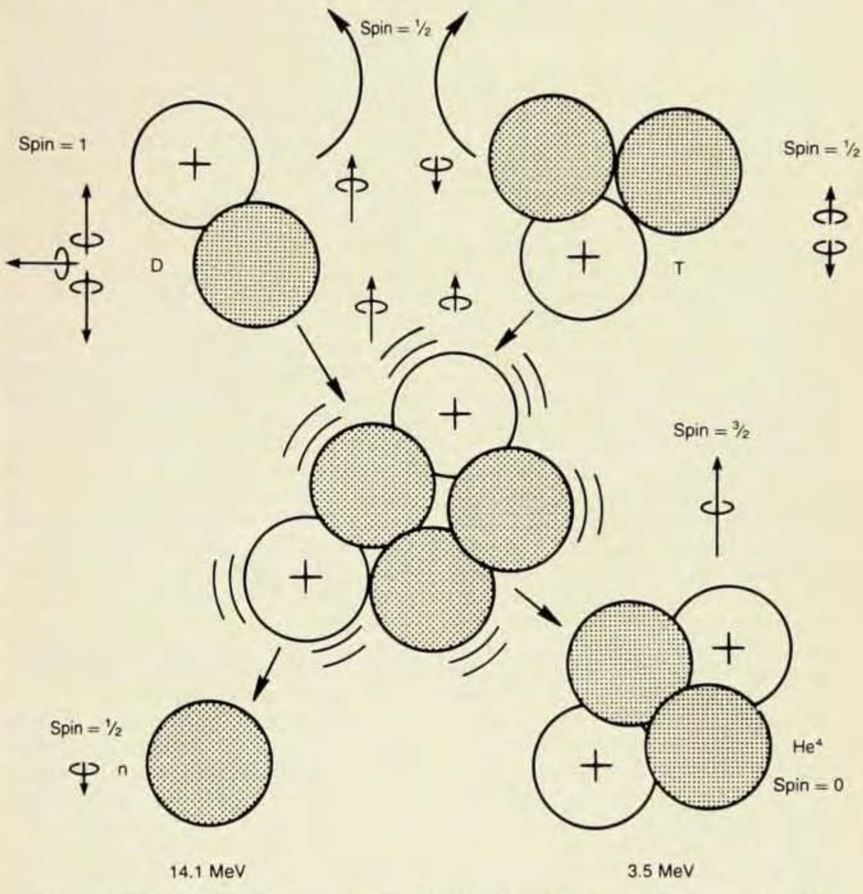
Polarized plasmas may prove useful for fusion reactors

A casual cocktail-party inquiry by Maurice Goldhaber (Brookhaven) has set in motion the detailed examination of a quite novel approach to fusion in magnetic-confinement reactors. Last winter Goldhaber asked Harold Furth, director of the Princeton Plasma Physics Laboratory, whether he had ever considered polarizing the nuclear spins in a magnetically confined reactor plasma. The answer was *no*, basically because naive considerations lead one to expect that such a polarized hot plasma would much too quickly become thermally depolarized.

But the depolarization mechanisms in a reactor environment had never been examined in detail; and if one could keep a fusion plasma highly polarized long enough, several very desirable consequences could be exploited. Therefore Goldhaber and Furth, together with Russell Kulsrud and Ernest Valeo of Princeton, set out to calculate the depolarization rates that would result from various mechanisms in a toroidal or mirror fusion reactor, and to examine the benefits one could expect from various polarization schemes. In a recent Princeton Plasma Physics Laboratory Report,[1] discussed at the International Conference on Plasma Physics (Göteborg, Sweden, 9–15 June), Kulsrud and his coworkers reach the surprising conclusion that a polarized D–T, D–D or D–He^3 plasma would maintain its polarization against collisions at better than 95% for about 100 seconds in a magnetic fusion reactor—five times the life expectancy of a plasma nucleus in a tokamak.



Deuterium–tritium fusion at reactor energies proceeds primarily through an intermediate spin-$\frac{3}{2}$ resonance of He^5, 107 keV above the sum of the D and T masses. A deuteron–triton collision in a spin-½ state will contribute almost nothing to the fusion cross section. Thus if one could align all D and T spins parallel to the reactor's magnetic field, the fusion cross section would be enhanced by 50%. The emerging energetic alpha and neutron come off with an $\ell = 2$, $\sin^2\theta$ angular distribution that would be particularly useful in mirror machines. Open (shaded) circles are protons (neutrons). Each spin-S state has $2S+1$ possible orientations.

