In conclusion, I wish to thank a number of colleagues, in particular Professor P. W. Bridgman and Professor E. M. Purcell, for several helpful discussions.

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* One may think of it as something like the Thomson Effect of thermoelectricity, with a stress gradient taking the place of a temperature gradient.

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On the Production of Nuclear Polarization*

M. E. Rose
Oak Ridge National Laboratory, Oak Ridge, Tennessee
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The spin dependence of nuclear forces (in particular, the $n-p$ interaction) has hitherto been investigated at thermal energies by the scattering of neutrons in ortho- and para-hydrogen.[1] For other nuclei the neutron interaction is ascertainable from neutron diffraction experiments.[2] A possible method of studying the spin dependence of the forces over the entire energy range so that the interactions for both spin orientations are, in principle, deducible, would involve the use of targets of polarized nuclei for scattering and absorption experiments with polarized neutrons.[3] The production of polarized neutrons at each energy above the thermal region may be achieved by using the target with aligned nuclear spins as polarizer as well as analyzer.

In the following we consider the process of aligning nuclear spins in order to estimate the expected order of magnitude of the nuclear paramagnetism.[4] In all cases except ordinary paramagnetic substances the alignment of the nuclear spins must be achieved by direct coupling of the nuclear moments with an external magnetic field H. The nuclear polarization factor f_N is given by

$$f_N=\frac{1}{I}\frac{\Sigma m_i \exp(-W(m_i)/kT)}{\Sigma \exp(-W(m_i)/kT)} \tag{1}$$

where I is the nuclear spin, m_i the component of spin in the direction of the field and the sums in (1) are over all magnetic substates of energy $W(m_i)$. For direct coupling $W(m_i)=-m_i\mu H/I$ where μ is the magnetic moment and f_N is given by the well-known Brillouin formula. For all practical cases ($\mu H/kT\ll 1$) we have

$$f_N=\frac{1}{3}\frac{I+1}{I}\frac{\mu H}{kT}. \tag{2}$$

To cite a few examples, the values of H/T in kilogauss/degree required to produce 20 percent nuclear polarization of H^1, H^3, He^3, Li^7, F^{19}, In^{115} all lie between 2000 and 3000 so that with a temperature of 0.01°K a reasonable magnetic field would suffice. For such nuclei a polarization of about 40 percent is perhaps within the realm of practical possibility if suitable arrangements are made for cooling by establishing thermal contact with the paramagnetic salt. Preliminary considerations indicate that a metallic contact between salt and nuclear sample may be entirely adequate from the point of view of both relaxation time and thermal conduction.[5]

In the case of nuclei in paramagnetic substances the field produced at the nucleus by hyperfine structure coupling should be sufficiently large, in some cases at least, to produce the required nuclear alignment in the range of temperature 0.1 to 0.01°K. The applied field is, therefore, used merely to align the electronic moments. If ΔW is the over-all splitting of the ground state multiplet and J_e the electronic angular momentum we find, in sufficient approximation,

$$f_N=\tfrac{1}{3}f_e\frac{I+1}{I}\frac{J_e}{2J_e+1}\frac{\Delta W}{kT};\quad J_e\geqslant I$$
$$f_N=\tfrac{1}{3}f_e\frac{I+1}{2I+1}\frac{\Delta W}{kT};\quad J_e<I \tag{3}$$

where f_e is the fractional saturation for the electronic moments. For present purposes we can take $f_e\sim 1$ so that $f_N=0.2$ requires $\Delta W/kT\sim 1$. Estimates of ΔW for the rare earth ions based on spectroscopic data for screening constants and average radius of the $4f$ shell (0.5A) indicate a splitting varying from 0.01 to 0.1 cm^{-1} so that the required temperature range would appear to be feasible. The situation in the case of the transuranic rare earths would appear to be about as favorable.

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[4] A consideration of the experiments with polarized nuclei and neutrons is given in M. E. Rose, Phys. Rev. **75**, 213 (1949).

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Scattering and Absorption of Neutrons by Polarized Nuclei*

M. E. Rose
Oak Ridge National Laboratory, Oak Ridge, Tennessee
November 8, 1948

In the following we consider scattering of S neutrons by a nucleus with spin I so that the interaction between neutron and nucleus is described by the two phase shifts η'