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Neutron Spin-Filter with Spin-Exchange Interaction of ^{3}He Nuclei and the Atoms of a Saturated Ferromagnetic

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The model of a spin - exchange interaction between the nuclear magnetic moment of ^{3}He and the magnetic moments of electrons in a ferromagnetic is proposed. If a ferromagnetic is saturated an interaction leads to a gradual rising of ^{3}He nuclear polarization inside a volume surrounded by this ferromagnetic. The conditions for a practical implementation of a neutron spin filter with the polarized ^{3}He nuclei are considered, as well as the variants of its design.

1. Polarization of ^{3}He Nuclei by the Alkali Metal Atoms

The physical origin of polarization of the noble gases with spin $I = 1/2$ is the hyperfine interaction $\alpha(\vec{I} \cdot \vec{S})$ between the nuclear and unpaired atomic magnetic moments. Magnetic moment of an unpaired electron with $S = 1/2$ may belong to a noble gas itself, or to the other atoms, which collide with noble gas ones. We shall consider collisions of ^{3}He and alkali metal atoms with a single unpaired electron on the outer atomic shell.

We shall assume that the colliding atoms form an insulated system with conservation of the total angular momentum (TAM), and their orbital momentum is zero. That means TAM is equal to the total spin of the system. Since the nuclear and electron spins are equal to 1/2, then TAM = 0 for a mutual state ($+I$, $-S$). That means a flip from ($+I$, $-S$) to ($-I$, $+S$) with the same TAM is possible. When the atoms collide in state ($+I$, $+S$) with TAM = +1, a flip to a state ($-I$, $-S$) with TAM = –1 isn't possible. Thus, when the alkali atoms are polarized (have certain projection of S), the flips of the ^{3}He nuclear spins going in the same direction and nuclear polarization gradually increases.

In practice a vapor of alkali metals (Rb, K, etc.) is optically pumped by a circularly polarized laser with the wavelength 795 nm. The light absorption produces a population of a certain magnetic sublevel in alkali atom [1]. Both ^{3}He and Rb atoms are confined in a sealed glass cell. The number density of Rb atoms in vapor $n_{Rb} \sim 10^{15}$ cm^{-3} is provided by the heating of a cell up to 150–180^{o}C. A cell is stored in a homogeneous magnetic field of an order of 30–100 Gauss and collinear to a direction of a laser beam.

After collision of ^{3}He and Rb with a mutual spins flip, Rb atom absorbs a quantum of laser light, returns to its initial state and ready to next collision. A probability of a mutual spins flip is about 0.1.

Thus, a nuclear polarization requires two mandatory conditions. First, the atomic unpaired electrons must be aligned in a certain direction. Second, a mutual flip of ^{3}He and atomic spins should occur during their collisions.

2. Polarization of ^{3}He Nuclei by the Ferromagnetic Atoms

We have considered collisions in a cell volume. We may also imagine another system when the inner cell walls are made of a saturated ferromagnetic. Ferromagnetic in a saturated state represents almost a single domain where all magnetic moments (and spins) of the

unpaired electrons have a given direction. Now, let us assume a possibility of mutual spins flip when ^{3}He collides with ferromagnetic atoms in a wall. After collision ferromagnetic atom quickly returns to its equilibrium state owing an exchange interaction, which is an origin of ferromagnetism itself.

The assumption about a mutual spins flip is a hypothesis. We may imagine such flip by the next way. In the rest frame of an atomic electron magnetic moment of ^{3}He which moving toward generates variable magnetic $B(t)$ with Fourier frequency spectrum $b(\omega)$. At the moment of collision both nuclear μ_I and electronic μ_S magnetic moments are in the common magnetic field B_z of a ferromagnetic wall. A common field generates Zeeman spitting $\hbar\omega_I = \mu_I B_z$ and $\hbar\omega_S = \mu_S B_z$, respectively. Since an electron normally stands in a state with minimal energy it should take energy $\hbar\omega_S$ for a flip. Particularly it may take a fraction $\hbar(\omega_S - \omega_I)$ from field $B(t)$ and missing part $\hbar\omega_I$ directly from nuclear spin and makes it to flip. In general the flips are possible with the frequencies ω_I and $\omega_S + \omega_I$ as well. At last, the energy for a spins flip is scooped from a kinetic energy of moving ^{3}He atom. This means requirement: $\mu_S B_z << kT$. At normal temperature it takes place even for the strong ferromagnetics with $B_z \sim 2$–3 T.

One should stress that the above described mechanism takes place in direct collisions of ^{3}He with ferromagnetic atoms on a wall surface. The Hamiltonian of interaction for this case is

$$H = \mu_I B_z + \alpha(\vec{I} \cdot \vec{S}). \tag{1}$$

In case of no direct collisions (interlayer of any sort) the second term in (1) is absent and polarization of ^{3}He is just thermal equilibrium

$$p_I = \tanh(\mu_I B_z / kT) << 1. \tag{2}$$

The time dependence of nuclear polarization in case (1) can be obtained from a model of fluctuated magnetic fields which are generated by the moving electron spins in the locations of nuclear spins I [2]:

$$\frac{dI_z(t)}{dt} = -\Gamma_\alpha [I_z(t) - S_z]. \tag{3}$$

Here an index denotes the components along B_z. The solution of (3) with equilibrium (not dependent on time S_z) and $I_z(0) = 0$ is

$$\begin{aligned} I_z(t) &= S_z\left(1 - e^{-\Gamma_\alpha t}\right), \\ \Gamma_\alpha &= 1/T_{IS} = n_S v \sigma_3 / d. \end{aligned} \tag{4}$$

Here T_{IS} is typical relaxation time of nuclear polarization due to hyperfine interaction, which depends on frequency components $b(\omega_S \pm \omega_I)$ and $b(\omega_I)$ of a fluctuated magnetic field, n_S – number of ferromagnetic atoms per cm^2, v – average speed of ^{3}He atoms, σ_3 – cross section of ^{3}He atom collision with spin flip, and d – distance between cell walls.