The benefits to be expected from the polarization of a D–T, D–D or D–He^3 plasma—enhancement of desired fusion cross sections, suppression of unwanted reactions, and control of the direction of emergence of fusion products—would of course come to nothing if one were unable to supply the reactor with adequate inputs (amperes) of polarized nuclei at acceptable power cost. Happily, two recently developed techniques for producing polarized nuclei in profusion show promise in this regard. A group led by Will Happer (Princeton) has been investigating[2] the polarization of xenon nuclei by spin exchange with optically pumped rubidium. Richard Cline, Thomas Greytak and Daniel Kleppner at MIT have recently reported[3] that their high-magnetic-field, cryogenic technique for stabilizing spin-polarized atomic hydrogen (PHYSICS TODAY, June 1980, page 18) can yield protons with 99% polarization. Both groups expect that their methods can be applied straightforwardly to produce amperes of highly polarized deuterons. The optical pumping technique, Happer told us, should also be directly applicable to He^3, which, like xenon, is a noble gas.

In most fusion reactions of light nuclei, some spin states contribute much more strongly to the cross section than others. For example, the most commonly considered reaction for fusion reactors, $D + T \rightarrow He^4 + n$, goes almost entirely through the spin-$\frac{3}{2}$ state. Because the deuteron and triton have spin 1 and ½, respectively, and orbital angular momentum can be neglected at reactor energies, this implies that these two heavy hydrogen nuclei will fuse most frequently when their spins are aligned

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with one another. By contrast, the D–D reaction, giving $He^3 + n$, is strongly suppressed when all the deuterons are aligned.

In an unpolarized D–T plasma, Kulsrud and his colleagues point out, the $\frac{1}{3}$ of all D–T collisions that occur in the spin-$\frac{1}{2}$ state contribute almost nothing to the fusion reaction. Thus if one could polarize all the deuterons and tritons parallel to the magnetic field of a tokamak or mirror machine, one would enhance the fusion cross section and hence the reactor's power output by almost 50%. (The spin-$\frac{1}{2}$ state does make a very small contribution to the fusion cross section.)

The D–D fusion reaction is more complex, and the details of its nuclear physics are less well known. But Kulsrud and his colleagues estimate that the fusion cross section in a D–D reactor would be enhanced by about a factor of two if all the deuteron spins were aligned *transverse* to the magnetic field. This factor of two is of particular importance because the output of a D–D reactor would be rather marginal; at a given pressure it produces only $\frac{1}{30}$ the power of a D–T reactor. But D–D reactors are attractive because they do not require the breeding of tritium.

If, on the other hand, all the deuterons were aligned *parallel* to the field, the D–D fusion cross section would be substantially suppressed. Such a suppression would not at first glance appear to be of any practical interest. But it is—in the context of a D–He^3 reactor. The prospect of a D–He^3 reactor has generated considerable enthusiasm because the D–He^3 reaction produces 14.7-MeV protons in place of the energetic neutrons generated in D–T fusion. Such a "neutron-free" reactor would avoid the radioactivation and structural damage caused by neutrons, which, unlike protons, cannot be diverted from the reactor walls. Furthermore, protons can be used to generate electric power directly, without the inefficient mediation of a neutron absorber blanket.

But an unpolarized D–He^3 reactor would not be truly neutron free. Deuterons would react with one another to produce enough neutrons to do some damage. However, if one polarizes the deuterons and helium nuclei parallel to the magnetic field, one gains two advantages: The D–D reaction and its undesirable neutron output is strongly suppressed, and one gains an enhancement of the D–He^3 cross section of 50%, as in the D–T case. This power enhancement is important because it should facilitate plasma ignition. An unpolarized D–He^3 plasma would require an ignition temperature an order of magnitude higher than one needs for D–T ignition.

These D–D polarization estimates were based on fifteen-year-old nuclear physics results from B. P. Ad'yasevich and his colleagues at the Kurchatov Institute, Moscow. Kulsrud cautions that a very recent calculation done at his request by Gerald Hale and Donald Donner, using new data and an elaborate computer code available at Los Alamos, predicts that the D–D polarization power-enhancement factor would be only about 1.6.

The angular distribution of the fusion products can also be controlled by polarizing the plasma. If, for example, one polarizes the deuterons and tritons transverse to the magnetic field in a D–T tokamak, one sacrifices the 50% cross-section enhancement, but one achieves a $1 + 3\cos^2\theta$ distribution of the emerging alphas and neutrons relative to the field direction. This tendency of the fusion products to emerge preferentially along the field lines has two desirable consequences: The alphas will follow the curving field lines more closely, thus improving their confinement and the magnetohydrodynamic stability of the plasma. Good alpha confinement is crucial to maintaining the temperature of an ignited plasma. Secondly, the neutrons, traveling roughly tangent to the field direction at their point of origin, will tend to avoid the inner wall of the tokamak (the hole in the doughnut). Because this part of the tokamak is crowded and hard to get at, one wants to minimize the neutron flux at the inner wall. "It's a real advantage," Furth told us, "for reactor designers to be able to control the direction of the neutrons and alphas. I think that's more important than the 50% power enhancement."

