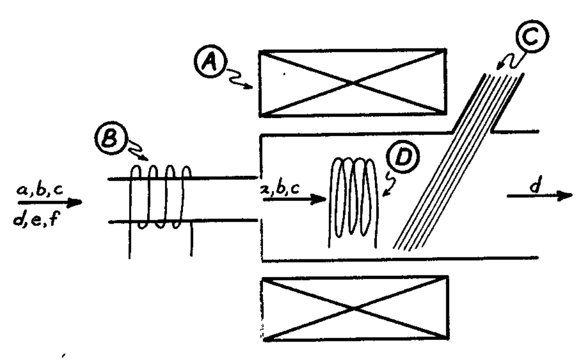

Figure 2 Schematic representation of a cryogenic spin filter for deuterium. a through f indicate hyperfine states. A-superconducting magnet; B-electron spin scrambler; C-microwave radiation driving c→d; D-r.f. coil driving a→b and b→c.

III. CONTRIBUTED ABSTRACTS

Large Volume, Storable Nuclear Spin Polarized HD and D_2 Solids

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The nuclear polarization method which is a starting point for our discussion here was first proposed[1] in 1967 for polarized H in solid HD. It is based on the fact that $(T_1)^{-1}$, the proton spin-lattice relaxation rate for J=0 HD molecules in the pure molecular crystal, is exceedingly slow for H nuclei at low temperatures ($T \lesssim 4K$) and moderate external magnetic fields ($H \gtrsim 0.1$ Tesla). An increase of the proton $(T_1)^{-1}$ can be obtained by adding a small concentration of proton-containing J=1 molecular species, for example o-H_2, which itself has a fairly efficient proton spin-lattice relaxation due to modulation of the intramolecular spin-spin coupling by quadrupolar intermolecular interactions[2], and which can relax protons of the J=0 host HD molecules via intermolecular spin-spin interaction (cross relaxation). The HD system thus endowed with coupling to the lattice energy reservoir can then be placed in a low temperature and high magnetic field environment in which it will thermally relax to the equilibrium polarization $\mathcal{P}$(H/T). For proton equilibrium polarization of 90%, H/T, measured in Tesla per degree Kelvin, is 1.4×10^3, which is achievable using a dilution refrigerator at 10 mK and a superconducting solenoid at 14T. By waiting at the low temperature and high magnetic field for a sufficient time, after equilibrium is attained, for the relaxation-catalytic o-H_2 to convert to the benign non-spin-polarizable J=0 p-H_2 species, the protons in the HD become isolated from the lattice, and relaxation times exceeding a day can be attained at ordinary liquid helium temperatures (~4K) and magnetic fields of only a fraction of a Tesla. These somewhat arbitrary temperature-field values at which the high nuclear polarization is metastably retained are called the 'parking' conditions, and we refer to the protons as being in a 'frozen-spin' state. The waiting period for conversion at the mk temperatures and high magnetic field may be two to three weeks in order to attain a sufficiently long relaxaton time at the parking conditions, but this is by no means prohibitive, and there may be ways of considerably reducing[3] this time, or even avoiding it entirely[4] for polarized D.

This scheme was originally envisaged for producing polarized proton targets for nuclear physics polarized beam experiments, where the advantages were large free proton constitution, very large size targets, and ability to function at liquid helium temperatures between 1K and 4K where high energy beam heating would present much less of a problem than at mK temperatures. Furthermore, a procedure was developed whereby the D in HD could be <u>independently</u> polarized to the same extent as the H, resulting in an effective polarized neutron solid target. The competitive proton targets consisted of a variety of non-purely-hydrogenic materials, in which the protons were dynamically polarized by means of well established techniques through interaction with electrons, and H/T of only 2.5 T/°K sufficed for 90% polarization under ideal conditions, which could be closely met for some materials. The advantages of our HD polarized proton (and deuteron) system were not at that time perceived to be sufficient to justify the radical change of technology. However, the recent suggestion of using spin-polarized hydrogens for optimizing controlled fusion reactions[5], which were the impetus for this conference, provide a very strong justification for our targets. Presently working dynamically polarized impure materials are not an adequate substitute for pure polarized solid HD or D_2, both of which are immediately feasible with our method.

The method described above for polarizing H in HD is based on the detailed dependences of $(T_1)^{-1}$ on T, H, $o\text{-}H_2$ and $p\text{-}D_2$ concentrations, which have been investigated to a considerable extent[6-11]. At 18 mK and 10T, H polarizations of 40% have actually been achieved[10], with some (certainly not insurmountable) thermal contact problems encountered at the lowest temperatures. Our laboratory has concentrated its efforts on understanding the relaxation time dependence on $o\text{-}H_2$ and $p\text{-}D_2$ concentration in the 0.3K to 20K temperature and 0 - 10T magnetic field regions, on determining the effect of radiation damage[12] on the T_1 values, and on polarizing deuterons[13] as well as H. Because of the smaller nuclear magnetic moment of D compared with H, D would require an H/T of 7.7×10^3 Tesla/°K for 90% polarization. This is probably beyond the present technological capabilities, but even if this H/T were to be obtained, under conditions of adequate heat removal for symmetry species conversion, the $p\text{-}D_2$ nuclear spin relaxation times and $p\text{-}D_2 \rightarrow o\text{-}D_2$ conversion times are such that it is questionable whether the method simply analogous to that of the polarized H in HD could ever work. This reservation holds also for nearly pure $o\text{-}D_2$. We have instead developed methods for polarizing D, mentioned above, in which the polarized protons in HD serve as intermolecular dipole-dipole coupled dynamic polarization partners of D (instead of polarized electrons in the more customary usage), and have achieved D polarizations[13] equal to those of equilibrium proton polarization at given H/T, in times as short as minutes.

The polarized D in HD can itself be useful for fusion experiments[14], but even more desirable would be polarized D_2. Fortunately, D_2 in the long-relaxation-time J=0 rotational state has a substantial nuclear polarizability, unlike H_2. Thus, it can exist in the 'frozen-spin' state, as can HD, and the only problem is how to initially polarize it. As mentioned above, the equilibrium polarization at presently attainable fields and temperatures is too low, and in addition, the $p\text{-}D_2$ to $o\text{-}D_2$ conversion is much slower than the $o\text{-}H_2$ conversion in HD. Nevertheless, we believe we can produce highly polarized D_2 by starting out with material of extremely low $p\text{-}D_2$ concentration, utilizing radio-frequency induced transitions and spin-coupling interactions with the polarized HD.

It is also of interest to produce polarized TD, in which the D and T are separately polarized. The triton has a spin of 1/2 and behaves very similarly to the H, and it would seem at first that TD should be amenable to the same techniques discussed for polarizing H in HD, especially since the H and T nuclear magnetic moments are comparable. In very small samples, this may be approximately the case, but for large samples, the low energy β^- emission of the tritons loads the dilution refrigerator too severely. Even if this were solved by elaborate use of very thin (~1 μm) samples, storage at 1-4 K temperatures would still present a problem, since we have shown in HD that high energy particles produce radiation damage which can severely shorten the relaxation time in these solids.[12] Extrapolating the dose-relaxation results from the beam experiments[12] to radioactive TD samples, we arrive at an approximate relaxation time of 100 seconds at 4K and about 1000 seconds at 1K, if one starts with a defect-free annealed sample. If the samples were of micron thickness, another order of magnitude could perhaps be achieved. Although these times are not long enough to be compatible with the symmetry species conversion method, they may be sufficient if polarization could be rapidly transferred to the triton by radio-frequency and spin-coupling techniques such as have been discussed for D, which we think is feasible.

Finally, the use and mode of employment of these solid hydrogens may vary considerably. A large quantity, ~ liter of solid, can be polarized in a single run, using a large dilution refrigerator inserted in a 10 cm bore superconducting solenoid, equipment items which are presently in existence.

Alternatively, since cryogenic transfers are quite straightforward because of high polarization retention at 4K, moderate quantities of polarized material can be transferred, stored, assembled into larger units, and easily manipulated. Formation of cryogenic pellets, a much discussed mode of fuel injection in fusion machines, appears to be feasible with our polarized material. Ablating the fuel in a magnetically insulated diode, which has been proposed by Katzenstein in this conference for tokamak injection, is another promising avenue. These modes of course require ascertaining that appreciable depolarization upon ablation either in the diode or in the fusion machine does not occur. Finally, these solid targets may also be of interest for making high intensity nuclear polarized 'hydrogen' charged beams. It is quite possible that raising the temperature through the melting and vaporization temperature regions[15,7] can be sufficiently rapid as to permit maintaining the high nuclear spin-polarization into the vapor phase. We hope to address problems such as these in our experimental program.

References:

1. A. Honig, Phys. Rev. Lett. 19, 1009 (1967).
2. T. Moriya and K. Motizuki, Prog. of Theor. Physics 18, 183 (1957).
3. For example, hydrostatic pressure can considerably shorten symmetry species conversion times by affecting the phonon distributions.
4. One can have long $T_1(D)$ and short $T_1(H)$ in a properly constituted sample, prepared without symmetry species conversion. If the aim is to polarize only D, this can be achieved from dynamic polarization with H of short $T_1(H)$ (see Ref. 13), and the polarized D can still be retained in the 'frozen-spin' state.
5. R.M. Kulsrud, H.P. Furth, E.J. Valeo and M. Goldhaber, Phys. Rev. Lett. 49, 1248 (1982).
6. W.N. Hardy and J.R. Gaines, Phys. Rev. Lett. 17, 1228 (1966).
7. R.S. Rubins, A. Feldman and A. Honig, Phys. Rev. 169, 299 (1968).
8. A. Honig, in Proc. II Int. Conf. on Polarized Targets, G. Shapiro, ed., Berkeley (1971); p. 99.
9. H.M. Bozler and E.H. Graf, in Proc. II Int. Conf. on Polarized Targets, G. Shapiro, ed., Berkeley (1971); p. 103.
10. E.H. Graf, Brookhaven National Laboratory Workshop on Physics with Polarized Targets (BNL20415) (1974), p. 345.
11. A. Honig, in Proceedings of the Symposium on Experiments Using Enriched Antiproton, Polarized Proton and Polarized Antiproton Beams at Fermilab Energies (ANL-HEP-CP-77-45). Ed.: H. Yokosawa, Argonne National Lab (1977); p. 186.
12. H. Mano and A. Honig, Nuc. Instr. and Meth. 124, 1 (1975).
13. A. Honig and H. Mano, Phys. Rev. 14, 1858 (1976).
14. The H, polarized or not, are diluting, but otherwise not particularly objectionable.
15. M. Bloom, Physica 23, 767 (1957).

DAMPING OF SPIN FLIP FLUCTUATIONS FOR D BY ^{7}Li

by John M. Dawson, U.C.L.A.

