Polarization measurements for the Jefferson Lab Hall A Helium 3 polarized target

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Abstract

This paper presents the content of a talk given at Old Dominion University the 03/31/1998. It is an overview of the TJNAF HALL A polarized Helium 3 target setup and describes the RMN and EPR polarimetry Technics developped to measure its polarization. We will also review briefly the Physics that could be studied with such a target.

1 Polarized ^{3}He target.Wwhat is it ? What is it for ?

The target setup is basically composed of two Helmholtz coil pairs,a Radio Frequency coil pair, a Pick up coil pair, a two chamber glass cell surrounded by an oven and a set lasers (**Figure 1.1** and **Figure 3.1**).

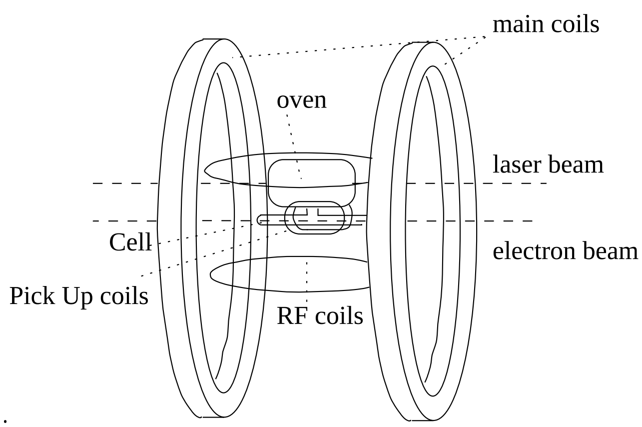

Figure 1.1 : target setup. Here, only one pair of main coils is represented.

The main coil axis defines the quantization axis of the Helium nuclei spin. These coils are also used to perform the Adiabatic Fast Passage for the Nuclear Magnetic Resonance (NMR) polarimetry (refer to paragraph 2). The Radio

Frequency (RF) coils are used to generate the RF signal in order to induce the NMR signal and the Pick Up coils detect the response of the Helium 3 nuclei.

Figure 1.2 shows the shape of the target cell.

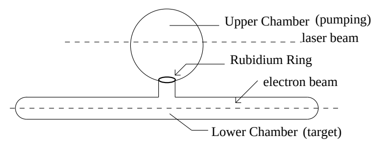

Figure 1.2 : the two chamber cell.

The upper chamber contains a Rubidium ring and a gaseous mixture of Rubidium and Helium 3. The lower chamber contains the polarized Helium. This chamber is the target chamber where the beam electrons are scattered off the polarized Helium 3 nuclei.

The polarization of the Helium nuclei is performed following two steps :

- Polarization of the Rubidium atoms by optical pumping.

-Transmission of the polarization to the Helium nuclei by spin exchange collisions.

Note : according to the Pauli exclusion principle, the two protons of the Helium 3 nucleus must have their spin antiparralel and the Helium 3 nucleus can be seen, from the spin 's point of view and in a first approximation, as an independant and stable neutron. Quite similary, the Rubidium is an alkali element and so has only one valence electron which determines its atomic polarization.

1.1 Rubidium polarization

A set of lasers with a total power of 120 Watts optically pumps the Rubidium atoms from the ground state $5S_{1/2}$ to the excited state $5P_{1/2}$. The momentum conservation implies respectively $\triangle m_z = -1$ and $\triangle m_z = +1$ transitions, depending on the circular polarization of the laser beam (right or left). The excited electrons then come back to the two states of the $5S_{1/2}$ level, since there is no momentum conservation constraint. The emitted light is consequently not polarized. Considering for example the diagram on **Figure 1.3**, the electrons return to the $5S_{1/2}$ levels following the $\triangle m_z = -1$ and $\triangle m_z = 0$ transitions. However, as the m=-1/2 is still pumped out, it depopulates in favour of the other.

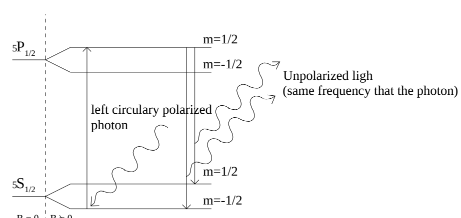

Figure 1.3 : optical pumping of the Rb atoms.

The energy gap between the levels 5S and 5P is 1.485 MeV, that is 795 nm.

The lasers are chosen consequently at this wavelengh. The depletion of one of the two S states implies the atomic spin polarization of the Rubidium gas valence electron.