In a D–T mirror machine, on the other hand, one would want to polarize the nuclei parallel to the field lines, with a resulting $\sin^2\theta$ angular distribution of the decay products. First of all, the consequent 50% cross section enhancement could be crucial for a mirror machine; its power output is much more marginal than that of a tokamak. Furthermore, the tendency of the alphas and neutrons to emerge perpendicular to the field lines keeps them away from the leaky open ends of the mirror (where the magnetic field lines emerge), thus improving α confinement and minimizing neutron irradiation.

Depolarization. When one speaks of maintaining the polarization of the plasma nuclei, one does not mean that their spins remain fixed in space. To the extent that it does not lose its polarization, the nucleus moving through the plasma will maintain its spin orientation relative to the curved magnetic field lines of the reactor.

But why should the nucleus remain polarized in this hot environment? Naively one would point out that the energy splitting between different nuclear spin orientations is extremely small—*ten orders of magnitude* less than the 10-keV thermal energy of the plasma. Thus at thermal equilibrium one would expect the different spin states to be equally populated. Such considerations had in fact kept the Euratom fusion group from looking seriously into the 1963 suggestion of Enrico Medi (University of Rome) that one might polarize reactor plasmas.

It turns out, however, that no such equilibrium spin population distribution is established during the 20 or so seconds a nucleus typically spends in the tokamak plasma. This is the central conclusion Kulsrud and his colleagues reach by examining in turn the various mechanisms that might depolarize a nucleus in a reactor plasma:

▶ Collisions. Simple electrostatic Coulomb scattering would not affect nuclear spins. But the time-varying magnetic field generated at the nucleus by a fast electron passing close by could flip its spin. It turns out, however, that the cross section for this spin–orbit depolarization process—essentially the nuclear Thomson scattering cross section—is exceedingly small. "It would take about a day for this mechanism to depolarize completely a nucleus in a typical reactor," Kulsrud told us.

▶ Spatial field variation. A nucleus traveling through the spatially varying magnetic field of a reactor sees a time-varying field in its own rest frame. But for this effect to produce significant spin flip, the field must change over distances on the scale of the nuclear gyration radius. In mirror and tokamak reactors this gyration radius is on the order of a centimeter, much shorter than the scale of magnetostatic field variation in such machines.

▶ "The most dangerous potential depolarization mechanism," Kulsrud told us, "the one we're least certain about, is random fluctuations of the magnetic field in the plasma." Spins can be flipped if instabilities generate random field fluctuations with frequencies near the precession frequency of the nuclear spin. This could be problematic for deuterons, whose precession frequency is very close to their gyration frequency. But for such field fluctuations to have serious consequences, the group calculates, they must have amplitudes of at least a few tenths of a gauss. There is however no reason to believe, Kulsrud told us, that such large fluctuations would occur near the nuclear-precession frequencies. If the fluctuations were just thermal, they would take 10^8 years to effect depolarization.

▶ Ionization and recombination. To achieve a polarized plasma one would begin with neutral atoms with spin-polarized nuclei. They are ionized upon entering the plasma, and a significant fraction later recombine with electrons at the walls and reenter the plasma to be reionized. Ionization is not expected to depolarize the nuclei, but recombination with an electron of opposite spin could be a problem. Such spin flip is, however, effectively inhibited in a magnetic-confinement reactor because the magnetic field, even at the walls, is much stronger than the critical field strength at which the Zeeman splitting becomes equal to the hyperfine splitting.

For polarization of a reactor plasma to be useful, Kulsrud explained, one needs to maintain 95% nuclear polarization for at least 20 seconds. With the unlikely exception of instability-generated large field fluctuations, none of the spin-flip mechanisms considered by the group appears to be able to depolarize the plasma on this time scale.

Polarizing the nuclei. Happer and his Princeton colleagues Nat Bhashkar and Thomas McClelland use alkali atoms to mediate between a circularly polarized dye-laser beam and the nuclei ultimately to be polarized. Their recently published paper describes the polarization of xenon nuclei through the mediation of rubidium; but Happer told us that the technique should prove even more efficient for polarizing the nuclei of the hydrogen isotopes. One would excite a mixture of some alkali vapor and monatomic hydrogen (produced by electric discharge or heating) with circularly polarized laser light at the S–P optical transition frequency of the alkali valence electron. The electrons thus polarized transfer their polarization by collision to the hydrogen electrons. In about a nanosecond (one hyperfine period) this electron polarization polarizes the hydrogen nucleus. One cannot efficiently polarize the hydrogen directly by laser light because the relevant transition frequency (the Lyman-α line) is in the ultraviolet.