The spin flip frequency of polarized deuterium is $\omega_{p1} = 0.86\ \omega_{CD}$ where ω_{CD} is the cyclotron frequency of deuterium. The cyclotron frequency of ^{7}Li is almost identical; it is $(6/7)\ \omega_{CD} = 0.857\ \omega_{CD}$. Thus, by adding a small amount of ^{7}Li to the plasma we should be able to heavily damp fluctuations at the spin flip frquency. The energy absorption rate is roughly

$$P \approx \frac{\omega_{pi}^2(\text{Li})}{4k}\ E^2(\omega)\ f_{oLi}\ \left(\frac{\omega-\omega_p}{k}\right)$$

For ion cyclotron waves propagating parallel to B this gives a damping rate of

$$\gamma \approx \sqrt{\pi/8}\ \frac{\omega_{pi}^2(\text{Li})\ \omega_{ci}^2}{k^2c^2\ kv_T(\text{Li})}$$

As an example, consider a plasma at a density of 4×10^{14} in a 50KG field; then

$$\gamma \approx \frac{4 \times 10^{22} n(\text{Li})}{k^3 c^2 v_T(\text{Li})} \approx \frac{4 \times 10^{-7}\ n(\text{Li})}{k^3}$$

where we have set $v_T(\text{Li}) = 10^8$. In order for the waves not to be damped by the deuterium k must be less than 10^{-1} so that

$$\gamma > 4 \times 10^{-4}\ n(\text{Li})$$

The Li density required to damp the disturbance in $10^2\ \omega_{ci}^{-1} = 4 \times 10^{-7}$ is 6×10^9. Thus, even very small ^{7}Li fractions (10^{-3}) should damp the waves in a few cyclotron periods.

Polarized Fuel and Inertial Fusion

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Although the workshop has emphasized magnetic fusion machines, some of the issues for inertial-confinement-fusion (ICF) devices can now be identified. There are two ways that an ICF reactor may benefit from polarized fuel. First, anisotropic emission of neutrons could protect the two most vulnerable parts of a reactor, the beam optics and the pellet injection system. This advantage is sensitive to pellet and reactor-vessel design parameters, since elastic neutron scattering in the pellet or reactor vessel would make the distribution isotropic. Anisotropic alpha-particle emission is a disadvantage because it may modify the propagation of the burn wave in the fuel. The enhanced fusion cross section is the second advantage of polarized fuel. It would reduce restrictions on the laser or particle-beam driver by increasing the fusion gain. The result would be a smaller, less expensive driver.

The use of polarized fuel in an ICF reactor would probably require a magnetic field inside the reactor vessel. That is a major design change. Polarized fuel may also require changes in target design, which could reduce the fusion gain. It will be difficult to address this issue any time soon.

One depolarization mechanism is unique to inertial fusion. Magnetic fields in the megagauss range are produced by the driver-target interaction. Those fields might not be produced when a target is irradiated with sufficient symmetry and they might not penetrate the

*Work supported by the U.S. Department of Energy under Contract No. DE-AC08-82DP40152.

fuel in reactor targets, but they may penetrate the targets in use today. Only a rapid penetration would depolarize the fuel, but even an adiabatic change of field would alter the polarization axis locally. Whether a pre-applied field would maintain the polarization depends on the plasma electrical conductivity and, hence, the temperature profile in the target.

PRODUCTION OF INTENSE BEAMS OF SPIN-POLARIZED HYDROGEN NUCLEI

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The magnetically insulated diode of Humphreys and Kuswa[1] can produce pulsed beams of hydrogen ions of Kiloampere intensity. It has been demonstrated that such beams can be injected and trapped in a Tokamak.[2] The ions in this device are obtained by the ablation of a solid hydrogen isotope bearing anode. This anode consists of polyethelene in the present work, but subsequent work by Kasnya[3] has demonstrated the successful operation of such a diode at liquid nitrogen temperatures, the ablated surface being a frozen film of water. Extension to liquid helium temperatures and solid hydrogen isotopes is straightforward. The work of Honig[4] has shown that solid samples of H-D can be produced with a high degree of polarization of the nuclear spin. Such samples are further shown to retain this high degree of spin polarization at temperatures as $4^{O}K$ and magnetic fields of a few kilogauss. If such spin polarized samples be the anode of a magnetically insulated diode, the ion beam produced by the diode discharge should retain the nuclear polarization state of the anode since the ablation process is too rapid to permit appreciable nuclear depolarization.

1. S. Humphreys and G. Kuswa, Appl. Phys. Lett. 35, 13, (1979).
2. S. Robertson and J. Katzenstein, Bull. Am. Phys. Soc. 27(8), 1136 (1982).
3. K. Kasnya, et al., Appl. Phys. Lett. 39(11), 887(1981).
4. A. Honig, Phys. Rev. Lett. 19(18), 1009 (1967); See also abstract in this Proceedings.

Depolarizing Resonances in Plasma Fusion with Polarized Nuclei

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There has been a proposal to use polarized D and T in plasma fusion to increase the reaction rate and reduce the background [PRL 49, 1248 (1982)]. Using the control mechanism offered by spin looks very promising for fusion. However, it is essential to insure that the nuclei stay polarized while in the plasma, otherwise even if a sufficiently intense polarized source of D and/or T can be developed, the plasma will quickly depolarize and the spin will give no benefits.

Four possible sources of depolarization have now been identified:

1. Depolarization when particles collide with the walls.
2. Depolarization induced by magnetic field fluctuations due to the plasma itself.
3. "Imperfection" depolarizing resonances due to imperfections in the magnetic field created by the coils.
4. "Intrinsic" depolarizing resonances due to the periodic variations in the magnetic field seen by the particles as they move in a helix or with other periodic motions.

I am not an expert on 1 and 2, and will thus concentrate on 3 and 4.

A depolarizing resonance will occur whenever two frequencies happen to become equal to each other or become integer multiples of each other. The precession frequency, ω_p, is the frequency at which each spin precesses; this is directly proportional to the value of the magnetic field, B, at the spin's position at each instant. The quantity ω_B is the frequency with which the spinning particle sees magnetic fields perpendicular to the spin axis. Whenever the equation

$$n\ \omega_p = m\ \omega_B$$

is satisfied, for any integers n and m, then a depolarizing resonance will occur.

The difficult problem is to calculate the strength of each depolarizing resonance. This calculation is, in general, a very non-trivial problem. It is generally believed that the depolarization is much worse when n and m are small integers. When n and m are both 1, there is a first order depolarizing resonance which can destroy the polarization in a few microseconds. Fortunately there is no first order depolarizing resonance for D and T. If m or n are higher integers, the resonances are certainly weaker; but calculating just how much weaker should be done in detail for a number of resonances with integers up to perhaps 10. In particular, last October I pointed out that because of the deuteron's g factor, you have for the helix motion of low energy deuterons (10 → 100 keV) that

$$7\ \omega_p = 5.999\ \omega_B$$

The quantity 5.999 seems to me close to 6. I have heard a good deal of verbal discussion that this resonance is very weak, but so far I have seen no written evaluation of this or any other higher resonance.

Coming from the high energy physics accelerator community, I so far have not been able to see, in a simple intuitive way, why there is so much less depolarization problem in a Tokamak than in a high energy synchrotron. The magnetic fields in a synchrotron are highly uniform compared to those in a Tokamak. Synchrotrons do have periodic vertical betatron oscillations, which induce our strong intrinsic depolarizing resonances, but Tokamaks have periodic helical motions which might also cause a problem. One must recall that if we do not install special correction dipole magnets to correct the imperfection resonances and fast (~ 2 μsec) pulsed quadrupole magnets to "jump" the intrinsic resonances, the synchrotron beams lose all their polarization.

I would recommend:

1. A careful study of the strength of all depolarizing resonances up to perhaps n and m equal 10. Hopefully this study could be written up in a clear way and checked by at least one independent group with competence in polarization problems.
2. Consideration of devices or methods that might help to maintain polarization (such as our correction dipoles and pulsed quadrupoles) in the event that some higher order depolarizing resonance becomes a problem either in calculation or in fact.

FIRST WALL RADIATION DAMAGE CONSIDERATIONS

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The two approaches proposed for polarizing the reacting nuclei in a magnetically confined plasma have been considered as to the effect on the first wall damage rate. Line sources of fusion neutrons emitted with the following angular distributions were considered:

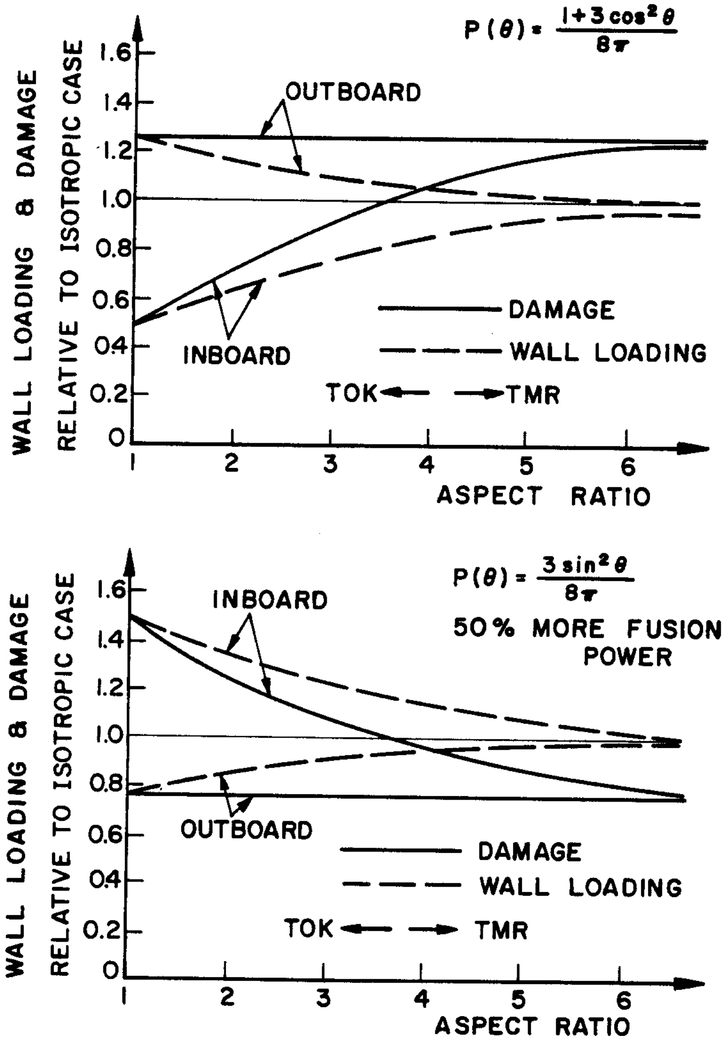
$$P(\theta) = \begin{cases} \dfrac{1}{4\pi} & \text{, isotropic (no polarization)} \\[2ex] \dfrac{1 + 3\cos^2\theta}{8\pi} & \text{, perpendicular polarization} \\[2ex] \dfrac{3\sin^2\theta}{8\pi} & \text{, parallel polarization.} \end{cases}$$

θ is the angle between the magnetic field and the emitted fusion neutron. The effects of polarization on neutron wall loading (energy current) and the neutron flux (at the source energy) which is proportional to the damage rate were investigated.