1.2 Spin exchange collisions

During a Rubidium-Helium atomic collision, the hamiltonian describing the interaction between the Helium nucleus and the Rubidium valence electron is :

$H = \frac{16\pi}{3} g_n \mu_n \mu_b \overrightarrow{K}.\overrightarrow{S} \psi_e(r=0)$

where Ψ_e, the electron wave function, is taken at r=0 since the reference frame is centered on the Rubidium nucleus (ponctual from the electron's point of view). g_n is the neutron g factor, μ_b the Bohr magneton, μ_B the Bohr nuclear magneton, $\overrightarrow{K}$ and $\overrightarrow{S}$ represent respectively the spins of the Helium nucleus and the Rubidium valence electron. The coupling $\overrightarrow{K}.\overrightarrow{S}$ traduces a possible spin exchange between the two systems. The cross section is of order 10^{-24}cm^2.

1.3 The cell geometry

The cell is composed of two chambers (**Figure 1.2**). The upper one is the pumping chamber containing a mixture of Helium and Rubidium gas. The Rubidium gas comes from the sublimation of the solid Rubidium ring. This chamber is surrounded by an oven maintained at 180 degrees Celsius, to accelerate the collision rate between the two species and to increase the Rubidium concentration in the upper cell :

$log(k_b T[Rb]) = 10^{(10.55 - \frac{4132}{T})}$

[Rb] is the saturated vapor Rubidium concentration expressed in cm^{-3}, k_b in CGS units and T in Kelvin. The average temperature in the lower chamber, where Rubidium is unwanted, is 65 ^{o}C. Consequently, the Rubidium density is 10^{-3} time lower in the scattering chamber than in the upper chamber.

1.4 The polarized Helium 3 target, what is it for ?

A polarized lepton beam and a polarized target allow measurements of the nucleon polarized structure functions g_1 and g_2, *via* the asymmetries :

$A_{\|} = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \propto (E + E' cos\theta) g_1 - \frac{Q^2}{\nu} g_2$

$A_{\perp} = \frac{\sigma_{\rightarrow\downarrow} - \sigma_{\rightarrow\uparrow}}{\sigma_{\rightarrow\downarrow} + \sigma_{\rightarrow\uparrow}} \propto g_1 + \frac{2E}{\nu} g_2$

$\sigma_{\uparrow\downarrow}(\sigma_{\uparrow\uparrow})$ stands for the cross section of the Helium-electron scattering reaction with the beam polarization antiparallel (parallel) to the target polarization. $\sigma_{\rightarrow\downarrow}$ and $\sigma_{\rightarrow\uparrow}$ are the cross sections of the reaction when the target is transversely polarized. The different kinematic variables are defined in **Figure 1.4**.

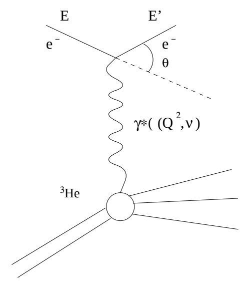

Figure 1.4 : definition of kinematic variables.

ν is the transfered energy (E-E'), that is the frequency of the virtual photon. $Q^2 = -q^2$ where q is the quadrimomentum of the virtual photon. Q^2represents the intensity of the scaterring i.e. as $Q^2 \propto 1/\nu^2$, the resolution of the elctromagnetic probe. θ is the electron scattering angle defined in the laboratory.

The measurements of polarized structure functions allow to test QCD by studying in one hand their Q^2 evolution interpreted in terms of parton model and on the other hand the sum rules.

1.5 The parton model

It was developped by Feynman and states that the nucleon is composed by free point-like particles called partons. Later the partons had been first identified to the quarks, which were developped to explain the baryon spectroscopy, and then to the gluons when one began to take into account the parton-parton interactions. The asymptotic freedom property of the strong interaction makes the partons to be free in the limit $Q^2 \to \infty$. This was the assumption of the Feynman Naive Parton Model that explains deep inelastic scattering as an incoherent sum of elastic scatterings on free partons. It follows that the cross section depends only on one variable, the Bjorken variable $x = \frac{Q^2}{2M\nu}$ (M is the nucleon mass). However experiments are performed at finite values of $Q^2$where the quarks interact through gluon exchange. Thus the gluons have to be considered as partons. This implies an additionnal Q^2 dependence of the cross sections. The Naive Parton Model is not a check of QCD since it describes free charged quarks interacting with charged leptons. This is the QED domain. However, the Q^2 dependence of the structure functions reflects quark interactions described by QCD and allows to study QCD predictions.

1.6 Sum Rules

Three sum rules have been and will be more precisely tested using polarized lepton beams and nuclear polarized targets. One of them are fundamental derivations of QCD (That is the Bjorken Sum Rule).