Optical pumping, Happer argues, is an intrinsically efficient way to polarize atoms and nuclei. Each polarized laser photon, with an energy of about 1 eV, polarizes a nucleus that ultimately returns MeV of fusion energy. To achieve the necessary amperes of polarized deuterons or tritons required by a reactor, he told us, would require only about a watt of laser output. Even if the laser efficiency were only a tenth of a percent, he points out, the power input required to polarize the plasma would be a trivial fraction of the fusion output. More than twenty years ago, Happer told us, Francis Pipkin and his students at Harvard were able to produce about a milliamp of spin-polarized deuterons with polarized light from relatively weak resonance lamps.

Because xenon is a noble gas, its electron configuration has no net spin that one could polarize. Thus the recent experiments of Happer and his colleagues involved the direct transfer of polarization from the rubidium valence electron to the xenon nucleus, a much less efficient transfer mechanism than one would have with hydrogen. "Having done it with xenon," Happer told us, "we can do it with helium—and much more efficiently with D or T."

The MIT group has for some time been using high magnetic fields and very low temperatures to stabilize spin-polarized atomic hydrogen against recombination into H_2 molecules—primarily to study cold atomic hydrogen as a quantum fluid. Last year they discovered a spin-off of this technique that may prove to be a practical way of providing large quantities of polarized deuterons for a fusion reactor. The spin-polarized atomic hydrogen stabilized in their apparatus begins as a 50-50 mixture of a pure spin-1 state, with nuclear and electron spins aligned, and a "mixed" state in which the nuclear spin is antiparallel to the electron spin.

The wave function for the mixed state has a small component for finding the electron spin polarized opposite to the predominant polarization of the stabilized atomic hydrogen in the strong magnetic field. It is only through this component that the hydrogen can recombine into molecules. Thus if one waits long enough, all of the mixed-state atoms will eventually recombine and adsorb on the vessel walls, leaving a monatomic gas with more than 99% of its nuclei aligned.

Greytak told us that the group is now attempting to do the same thing with deuterium; tritium will be more difficult, and the MIT group has not yet considered He^3. Greytak is confident that one should be able to produce amperes of polarized deuterons at acceptable power cost by this method.

One would introduce the polarized nuclei into a reactor as a neutral gas, because the confining magnetic field of the reactor would keep charged particles out. If one chooses to introduce the gas as an energetic "neutral beam," one requires an intermediate stage of ionization, acceleration and reneutralization before injection. Kulsrud and his colleagues have calculated that the preinjection stages would not significantly depolarize the nuclei if they do not experience abrupt changes of magnetic field strength or direction.

"We don't yet know whether all this will work," Furth told us, "but it illustrates that there are still fundamental new ideas to be explored in magnetic-confinement fusion. It's not all just engineering details. This is, I believe, a message of good cheer." —BMS

References

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Electroweak interference confirmed

Before 1973, all observed weak interactions had involved charge exchange between the participating particles, implying that the carriers of the weak force were themselves always electrically charged. But if one is to unify the weak and electromagnetic interactions in a single gauge-invariant framework, one requires a weak analog of the uncharged photon—an electrically neutral, weak, spin-one boson. The discovery of the neutral-current weak interactions at CERN in 1973 (for example, the elastic scattering of neutrinos off nucleons) was thus a crucial piece of evidence for the Weinberg–Salam–Glashow electroweak gauge theory—the scheme that has since come to be regarded as the "standard theory" for the unification of the electromagnetic and weak interactions. Sheldon Glashow and Steven Weinberg (both then at Harvard) and Abdus Salam (Imperial College, London and International Centre for Theoretical Physics, Trieste) shared the 1979 Nobel Prize in Physics for this work.

If the neutral weak boson (called Z^0, and expected to have a mass of about 90 GeV) does indeed exist, one should be able to see interference effects between electromagnetic and weak exchange mechanisms. Whenever a photon is exchanged, a Z^0 can be exchanged in the same reaction. The key experimental signature would be the observation of a forward–backward asymmetry due to the interference of the axial-vector part of the weak interaction with the purely vectorial electromagnetic interaction. (This should not be confused with parity violations observed in purely weak processes; these come from interference between the vector and axial-vector parts of the weak interaction alone.) At collision energies much below the Z^0 mass, however, the interference of the weak interaction with electromagnetic processes would be very small.

But PETRA, the e^+e^- colliding-beam storage ring at DESY (Hamburg), has for more than a year now been operating reliably with high luminosity at collision energies around 35 GeV. At this center-of-mass energy (more than a third of the supposed Z^0 mass), the Weinberg–Salam–Glashow theory pre-