For perpendicular polarization, no increase in fusion power density is obtained and the neutrons are emitted preferentially parallel to the magnetic field. In the limiting case of an aspect ratio of one in a tokamak reactor, both the wall loading and the damage rate at the inner edge of the torus decrease by 50% (see Figure). This percentage reduction decreases as the aspect ratio increases. For realistic aspect ratios of 3 or 4 only ~ 20% decrease in damage on the inboard inside occurs. However, the damage is increased on most of the outboard first wall. Therefore, the life of the first wall is reduced. The small reduction in wall loading at the inboard first wall will result in only a slight decrease (~ a quarter of a neutron mean free path) in the inboard shield thickness. In the case of an infinite aspect ratio, which corresponds to a linear machine such as a tandem mirror, the wall loading is the same as that in the case without polarization while the damage rate increases by 25%. Therefore, perpendicular polarization will not have a major advantage for the neutronics performance of either tokamak or tandem mirror reactors.

For parallel polarization a 50% increase in fusion power density is obtained and the neutrons are emitted preferentially perpendicular to the magnetic field. There are two bases for comparison in this case. One can compare on the basis of equal fusion power density in the plasma. A better approach is to compare the wall damage on the basis of equal plasma physics conditions (magnets, heating, etc.) which implies approximately the same capital cost. The 50% increase in fusion power with parallel polarization will, therefore, tend to reduce the cost of produced electricity. However, the wall damage rate will affect the economics through the availability of the plant due to first wall changeout brought on by wall damage. Our results indicate that in the limiting case of an aspect ratio of one, the peak damage rate and wall loading occurring at the innermost edge of the torus is a factor of 2.25 higher than that in the nonpolarized case. For realistic aspect ratios of 3 or 4 less than ~ 70% increase is obtained. The impact of this damage increase on the plant availability needs to be considered in order to determine whether a net economic gain can still be achieved. The increase in wall loading at the inboard first wall will result in an inboard shield thickness increase of only a few centimeters. In the case of a tandem mirror there is a clear gain to be realized resulting from a wall damage rate increase of only 12.5%.

We conclude that polarizing the reacting nuclei parallel to the magnetic field results in a clear improvement in the economics of a tandem mirror reactor. In a tokamak reactor the gain is largest for large aspect ratios and decreases as the aspect ratio decreases due to the reduced plant availability resulting from the increased wall damage rate. A detailed analysis is needed to determine whether a net gain can still be achieved for realistic aspect ratios. However, the availability is influenced by many factors and should not be a direct inverse of the damage rate. On the other hand, perpendicular polarization does not improve the neutronics performance of either tokamak or tandem mirror reactors.



IV. SUMMARIES OF SUBPANEL DISCUSSIONS

Plasma Physics Subpanel

Secretary - J.D. Callen

The critical physics issues for spin-polarized fusion fall into two areas. The first area concerns how the spin-polarized fuel might be introduced into the plasma and the tradeoffs between various methods for doing this. The second area concerns depolarization mechanisms in the plasma. A brief discussion of the critical issues identified in each of these areas follows.

Fusion fuel is usually injected into tokamak or tandem mirror magnetically confined plasmas by one of three methods: gas puffing, pellets, or energetic neutral beam injection. For a reference fusion reactor ($n \sim 3 \times 10^{14}$ cm^{-3}, $T \sim 10$ keV, $\tau_p \sim 1$ sec, Volume $\sim 3 \times 10^7$ cm^3) the particle loss rate from the plasma is approximately 10^{22} #/sec corresponding to about 1600 amperes of particles. Some important considerations for sustaining such a plasma with spin-polarized fuel are as follows:

1) Gas Puffing. Here, typically, room temperature gas is bled into the plasma, originally as a diatomic gas (H_2), and penetrates less than a cm where it becomes dissociated, with the Franck-Condon (few eV) neutral penetrating another few cm into the plasma. This atomic neutral then suffers numerous charge-exchange and ionizing collisions and can have a probability of about 0.2 (via not very well understood processes that may not be obtained in a reactor) for reaching the plasma center to fuel it. The rest of the nuclei leave the plasma and either: i) flow into a divertor (tokamak) or end plug (tandem mirror) chamber (with only about 10% recycling back into the plasma); or, depending upon the setup, ii) bombard a nearby wall (as neutrals or ions with say 100 eV), with eventually about 90% of them recycling back into the plasma, primarily as diatomic molecules. In the latter case, the nuclei bury themselves in the wall some distance, and in steady state diffuse back out to the surface where they recombine and desorb. For a close wall with 90% recycling, only about 160 amperes of particles are required to fuel a fusion reactor, but the average nucleus recycles some 50 times with the wall before being pumped out of the system. For a low recycling (< 10%), diverted edge plasma, the neutrals reaching the plasma center need not have recycled from a wall, but a larger fuel input rate (8000 amperes?) is required.

2) Pellet Fueling. Large (10^{20}-10^{22} particle) hydrogenic ice pellets are to be injected at high velocities (> 10^4 m/sec) into the plasma. (At present 10^{20} particle pellets have been injected at up to 10^3 m/sec.) The pellets penetrate further into the plasma than gas puffing, but usually not all the way to the plasma center so edge recycling plays a role here as well. The pellets get absorbed by ablation due primarily to plasma electrons and there is a question if the nuclei so absorbed would retain their spin polarization during the ablation, ionization and heating processes.

3) Energetic Neutral Beam Injection. This technique is used in tokamaks primarily for heating and, since the energetic neutrals ($\gtrsim$ 120 keV) can penetrate all the way to the plasma center, would be a good way to inject spin-polarized nuclei into next generation experiments (e.g., TFTR). How-

ever, in both tokamak and tandem mirror reactors, most of the fuel should be introduced with gas puffing or pellets to avoid overheating the plasma. Also, the magnetic field inhomogeneities from the plasma edge back to the neutral beam source would have to be carefully designed to cause only adiabatic variations of the spin polarization of these fast neutrals.

After spin-polarized nuclei are injected into a plasma, they need to retain their polarization for at least a particle confinement time ($\gtrsim$ 1 sec, or $\gtrsim$ 10 sec for 90% recycling from a wall) to produce the special features of polarized fusion. Some depolarization mechanisms that could occur on this time scale are as follows:

1) Primary Resonance Plasma Fluctuations. Since the spin precession frequency is often close to the gyrofrequency for polarized fuel nuclei (e.g., $\omega_{pr} \simeq 0.86\ \Omega_D$ for deuterons), magnetic fluctuations near the gyrofrequency in the inhomogeneous magnetic field ($\Delta B/B \gtrsim 0.3$ within the plasma) could be in primary resonance with the spin precession and rapidly depolarize the nuclei for $B_\omega > 1$ gauss. The thermal noise level is fortunately much lower than this but any collective plasma instabilities, perhaps (as suggested by B. Coppi) driven by the anisotropic alpha particle distribution from spin-polarized fusion, could easily exceed this level. Such instabilities should be rare in reactor confined plasmas, but detailed analyses of possible instabilities are required. If undesirable fluctuations do occur, J. Dawson has suggested that a small amount of Li^7, which has a gyrofrequency of 0.859 Ω_D, could be added to the plasma to damp waves at ω_{pr}. It should also be noted that perpendicular neutral beam injection, which tends to induce ion cyclotron instabilities, and at least fundamental ion cyclotron wave heating, probably cause short spin decorrelation times and thus are likely to be incompatible with polarized ion fusion.

2) Higher Order Resonances. Generally speaking, if some harmonic of the spin precession frequency is equal to a harmonic of some other process or combination of processes (e.g., bounce and gyro-motion), then a higher order resonance occurs and, if strong enough, could lead to depolarization. However, because of the small magnetic moment of the nucleus, the strength of resonances at higher harmonics of the spin precession frequency are smaller than those at the fundamental by powers of a small number. While no significant resonances have as yet been identified, it is important to keep this possible mechanism in mind.

3) Wall Recycling. As discussed in regard to fuel injection, nuclei emerging from the plasma (as ions or neutrals, often with $\gtrsim$ 100 eV) bury themselves in any nearby walls and then slowly diffuse back to the wall surface where they are desorbed, usually in a diatomic form. Lattice vibrations and diffusion in or on the irregular surface cause significant fluctuating fields that can apparently lead to depolarization times on the order of 1 msec. This could be short compared to the dwell time of nuclei in the wall (~ 10 msec?) unless the wall is hot (to keep the dwell time short) and/or of a special material (say graphite). Some relatively straightforward experiments, particularly using NMR techniques to measure lattice

vibration rates even without nuclear spin polarization, could help clarify some of the time scales involved here. While this depolarization process is most important for gas puffing in a high recycling mode, it would also play a role in the other fueling schemes to the extent that wall recycled nuclei migrate back into the plasma.

Reactor Subpanel

Secretary - R.R. Borchers

The group met to discuss the questions posed:

1. Would the directivity of the alpha particles or neutrons be of real value in a reactor?

2. Does polarized fuel qualitatively affect costs or performance?

   In view of its general visibility and interest the group also decided to add the question:

3. What advantage is improved reactivity?

   Two presentations were made:

   1) Steve Tamor pointed out that if because of polarization, a reactor confined non-reacting species, they would accumulate and reduce overall reactivity.

   2) Geoffrey Shuy discussed the SAI work on D-^{3}He with neutron suppression.

Most of the group's work consisted of discussing the entries to Tables I and II on the advantages and disadvantages of various aspects of polarized fuels in tandem mirror reactors.

It was agreed that the application of these techniques to other magnetic concepts would follow easily.

Our most important conclusions were:

1. D-^{3}He is probably only more interesting than catalyzed D-D if the D-D reaction can be suppressed. ^{3}He fuel is a problem but not insurmountable.

2. In order for the fuel to reach the reacting plasma in a tandem mirror either pellets or beams were necessary since halo ions are not recycled.

3. Directivity of polarization parallel to the field is useful in tokamaks. Mirrors would prefer polarization perpendicular.

All of the advantages of polarized fuels depend on quantitative analyses with realistic angular distributions. We found no easy way to assess cost differentials.