If one consider the other interactions which affect nuclear polarization with the characteristic rate constant Γ, then the solution (4) will be

$$I_z(t) = S_z \cdot \frac{\Gamma_\alpha}{\Gamma_\alpha + \Gamma}\left[1 - e^{-(\Gamma_\alpha + \Gamma)t}\right]. \quad (5)$$

For a saturated ferromagnetic (electron polarization is 1), a nuclear polarization of ^{3}He may be expressed as

$$p_3(t) = \frac{\Gamma_\alpha}{\Gamma_\alpha + \Gamma}\left[1 - e^{-(\Gamma_\alpha + \Gamma)t}\right]. \quad (6)$$

If one take for iron (4 unpaired electrons) $n_S = 4\times1.2\times10^{15}$ cm^{-2} and d = 5 cm, then will obtain $\Gamma_\alpha \approx 10^{15}\cdot(v\sigma_3)$ c^{-1}. Now if we assume $v\sigma_3$ is of order as for Rb - ^{3}He collisions, we shall get Γ_α ~ 1/20 hours.

Cross section σ_3 is the crucial quantity for a practical application of above mechanism. However it is hard to judge about it definitely from a general point of view. System Rb - ^{3}He with collision of just two individual atoms is relatively simple. The quality picture assumes that for a mutual spins flip ^{3}He nucleus and Rb electron should get quite closer. In a case of ferromagnetic wall a picture gets much complicated because of interaction between the atoms inside it. An individual ferromagnetic atom of an iron group has the unpaired electrons on a 3d-shell with outer 4s- coupled shell. The outer shell prevents ^{3}He nucleus gets near to 3d-electrons. However in a macroscopic sample exchange interaction provides overlapping of orbitals with forming of zone structure in ferromagnetic. The electrons of s-shell spread among the big number of atoms and form a paramagnetic gas, which give not significant contribution to the magnetic properties of a ferromagnetic. The electrons of d-shell still hold their place in every atom. Thus it's probably that ^{3}He nuclei may interact with 3d-electrons quite effectively due to spreading of s-shells in a ferromagnetic sample. In the rare-earth ferromagnetic one can expect interaction of ^{3}He nuclei with f-shell electrons as well [3].

3. Relaxation of Nuclear Polarization

The most obvious reason for a decay of nuclear polarization p_I is a gradient of a magnetic field of any behavior $dB(x)/dx$ transverse to a direction of p_I. Transverse magnetic field makes a spin to presses around it. If a field magnitude is different in the points of some region, the precession frequencies are different too, which cause a destruction of a uniform alignment (polarization) of the spins along a region.

The gradients may arise because of the outer irregular fields, paramagnetic admixtures in a volume (oxygen) or in a surface. A specific case is a rough wall surface. Magnetic field near it sharp ledges may be very inhomogeneous and destroy polarization of ^{3}He. Moreover, it's hard to clean up a rough surface from oxide and oil layers after mechanical processing. Besides, a ferromagnetic must be saturated, otherwise the domains with different direction of magnetization may cause a particular loss of polarization.

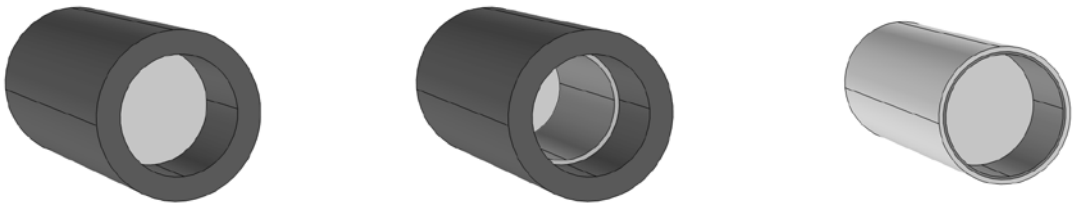
As result the minimal technical demands for practical application should be:

1. ^{3}He must be free from any paramagnetic admixtures (getter).
2. Low roughness of a ferromagnetic surface (polishing, rolling).

3. High purity of the all inner surfaces. Absence of oxide, oil layers, and hydrogen as much as possible (chemical and us- clearing, pumping out with heating).
4. Magnetic saturation of ferromagnetic wall.

4. Designs of Spin Filter

A) Side wall is a permanent magnet with magnetization along the axis.
B) Inner surface of a cell is a soft magnetic material - thin ferromagnetic layer, which may have practically rectangular hysteresis loop. That may provide high residual magnetization. Outside is a permanent magnet like in A) to keep inner layer in a highly saturated state.



A B C

C) Inner surface of a cell is covered by a hard magnetic material (thin permanent magnet).

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