Table I

Polarized Fuels in Tokamaks

Effect	Advantages	Disadvantages	Comments
Directivity of alphas & neutrons Perpendicular to field	•Less wall damage per unit of power •Neutral beam parallel to magnetic field has less streaming •Obtain higher reactivity	•Alpha losses •More shielding •More problems on inside -blanket -shield -first wall	
Directivity of alphas & neutrons Parallel to field	•Less damage to RF launchers •Better alpha trapping •Neutrons go to outside •No blanket inside •Easier divertor/limiter design •Less neutron streaming for perpendicular neutral beam injection	•Higher wall damage •Do not get reactivity enhancement	
Reactivity increase for Parallel Polarization	•Higher Q or lower fields or Beta •Possible improvement in liquid metal MHD losses	None	1.5 increase in reactivity equivalent to 10% increase in magnetic field and 20% decrease in Beta
Neutron Suppression in D-D by 5 to 20 times	•Smaller magnets •Less shielding •Low activation •Reduces need for shielding and activation •Smaller magnets •Ease of siting and licensing •Longer component lifetime		D-He3 becomes interesting

<u>Table II</u>

Polarized Fuels in a Tandem Mirror Reactor

Effect	Advantages	Disadvantages	Comments
Directivity of alphas & neutrons Perpendicular to field	•Less end streaming •Less first wall damage •Better alpha trapping •Simpler direct converter design •More uniform n heating •Obtain higher reactivity	•Thicker shields •Shorter choke coil life?	•Need pellet injection or beams •Power balance with beams difficult •Possible effects on microstability and MHD
Directivity of alphas & neutrons Parallel to field	•Specifically for a materials test facility •Smaller blanket and shield •Reduction in particle trapping in barrier	•Reduced alpha trapping •More end streaming •More first wall damage •Higher peak heating in blanket •Cannot get enhanced reactivity	
Increased Reactivity	•Higher Q •Possible earlier demonstration & reduced technology •Lower $\overline{B}$ and β	None	1.5 increase in reactivity is about equivalent to 10% increase in field and 25% decrease in Beta
Neutron Suppression in D-D by 5 to 20 times	•Reduces need for shielding and activation •Smaller magnets •Ease of siting and licensing •Longer component lifetime		

Nuclear Physics Subpanel

Secretary - H.H. Barschall

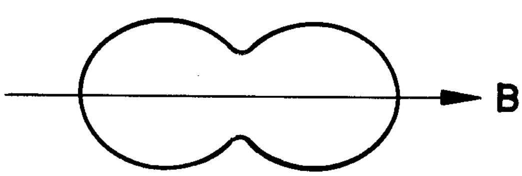
The Reaction $^2H + {}^3H \rightarrow {}^4He + n$ ("DT reaction")

At energies of interest in fusion this reaction proceeds for all practical purposes entirely via a $3/2^+$ compound state at a center of mass energy of 107 keV. The resonance parameters are accurately known. Only S-wave interactions lead to this state. This simplifies the analysis enormously. There is probably no other charged-particle reaction except the very similar $^2H + {}^3He$ reaction for which the situation is as simple, well-understood and predictable as for this reaction.

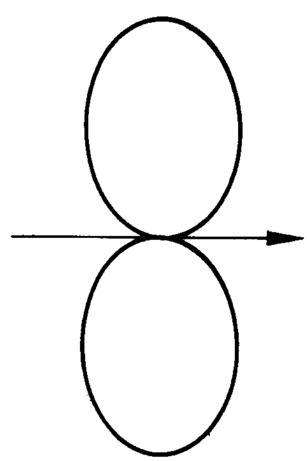
Table I lists the effect of the various directions of spin on the reaction cross section. Here σ_0 denotes the cross for unpolarized projectile and unpolarized target.

Table I

	^2H	^3H	Differential Cross Section	Total Cross Section
(1)	+1	+½	$\frac{\sigma_0}{4\pi} \cdot \frac{9}{4} \sin^2\theta$	$\frac{3}{2}\sigma_0$
(2)	0	+½	$\frac{\sigma_0}{4\pi} \cdot \frac{1}{2} (1 + 3\cos^2\theta)$	σ_0
(3)	-1	+½	$\frac{\sigma_0}{4\pi} \cdot \frac{1}{4} (1 + 3\cos^2\theta)$	$\frac{1}{2}\sigma_0$



Angular distribution of reaction products if deuteron spin is perpendicular to the magnetic field.



Angular distribution of reaction products if both deuteron and triton spins are aligned with the magnetic field.

The first line leads to a 50% increase in the cross section with a preferential emission of the reaction products perpendicular to the magnetic field. The second line produces reaction products parallel to the magnetic field, but no enhancement of the cross section. A combination of the second and third line produces likewise a preferential emission parallel to the field, but a 25% decrease in the cross section.

These are the largest possible anisotropies and enhancements which would be expected only if all nuclei are aligned.

Presumably line 1 is the desired arrangement for tandem mirrors, line 2 for low aspect ratio tokamaks. For the configuration on line (2) the tritium nuclei need not be polarized, which means that this configuration is much easier to develop than that in line (1).

The angle θ is taken with reference to the magnetic field. Since the direction of the field may oscillate in space, the angular distribution oscillates correspondingly with respect to the wall.

The Reaction $^{2}H + {}^{3}He \rightarrow {}^{4}He + p$

This reaction differs from the preceding reaction only by the Coulomb energy difference which moves the resonance from 107 keV to 450 keV. Although this reaction requires higher temperatures, the fact that the resonance occurs at higher energy still results in making this reaction as simple as the DT reaction so that exactly the same effects of nuclear polarization should be expected, i.e., for parallel spins a 50% increase in the cross section.

The Reactions $^{2}H + {}^{2}H \rightarrow {}^{3}He + n$ and $^{2}H + {}^{2}H \rightarrow {}^{3}H + p$

These reactions are known to involve P-wave interactions even at the lowest energies as well as two different S-waves. Most analyses indicate that only one of the three P-waves is important at low deuteron energies, but there is a great deal of uncertainty in the relative importance of the two S-waves.

The fact that P-waves are important generally introduces complications because the cross section and the angular distributions now depend not only on the orientation of the spins, but also on the direction of motion of the interacting nuclei with respect to the spin orientation. Fortunately for the most important case, i.e., parallel spins only S-wave interactions contribute.

The most important issue is the change in cross section expected for parallel spins compared with the unpolarized case. On the basis of available data no reliable answer can be given.

The difficulty is illustrated in Table II in which the contributions of the three most important phase shifts to the cross section at a CM energy near 150 keV are given.

Table II

	^1S	^5S	^3P
R Matrix	1.0	3.5	4.5
Ad'yasevich	3.9	0	5.7

The R-Matrix analysis by Hale and Dodder shown in the first line is the generally accepted description of the four-nucleon system. It leads to the reductions in cross section for $^2H + ^2H \rightarrow ^3He + n$ for parallel spins by the factors shown in Table III as a function of CM energy.

Table III

Deuteron energy (keV), CM	50	100	150	200
$\sigma_{1,1}/\sigma_0$	0.75	0.58	0.48	0.42

Since for parallel spins the D-^{3}He reaction cross section is increased by 50%, the neutron producing reactions would decrease effectively by a factor of 3 or 4. On the other hand, if Ad'yasevich's analysis were correct, this factor would be very much larger. There is at present no information available to check Ad'yasevich's analysis, nor can one be sure that the measurements on which it is based are more reliable than earlier measurements.

This discrepancy cannot be resolved with the presently available information. Even if the ratios in Table III turned out to be very small, the suppression of the neutron producing reactions would be limited by the degree of polarization of the deuterons that can be achieved.

Recommendations

1. An effort should be made to obtain Ad'yasevich's data. It should then be included in the Hale-Dodder analysis.

2. A measurement of the angular distribution of the analyzing power of the ^2H ($\vec{d}$, p) reaction (second rank tensor) with an accuracy of 1% should be attempted.

3. A direct measurement of the $^2\vec{H}$ ($\vec{d}$, p) reaction cross section should be attempted. This is a difficult measurement that would take 2-3 years and would require substantial funding.

Sources Subpanel

Secretary - L.W. Anderson

Possible polarized fuels for a plasma reactor are polarized deuterium, polarized tritium, and advanced materials such as polarized ^3He. There are a number of methods for injecting polarized fuels into a plasma reactor. Fast polarized ion beams, fast polarized atom beams, directed plasmas containing polarized ions, thermal polarized atom beams, and solid polarized pellets may be used to fuel a plasma reactor. The subpanel on sources discussed each of these possible ways to fuel a plasma reactor.

1) Fast Polarized Ion Beams. At the present time there are in use several types of ion sources for producing polarized hydrogen isotopes; the Lamb shift sources, the sources utilizing a ground level atomic beam with an electron bombardment ionizer, and the sources utilizing a ground level atomic beam with direct production of H^- by bombardment with Cs^0. There is general agreement by experts such as T. Clegg and W. Grüebler that it is not possible to scale existing polarized ion sources up in size so that they can produce a polarized ion current as large as 1A. T. Clegg believes that if a very large polarized atom flux were available it might be possible to use a very large ECR ionizer or a very large version of Grüebler's ionizer to produce a polarized ion current of up to 1A. The m_I state of a D^+ beam produced in such an ionizer is the same as the m_I state of the deuterium atom before ionization. Thus if one wishes to produce polarized deuterium ions with $m_I = 0$ then one must produce a high flux of deuterium atoms with $m_I = 0$.

2) Fast Polarized Atom Beams. Fast atom beams can be produced by neutralizing either fast positive or negative ion beams. The resulting fast atoms will have the same nuclear polarization as the fast ions from which they are produced provided neutralization occurs in a magnetic field $B \gg B_c$ where B_c is the critical magnetic field of the atom. We expect that fast polarized atoms can be transported adiabatically (without significant loss of polarization) into a plasma reactor.

3) Directed Plasmas Containing Polarized Ions. J. Katzenstein has produced directed plasmas that can enter a plasma confinement device by polarizing the plasma so that the plasma enters the device with a velocity $v = E/B$. The ions in his plasma have 120-200 keV of energy. Using a magnetically insulated diode with a solid polarized deuterium anode he hopes to inject a plasma containing polarized ions into a plasma reactor. He believes that repetition rates of 10^3 Hz and ion currents of 5A are possible. Questions that need to be studied are the following:

   (a) What is the polarization of the deuterium ions ablated from the solid polarized deuterium anode?
   (b) Can the polarized ions be transported adiabatically (without loss of polarization) into the plasma reactor?

4) Thermal Polarized Atom Beams. Two different proposals for producing thermal polarized atom beams were discussed by the sources subpanel. W. Happer, J. Cecchi and R. Knize propose producing a thermal beam of

polarized deuterium or tritium by spin exchange with an optically pumped alkali such as Rb. D. Murnick and M. Feld have used rate equations appropriate to a general optical pumping experiment to discuss the optical pumping proposal quantitatively. They estimate that with a laser intensity of a few tens of W/cm^2 it may be possible to produce in a volume of a few cm^3 about 10^{18}-10^{19} polarized deuterium atoms/sec. D. Kleppner and T. Greytak propose the cryogenic production of polarized deuterium atoms. They estimate that with existing dilution refrigerators it may be possible to produce $2x10^{20}$ polarized deuterium atoms/sec. The deuterium atoms will have an average energy of about 8^oK. Both Happer and Kleppner believe that the deuterium can be produced in any m_I state. Although very high flux thermal polarized atom beams have not been produced there are reasons to be optimistic that high flux beams can be produced.

5) Solid Polarized Pellets. A. Honig discussed the production of polarized solid deuterium using forbidden rf transitions in solid HD and transferring the polarization to solid deuterium. He believes based on his measurements that it is possible to produce and store large quantities of solid polarized deuterium. D. Kleppner and T. Greytak discussed another method of producing solid polarized deuterium. They are also optimistic about the production of substantial amounts of solid polarized deuterium. Kleppner and Greytak believe that the solid polarized deuterium produced in their method can be formed in any m_I state. Using Honig's method it is possible to produce solid polarized deuterium with $m_I = +1$ and it may be possible to produce solid polarized deuterium with $m_I = \overline{0}$. It is not known whether depolarization will occur during ablation in the reactor. It may be possible to produce solid polarized tritium but this will involve problems of thermal loading of the refrigerator and of radiation damage in the polarized solid that may rapidly relax the polarized spins.

6) Polarized Fast $^3He^o$ Beams. D. Murnick discussed a proposal to produce intense polarized fast neutral beams of ^3He. The process involves the production of fast ^3He in the 2^3S_1 level using the reaction $^3He^+ + Na \rightarrow {}^3He^o(2^3S_1) + Na^+$ followed by the simultaneous use of optical pumping and rf transitions to pump atoms in both hyperfine sublevels of the 2^3S_1 level into the state with $m_S = 1$ and $m_I = 1/2$.

V. WORKSHOP SUMMARY

Workshop Summary

D.W. Kerst

Since the previous summaries have been excellent expositions of the nuclear physics, reactor, plasma, and polarized source problems, most details need not be repeated, but several topics bear further emphasis.

First, there are some of us who may be familiar with the notion of bulging field lines forming a magnetic mirror for confinement, but who are not clear about what a tandem mirror incorporates. This first illustration shows one end of a power-plant sized tandem mirror. The main reaction cell and its solenoid is to the left, off the picture. What we see are the end plugs. These plugs include separate short mirrors into which costly sacrificial plasma can be injected having parameters that enable an electrostatic potential to be created which assists in end loss confinement. Additionally, other difficulties are introduced by such end plugging, and these require further structures added on to control heat conductivity and stability. An expensive and lossy end structure can economically plug a long reaction chamber. The second illustration shows the whole mirror power plant. By contrast, the third figure shown is the TFTR tokamak described earlier which is toroidal and not of full reactor size.

The mirror end plugging equipment would be exposed to neutrons emitted generally along the field direction. It may be difficult to shield well in that direction. Furthermore, neutrons near the field direction would pass through the side wall at an angle which gives them a long path in the first wall surface adjacent to the reaction in the central cell. To lower the resultant first wall damage one would choose a polarized fuel which emits neutrons preferentially perpendicular to the magnetic field, namely a D-T reaction with spins parallel. However, then the end mirror coils near to the reaction chamber ends are badly exposed. The problems of engineering choices are thus evident. If reactors are to have one to ten megawatts of neutron flux passing through the first wall, with the limitation being lifetime for damage in the very-few-year range, then the size and thus the cost of the reactor is quite sensitive to gains that polarized fuels might provide.

For toroidal devices, particularly for tokamaks with a coil structure in the center of the toroid, neutrons emitted perpendicular to the predominantly toroidally directed field would produce somewhat larger damage of the central structure; consequently, fuel reactions polarized at right angles to each other would be the tokamak choice with the tritium spin along the field. Then the neutrons emerging along the toroidal field have four times the intensity of those emerging perpendicular to the toroidal direction.

Note that there would be no reactivity gain for perpendicular fuel polarization in the tokamak case -- only a gain due to directionality. However, the mirror with parallel polarization could have a gain of 1.5 in reactivity in addition to the possibility of improvement resulting from favorable directionality.

When trial designs with the engineering choices for shields, coils, walls, etc., are made, and when sizes, optimum β (plasma pressure/magnetic pressure) and costs are determined, then the gain from polarized fuels will be evident. These designs choices are thus presently needed. If the gain is slight, then the complications accompanying polarization may not be judged sufficiently great. The vigor of pursuit of polarization technology will depend on the perception of these gains.

One rough estimate which was shown by the reactor study section emphasizes this point. The illustration showed that at an inverse aspect ratio of 3, as in tokamak designs, there may be a decrease in wall flux, Γ, or damage, D, of only about 20 percent, because of the angular distribution of intensity of neutrons not being optimum for all points on the walls. A realistic engineering study would be needed to determine the gain resulting from the effect of the complete angular distribution.

The examples mentioned for polarized fuels refer to structures which are now being developed for confinement. There may be other systems which can be designed especially to benefit from using polarized fuels. For example, a case which gives promise of greatly diminishing neutron damage by polarization involves the higher temperature reactions D-D and D-^{3}He. The D-^{3}He reaction is neutron-free, but the D in the mixture would create neutrons from the D-D reaction. However, this D-D reaction is suppressed to 1/2 or, possibly 1/20 when spins are parallel. With this polarization the D-^{3}He reaction would produce very few neutrons, and a reactor based on this fuel would have many advantages to offset the disadvantages of higher temperature and rare fuel. Whether polarization gives a factor of 2 suppression or a possibility of 20-fold suppression awaits additional experiments. The polarized D-D reaction thus needs more detailed study, especially the branch which makes tritium -- a prolific energetic-neutron producer.

In any event the D-^{3}He reaction has the same 50 percent increase in reactivity with spins parallel that the D-T reaction enjoys.

Plasma questions and atomic physics questions are involved in the injection process and in the mechanisms of depolarization, which must be restrained. Fuel is introduced by gas puffing, by pellet injection, or by particle beams. Gas puffed in is ionized near the hot plasma boundary, and, in a tokamak with a divertor, much of it goes right out of the divertor, and a small amount, about 20 percent, would get to the middle of the plasma; thus to make up for losses 1,600 amperes equivalent are needed inside the plasma so 8,000 amperes equivalent would have to be injected. On the other hand, if refluxing from the wall is not diverted, it will refuel the plasma and the make-up required of puffing would be equivalent to only 100-200 amperes of new fuel.

If refluxing is minimized by an edge divertor, then the polarized gas which is puffed in can retain polarization while it is ionized and while it enters the reacting plasma; however, if refluxing from the wall replaces the escaping fuel, then there are processes inside the wall which will depolarize the refluxing atoms in a time the order of a millisecond long. The persistence of polarization on reflection from a wall is thus a question that should be examined experimentally with the possibility that some favorable materials or conditions will be found. Since fuel would reflux from the wall about 10 times during the reaction, depolarization must not be easily lost on reflection.

Polarized pellets of ~ 10^{22} atoms could be injected into the reacting plasma's center with a speed of ~ 10^4 meters/sec. The violent evaporation and dispersal may evolve processes which depolarize the fuel. Nothing is known of this from the cases which have been tried at speeds of 10^3 meters/sec with as yet unpolarized pellets. This must be explored experimentally.

Neutral beams used for plasma heating at present are unpolarized. At the 120 keV energy needed for penetration, they would overheat the plasma if currents as large as refueling currents were injected. Thus, a mixture of polarized neutral beams and puffing polarized cold gas or polarized pellet injection would be required.

It has been suggested that neutral mixed beams of electrons and fuel ions could be injected. Such beams might be produced by pulsed ion-producing diodes which have been shown to give very large ion currents above the 100 keV range. With the accompanying electron stream, the mixed beam would penetrate by its internal electric polarization force holding the positive and negative streams together as they cross the magnetic field. This is the way plasma guns are used to fill many closed confinement systems. There are turbulent effects and magnetic fluctuations during such a process as the cloud evolves into a largely trapped state. Thus persistence of polarization throughout the turmoil would need to be established. Again, the total fuel requirement could not be put in at 100 to 200 keV because of overheating the reaction. Energies in the several kilovolt range provided by the usual Marshall plasma gun would be suitable. The polarized fuel would have to be supplied to such injectors with polarization surviving not only the violent gun discharge process but also the trapping process.

Within a confined magnetized plasma there are numerous possible waves, disruptions, and turbulence processes which might depolarize fuel before it burns. So far the most dangerous case analyzed arises from the deuteron spin precession frequency being 86 percent of its gyrofrequency. Then waves involving the cyclotron frequency might cause depolarization under some conditions. Good plasma confinement requires avoidance of destabilizing waves, and thus eliminating them would also help maintain polarization. It has been suggested that dissipating depolarizing waves at the deuteron precession frequency could be accomplished by the addition of a little ^7Li, which has almost the same frequency for gyration.

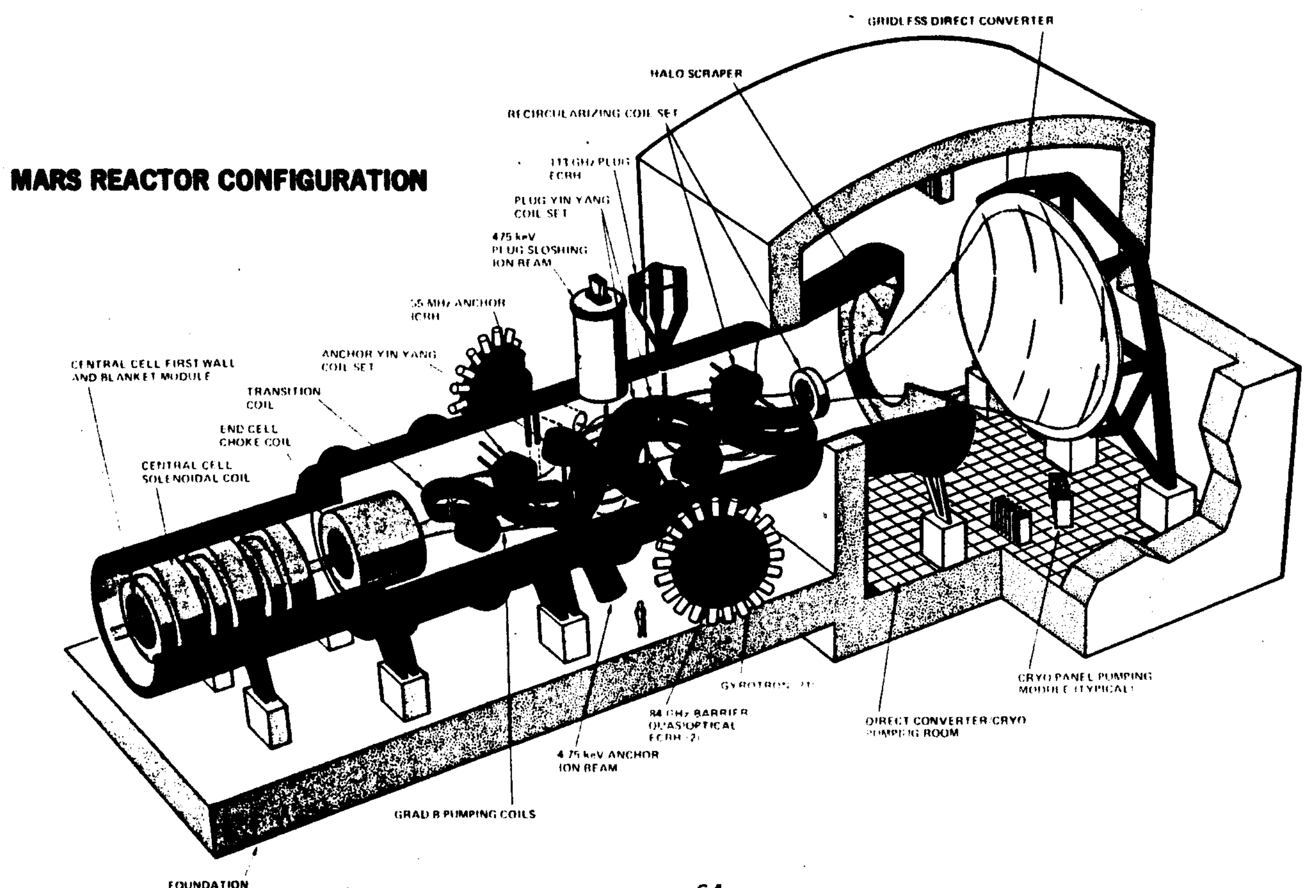
The experience with polarized particle beams in high energy accelerators suggests that, due to non-linearities in force fields, integrals of the fuel particle precession frequency coinciding with integrals of other frequencies in the plasma motion might destroy polarization, as it does in accelerators. The perturbing forces sufficient to depolarize are too small for measurement in acceleration.

If in unfavorable conditions field irregularities of less than one gauss are required to avoid depolarization, then adiabatic entry into larger irregularities would be harmless. Much larger field irregularities are seen in plasmas; but the fluctuations are usually of low frequency and long enough wavelength to be out of the range of depolarization resonance with a moving deuteron. However, some confinement systems (RFP and compact tori -- not tokamaks) have an interchange between toroidal to poloidal field going on. The fluctuation spectrum of this possibly dangerous activity has been the subject of theoretical study at Los Alamos.

Several polarized source schemes have been discussed with the resulting evidence that it was difficult to get polarized particles at a rate exceeding 1 ampere equivalent, although the power consumed would not be excessive. Possibilities of producing polarized refrigerated atoms or solid deuterium seem better. A yield of 1 liter per day was considered in sight. Such a supply suggests that it could be fed into sources such as existing fusion experiment high-power neutral beam injectors, provided depolarization in the source could be avoided and provided a spin axis field could be provided.

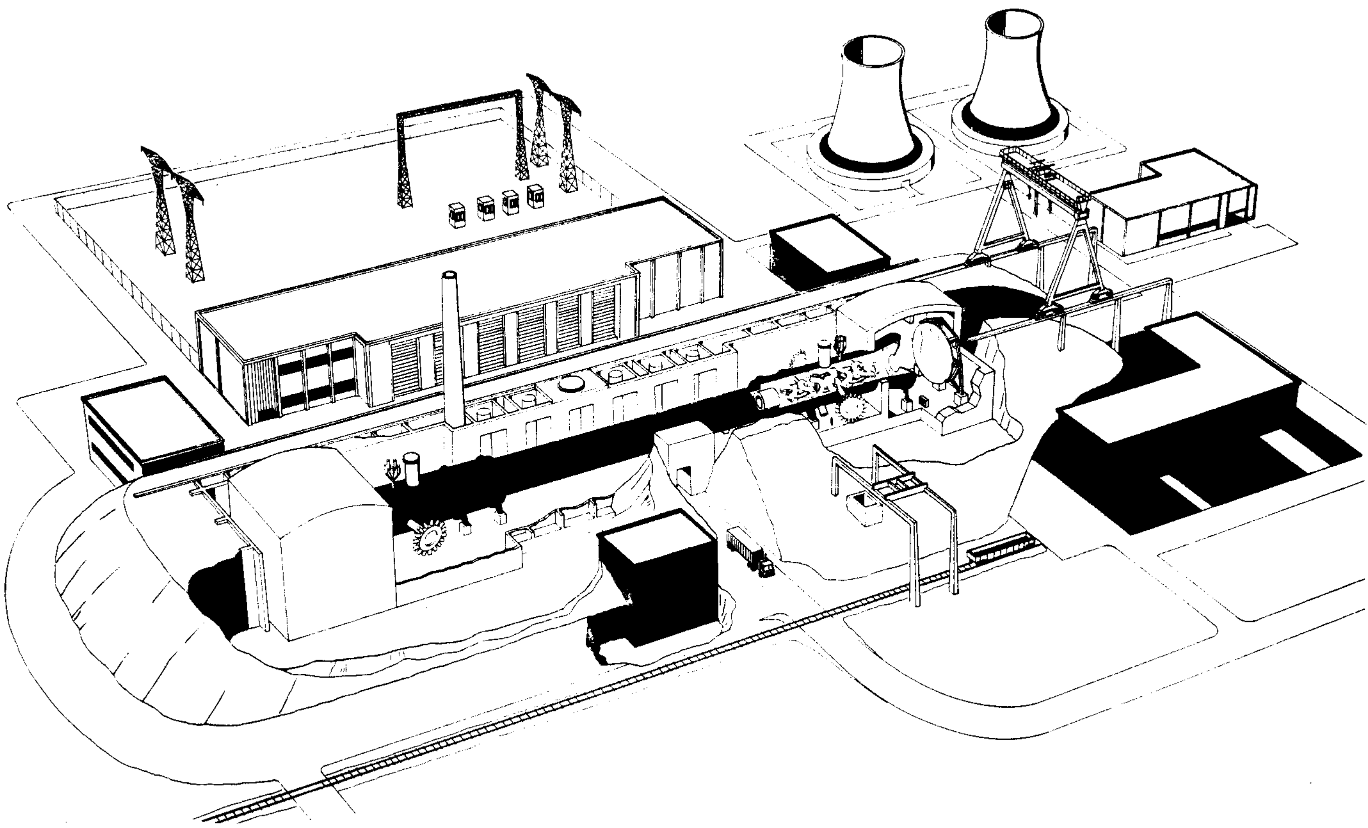
Finally, two classes of experiments are suggested: integral experiments in existing, or small, confinement systems with neutron diagnostics if enough fuel supply can be developed; and elemental tests of processes contributing to depolarization, if the diagnostics can be accomplished. Such experiments could be polarized D-D cross-section measurements, wall reflection tests similar to those done in Marburg, N.M.R. tests of spin relaxation times, and polarized pellet vaporization tests.

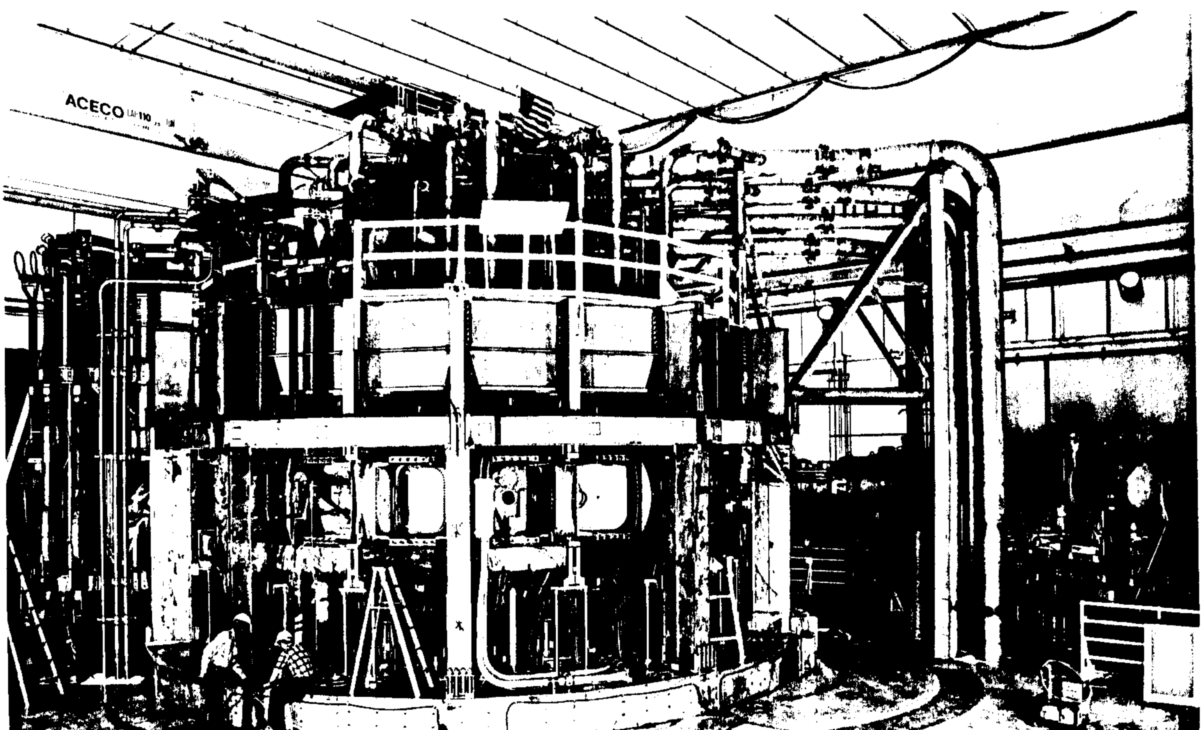
There no doubt will be ad hoc experiments suggested as a result of these discussions and special designs examined to learn how to engineer structures for best utilization of polarized fuels.



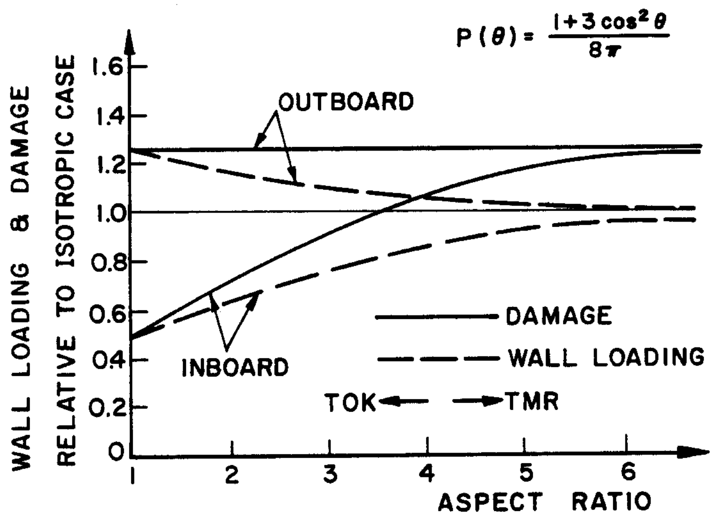
MARS REACTOR CONFIGURATION

MARS Power Plant

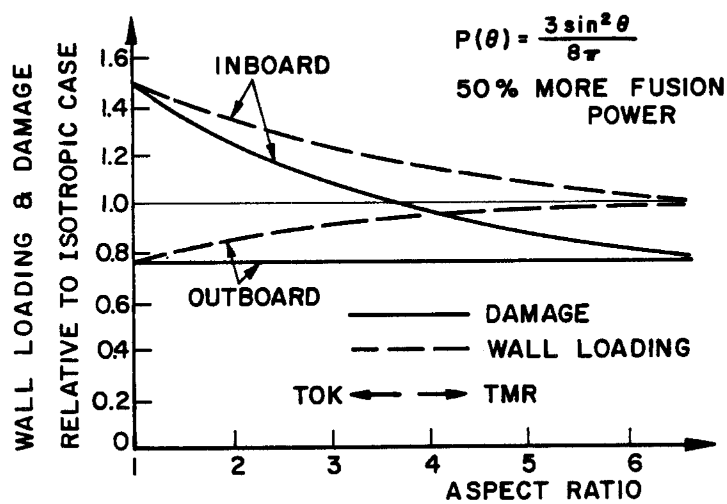




Tokamak Fusion Test Reactor (TFTR) at Princeton University.



P(θ) = (1+3cos²θ)/8π
WALL LOADING & DAMAGE
RELATIVE TO ISOTROPIC CASE
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
OUTBOARD
INBOARD
DAMAGE
WALL LOADING
TOK
TMR
1
2
3
4
5
6
ASPECT RATIO



P(θ) = 3sin²θ/8π
50% MORE FUSION POWER
WALL LOADING & DAMAGE
RELATIVE TO ISOTROPIC CASE
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
INBOARD
OUTBOARD
DAMAGE
WALL LOADING
TOK
TMR
1
2
3
4
5
6
ASPECT RATIO

APPENDICES

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Fusion Reactor Plasmas with Polarized Nuclei

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Nuclear fusion rates can be enhanced or suppressed by polarization of the reacting nuclei. In a magnetic fusion reactor, the depolarization time is estimated to be longer than the reaction time.

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Recent technological developments[1,2] have made possible the generation of polarized gases in quantities of practical interest for the production of polarized fusion plasmas. The dependence of nuclear fusion reactions on nuclear spin[3] suggests that polarization of the reacting particles may be advantageous in providing control of the reaction rates and the angular distribution of the reaction products.

The large cross section for the reaction D(T, n)^{4}He at low energy arises primarily from a $J=\frac{3}{2}^+$ resonant level of ^{5}He at 107 keV above the energy of the free D and T nuclei.[4] At low energies, the reaction occurs only in the $l=0$ state, so that the angular momentum must be supplied by the spin of the D and T nuclei. Since D has spin 1 and T spin $\frac{1}{2}$, their possible combined spin states are $S=\frac{3}{2}$ and $\frac{1}{2}$. The reaction is due almost entirely to interacting pairs of D and T nuclei with $S=\frac{3}{2}$. The statistical weight of this state is 4 while that of the $S=\frac{1}{2}$ state is 2. Thus, for a plasma of unpolarized nuclei, effectively only $\frac{2}{3}$ of the interactions contribute to the reaction rate.

We consider now the case of a magnetic D-T reactor where the fractions of D nuclei polarized parallel, transverse, and antiparallel to $\vec{B}$ are d_+, d_0, and d_-, respectively, while the corresponding fractions of the T nuclei are t_+ and t_-. Then the total cross section is

$$\sigma=(a+\tfrac{2}{3}b+\tfrac{1}{3}c)f\sigma_0+(\tfrac{2}{3}b+\tfrac{4}{3}c)(1-f)\sigma_0, \qquad (1)$$

where $a=d_+t_++d_-t_-$, $b=d_0$, $c=d_+t_-+d_-t_+$, and $f\sigma_0$ is the cross section for the $\frac{3}{2}^+$ state. The magnitude of f has been estimated at about 0.95,[4] but may be greater than 0.99.[5] (The remainder of the cross section is ascribed to a $\frac{1}{2}^+$ state that lies 3 MeV about the $\frac{3}{2}^+$ state.) For an unpolarized plasma, $a=b=c=\frac{1}{3}$ so that $\sigma=\frac{2}{3}\sigma_0$. On the other hand, if all the nuclei are polarized along $\vec{B}$, then $a=1$, $b=c=0$, and $\sigma=f\sigma_0$, so that the enhancement of reactivity is $\frac{3}{2}f$.

The resultant angular distributions of the neutrons and α particles are

$$\frac{d\sigma}{d\Omega}=\frac{f\sigma_0}{2\pi}\left[\tfrac{3}{4}a\sin^2\theta+(\tfrac{2}{3}b+\tfrac{1}{3}c)\left(\frac{(4/f)-3+3\cos^2\theta}{4}\right)\right], \qquad (2)$$

where θ is the pitch angle relative to $\vec{B}$. If all the nuclei are polarized parallel to $\vec{B}$, the angular distribution of the neutrons and α particles is $\sin^2\theta$; if the D nuclei are polarized transverse to $\vec{B}$, then the distribution is $(4/f)-3+3\cos^2\theta$. The polarization of the neutrons also varies with θ. At $\theta=90°$, it is given by

$$n_+-n_-=\frac{\frac{3}{4}(d_-t_--d_+t_+)+\frac{1}{6}d_0(t_+-t_-)+\frac{1}{12}(d_+t_--d_-t_+)}{\frac{3}{4}a+\frac{1}{6}b+\frac{1}{12}c}, \qquad (3)$$

where n_+ and n_- are the fractions of neutrons polarized parallel and antiparallel to $\vec{B}$. (We have set $f=1$.) Since these results depend only on the vanishing of the orbital angular momentum prior to the reaction, they are roughly independent of energy within the range of fusion interest.

The D-D reaction is more complex than the D-T reaction and its properties are less well known; therefore, we can give only an indication of the potential effects of polarization. From the results of Ad'yasevich and Fomenko[6] it can be demonstrated that enhancements of order 2 can be obtained at low energy. For an ordinary thermal ion distribution, such enhancements can be obtained by polarizing the deuterons transverse to the magnetic field. Alternatively, if colliding-beam or beam-target methods are used, the two ion components should be polarized in opposite directions relative to the field. If, on the other hand, the ions are all polarized parallel to the field, one may conclude from these results that the reaction rate is suppressed by a substantial factor. While the results of Ad'yasevich and Fomenko provide a good fit to one class of data,[6] other recent measurements[7] lead to substantially different conclusions, indicating D-D enhancement factors smaller than 1.6.

There would be little pratical value in polarizing nuclei if the depolarization rates were rapid compared with the fusion reaction rate. At first sight, it would appear that, because of the small energy difference between the two polarization states ($\Delta E \approx 10^{-7}$–10^{-6} eV $\ll kT$), an unpolarized equilibrium would be rapidly established. However, as far as we can see, the *mechanisms* for depolarization of nuclei in a magnetic fusion reactor are suprisingly weak. We will consider four such mechanisms:

(1) *Inhomogeneous static magnetic fields.*—Let $\omega_2 = eB_0/2m_p c$ be the deuteron cyclotron frequency, and let $\Omega_2 \equiv \Delta E/\hbar = g_2 eB_0/2m_p c$ be the deuteron precession frequency, where ΔE is the Zeeman energy for a change of spin orientation $\Delta m = 1$, and g_2 is the magnetic moment of the deuteron in nuclear magnetons. Similarly, let Ω_3 and g_3 be the precession frequency and magnetic moment of the triton. Then $\Omega_2 = 0.86\omega_2$, and $\Omega_3 = 5.96\omega_2$. If a nucleus with velocity v passes through static magnetic-field inhomogeneities of scale s, it sees them at a frequency v/s. As in the case of the adiabaticity of the ordinary magnetic moment of the particle gyromotion, frequencies below the nuclear precession frequency —i.e., static inhomogenities on a scale that is large compared with the ion gyroradius ($s \gg \rho_i$) —cannot change the polarization.

(2) *Binary collisions.*—Simple electrostatic Coulomb scattering does not affect the nuclear spins, but there are many other potential depolarization mechanisms: The triton can interact with electrons, deuterons, and other tritons by spin-orbit and spin-spin interactions; the deuteron can also interact by means of its quadrupole moment. Fortunately, the associated depolarization rates turn out to be quite small.[8] During each collision, the change in polarization from state α to state β is small and of random sign. We have calculated the cross section σ_i for the rate of increase

$$d(\beta^2)/dt = n\sigma_i v_{\rm rel} \tag{4}$$

by process i, where n is the particle density and $v_{\rm rel}$ is the relative velocity. The cross sections for interaction with electrons are found to be of the same order as for ions; because of the factor $v_{\rm rel}$ in Eq. (4), depolarization by electrons therefore predominates. For spin-orbit depolarization of T, we have

$$\sigma_i = (4\pi/3)g_3^2 r_p^2 \ln(c/\omega_p\lambda) = 1.7\times10^{-29}\ \text{cm}^2,$$

where $r_p \equiv e^2/m_p c^2$, $\omega_p^2 = (4\pi n e^2)/m_e$ and $\lambda = \hbar/m_e v$. For spin-spin depolarization, $\sigma_i = \frac{11}{9}\pi g_3^2 r_p^2 = 8\times10^{-31}$ cm^2. For the d_0 state of D, σ_i is smaller by $(g_2/g_3)^2 = 0.083$ than for T; for the d_+ or d_- states, it is smaller by $\frac{1}{2}(g_2/g_3)^2 = 0.042$. Interaction with the quadrupole moment is negligible for electrons. Using typical reactor parameters, $n = 2\times10^{14}$ cm^{-3}, $T = 10^4$ eV, we find the rate of depolarization to be 2.1×10^{-5} s^{-1} for T, 1.75×10^{-6} s^{-1} for the d_0 state of D, and 0.9×10^{-6} s^{-1} for the d_+ or d_- state of D. These rates are small compared with the typical 1 s^{-1} rate for fusion energy multiplication or the 10^{-2} s^{-1} rate for complete fuel burnup. There is also a contribution from elastic nuclear scattering, which we estimate at $\Delta\beta^2 \lesssim 10^{-4}$ per fusion event.

(3) *Magnetic fluctuations.*—A polarized moving nucleus will tend to be depolarized by those harmonics of the fluctuating fields which are left-circularly polarized with respect to $\vec{B}$, if the Doppler-shifted frequency in the frame of the nucleus is equal to its precession frequency. Defining the intensity of magnetic fluctuations as I_ω, where $(\delta\tilde{B})^2 \equiv \int I_\omega d\omega$, then

$$\frac{d(\beta^2)}{dt} = \left(\frac{ge}{2m_p c}\right)^2 I_\omega(\Omega) = \frac{(geB/2m_p c)^2}{\Delta\omega}, \tag{5}$$

where $\Delta\omega$ is the bandwidth around Ω over which $\tilde{B}^2$ extends in the frame of the nucleus.[9] The resonant frequency in the laboratory frame is $\omega = \Omega_i - k_z v_z - n\omega_i$, where k_z is the component along $\vec{B}$ of the wave number of the fluctuation. The cyclotron frequency term $n\omega_i$ in this equation ($n = 0, \pm1, \pm2$, etc.) is produced by the gyromotion of the nucleus, with the amplitude of the higher harmonics seen by the nucleus reduced by $J_n(k_\perp \rho_i)$. In thermal equilibrium, plasma fluctuations are very small: For a 10^4-eV Planck spectrum of electromagnetic waves, we find that $d(\beta^2)/dt \sim 10^{-14}$ s^{-1}. A depolarization rate sufficiently large so as to prevent reactor operation [i.e., $d(\beta^2)/dt \gtrsim 1\ s^{-1}$] would imply $\tilde{B} \gtrsim 3(\Delta\omega/\Omega)^{1/2}$ G in the case of either D or T. For a highly non-Maxwellian plasma velocity distribution, microinstabilities around the deuteron cyclotron frequency could indeed give rise to significant depolarization through direct interaction ($n=0$) with the precession of the deuteron ($\Omega_2 = 0.86\omega_2$). In a roughly Maxwellian plasma, however, such waves are strongly damped, so that their amplitude should be small. Spatial gradients of plasma temperature and density tend to excite lower-frequency field perturbations with longer wavelengths, which could interact through higher-n resonances. For example, with $n=-1$, the Ω_2 resonance can occur for a transverse Alfvén wave at $\omega = 0.15\omega_2$, while the higher-frequency triton precession ($\Omega_3 = 5.96\omega_2$) could resonate with a whistler mode propagating at an angle to $\vec{B}$. Because of the complexity of the plasma wave spectrum, it is difficult to place detailed upper limits on "anomalous" depolarization in a magnetic fusion reactor, but for a moderately close approach to thermal equilibrium (i.e., avoidance of steep gradients, especially in velocity space), the desired degree of quiescence seems likely to be attainable.

(4) *Atomic effects.*—The polarized nucleus of a hydrogenic atom is not depolarized by ionization, but if recombination (or charge exchange) couples the nucleus to an electron of opposite spin, it can be depolarized with 50% probability. This process, however, is inhibited by an external magnetic field B sufficiently strong compared with the critical field B_c at which the Zeeman splitting equals the hyperfine splitting: The probability of spin exchange is then reduced[10] by the factor $(B_c/2B_0)^2$. Since B_c is only of order 3×10^2 G for D and 10^3 G for T, multiple processes of recombination into atomic hydrogen, followed by reionization, could take place in a 5×10^4 G field without significant depolarization. Recombination into molecular hydrogen could expose the nucleus to more rapid depolarization by spin-orbit coupling associated with the molecular tumbling; however, the boundary conditions at the edge of hot plasmas can be designed to discriminate against molecular recycling (e.g., in the case of tokamaks with divertors, or mirror machines with axial plasma outflow).

One obvious economic advantage of polarizing the nuclear fuel of a reactor is the enhancement of fusion power (1.5 for D-T, $\gtrsim 1.6$ for D-D). This enhancement would be particularly helpful for small-sized reactors with intrinsically low power multiplication.[11] The ability to *suppress* reactions is also of practical value: For example, if the nuclei of a D-He^3 fuel mixture are all polarized parallel to $\vec{B}$, the D-D reaction rate will tend to be suppressed, while the D-He^3 rate is enhanced by 1.5 (similar to D-T). In this way, it may be possible to approximate a neutron-free fusion reactor without resorting to high-temperature, low-power processes such as p-Li.

In the case of the D-T reaction, the ability to control the anisotropy of the emitted α particles allows enhancement of the fraction trapped into well-confined orbits (d_+t_+ being favorable for mirror machines and d_0 for tori) and improvement of magnetohydrodynamic stability properties (d_0 being favorable for tori). Control of α-driven plasma currents and microinstabilities may also be possible. Reactor shielding and blanket design would benefit: e.g., in tori, tangential emission (the d_0 case) could minimize the neutron load on the constricted small–major-radius side of the vessel. The polarization of the neutrons should prove useful in research.

A fusion reactor could be fueled with polarized atomic hydrogen gas, using the optical pumping method described in Ref. 1. The incremental energy requirement per nucleus is very small (a few electronvolts) compared with the mean energy of fusion plasma particles. Polarized atomic hydrogen (or deuterium/tritium) could also be used as a plasma source for multiaperture ion acceleration in a conventional neutral beam line.[12] A moderate magnetic field ($\lesssim 1$ kG) along the direction of acceleration is needed to maintain polarization; following charge-exchange neutralization, the field direction can be rotated from longitudinal to transverse and matched smoothly into the main confining field. Injection of polarized frozen hydrogen pellets would be attractive, but appears problematical—as does the use of polarized targets for inertial fusion.

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[1]N. D. Bhaskar, W. Happer, and T. McClelland, Phys. Rev. Lett. 49, 25 (1982).

[2]I. F. Silvera and J. T. M. Walraven, Phys. Rev. Lett.

44, 164 (1980); R. W. Cline, T. J. Greytak, and D. Kleppner, Phys. Rev. Lett. 47, 1195 (1981).

[3]M. Goldhaber, Proc. Cambridge Philos. Soc. 30, 561 (1934).

[4]J. P. Conner, T. W. Bonner, and J. R. Smith, Phys. Rev. Lett. 88, 468 (1952).

[5]W. Haeberli, in *Nuclear Spectroscopy and Reactions*, edited by J. Cerny (Academic, New York, 1974), Pt. A, p. 185.

[6]B. P. Ad'yasevich and D. E. Fomenko, Yad. Fiz. 9, 283 (1969) [Sov. J. Nucl. Phys. 9, 167 (1969)].

[7]G. Hale and D. Dodder, in *Few Body Systems and Nuclear Forces II*, Lecture Notes in Physics Vol. 87, edited by H. Zingl, M. Haftel, and H. Zankel (Springer-Verlag, New York, 1978), p. 523, and private communication.

[8]L. Wolfenstein, Phys. Rev. 75, 1664 (1949).

[9]J. A. Pople, W. G. Schneider, and H. J. Bernstein, in *High-Resolution Nuclear Magnetic Resonance* (McGraw-Hill, New York, 1959), Appendix B.

[10]H. Kopfermann, in *Nuclear Moments*, Pure and Applied Physics Vol. 2, edited by H. S. W. Massey (Academic, New York, 1958), Chap. 1.

[11]D. L. Jassby, Nucl. Fusion 17, 309 (1977).

[12]W. B. Kunkel, in *Fusion*, edited by E. Teller (Academic, New York, 1981), Vol. I, Pt. B, Chap. 12.

APPENDIX B

Polarized Fuel Reactor Related Questions to be Addressed by Subpanels at Workshop

A. Plasma Physics

1. How should the polarized nuclei be introduced into the plasma?

2. What are the dominant depolarization mechanisms and consequent polarized nuclei lifetime in the plasma?

B. Nuclear Physics

The following questions refer to CM energies below 100 keV.

1. How well do we know the total reaction cross sections for polarized nuclei for the reactions:

   (a) $D + T \rightarrow {}^4He + n$
   (b) $D + D \rightarrow {}^3He + n$
   (c) $D + D \rightarrow {}^3H + p$
   (d) $D + {}^3He \rightarrow {}^4He + p$

2. What anisotropy in the products would one expect for reactions (a) and (b)?

3. How is the ratio of cross sections for reactions (b) and (d) affected by various polarizations of the projectiles?

C. Sources

1. How can one make a high current polarized ion source for either positive or negative ions?

2. How can the appropriate nuclear polarization for deuterium be produced?

3. What depolarization problems arise in neutralizing the polarized beam?

4. What depolarization may occur in transporting the ion beams to the reactor?

5. How can one produce large thermal polarized atomic beams of deuterium and tritium?

6. Can one produce solid targets of polarized deuterium or tritium?

D. Reactors

1. Is directivity of alphas or neutrons of real value in a reactor?

2. Does use of polarized particles qualitatively affect costs or gross design of a fusion reactor? tokamak? tandem mirror? other?

APPENDIX C

4/12/83

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APPENDIX D

Program
Polarized Fuel Reactor Workshop

Monday, March 28, 1983

9:00 a.m.	Lake Shore Room in Wisconsin Center Introduction - G.L. Kulcinski Chairman - G.K. Walters W. Dove, "DOE Interest in Polarized Fusion" M. Goldhaber, "Polarized Nuclei" R.M. Kulsrud, "Polarization of Nuclei in Nuclear Fusion - Review" G. Hale, "Cross Sections for Polarized Fusion Reactions"
Lunch	
1:30 p.m.	Lake Shore Room in Wisconsin Center Chairman - R.V. Pound W. Haeberli, "Current Status of Polarized Beam Technology" W. Happer, "The Production of Polarized Nuclear Spins by Laser Optical Pumping" D. Kleppner, "Spin Polarized Deuterons for Fusion Applications"
4:30-5:00	Brief Organizing Session for Subpanels
6:00-7:30	Reception - Elvehjem Museum of Art to view Japanese prints from the J.H. Van Vleck collection.
7:30-9:30	Dinner - University Club

Tuesday, March 29, 1983

9:00 a.m. Subpanel Discussions

Topic	Secretary
Plasma Physics	J.D. Callen - Room 215
Nuclear Physics	H.H. Barschall - Room 314
Sources	L.W. Anderson - Room 311
Reactors	R.R. Borchers - Room 138

Lunch	
1:30 - 2:30	Lake Shore Room in Wisconsin Center Brief Report of Subpanel Secretaries
2:30 - 5:00	Reconvene or Restructure Subpanels
Evening	Free

Wednesday, March 30, 1983

9:00 a.m.	Lake Shore Room in Wisconsin Center Chairman: John Dawson Report of Subpanel Conclusions and Discussions
Lunch	
1:30-3:00	Lake Shore Room in Wisconsin Center Chairman: M. Goldhaber Summary of Workshop - D.W. Kerst