1.6.1 The Bjorken Sum Rule

It comes directly from QCD and is seen as a fundamental test for QCD. It has been derived from current algebra and isospin symmetry. The sum rule is written :

$\int_0^1 (g_1^{proton}(x) - g_1^{neutron}(x))dx = \frac{1}{6}\frac{G_a}{G_v}$

where $G_a$and G_v stands for the axial and vectorial coupling constants of the neutron weak decay.

1.6.2 The Ellis Jaffe sum rule

$\int_0^1 (g_1^{neutron})dx = \frac{1}{2}(\frac{4}{9}\triangle u + \frac{1}{9}\triangle d)$

The sum rule on the proton is obtained by isospin symmetry. These sum rules are based on the assumption that the strange sea is not polarized. EMC (CERN), E143 and E154 (SLAC) shown violation of the sum rules and thus the irrelevance of this assumption. Incidentally the design of the E142-E154 polarized target was close of the Hall A target design.

1.6.3 The Gerassimov-Drell-Hearn Sum Rule

$\int_{thr}^{\infty} (\sigma^{1/2} - \sigma^{3/2})\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha}{M^2}k_n^2$

where $\sigma^{1/2}$and $\sigma^{3/2}$ are the virtual photo-absorption cross section with respectively 1/2 and 3/2 helicity. the difference $\sigma^{1/2}$- $\sigma^{3/2}$ is computed via $A_{\parallel}$and $A_{\perp}$.

α is the electromagnetic coupling constant and k_n the anomalous magnetic moment of the nucleon.

1.6.4 Hall A Approved Experiments.

Some experiments using the Helium 3 polarized target and testing the sum rules have been approved :

-E94-010 (Z-E Meziani, G D Cates) : Measurement of $g_1^{neutron}$ At Low Q^2 : Connection between the Bjorken and Gerassimov-Dreal-Hearn sum rules. It will study the Q^2 evolution of the Bjorken sum rule in the domain $0.15GeV^2 \leq Q^2 \leq 2GeV^2$.

-E94-021 (W Korsch, R McKeown) : The Electric Form Factor of the Neutron Exctract from the ^{3}He(e,e'n)pp Reaction.

-E95-001 (H Gao) : Precise Measurement of the Inclusive Spin Dependent Quasi-Elastic Transvers Asymmetry A_T, from ^{3}He (e,e') at low Q^2.It will determine the form factor of the neutron (0.1 GeV^2<Q^2<0.5 GeV^2) and test three bodies calculations.

-E97-103 (T Averett, W Korsch) : Search For Higher Twist Effect in The Neutron Spin Structure Function $g_2^{neutron}$.

-E97-110 (JP Chen) : The Gerassimov Dreal-Hearn Sum Rules and the Spin Structure of the He3 and the Neutron Using Nearly Real Photons. It studies the low Q^2 dependance of GDH to test the Chiral Perturbation Theory, the quarks model and the Resonance Saturation Model, giving different predictions. It will also test Helium 3 nucleus models to estimate how far the Helium 3 nucleus can be viewed as a neutron and the contibutions of the two protons.

2 The NMR polarimetry

The polarimetry is performed by two independent methods : the EPR polarimetry (Electron Paramagnetic Resonance) and the NMR polarimetry (Nuclear Magnetic Resonance). I shall focus on this latter since the system is on its way at Jefferson Lab.

2.1 What is NMR ?

One considers a spin system. To make it simple let's take it as a spin $\frac{1}{2}$ system with two degenerated states : $|\uparrow>$ and $|\downarrow>$in abscence of magnetic field,. When an external magnetic field B_0 is applied, the degeneration is raised and one gets an energy gap between the two states $\triangle E = \gamma\hbar B_0$ where γ is the gyromagnetic ratio of the system.

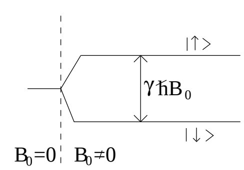

fig. 2.1

Now one applies a sinusoidal radio-frequency field $B_1(\omega)$. We induce transitions between the sates $|\uparrow>$ and $|\downarrow>$ with a transition probability having the folowing shape:

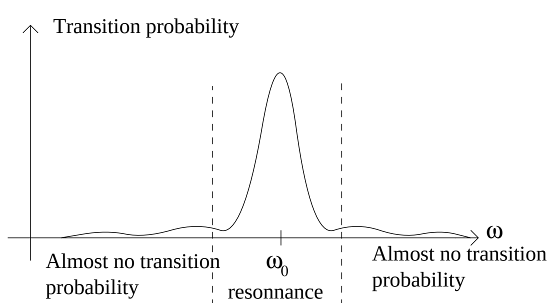

fig. 2.2

where $\omega_0 = \gamma B_0 = \frac{E(\downarrow)-E(\uparrow)}{\hbar}$.

This only traduces the fact that the system has discret energy levels and therefore can only absorbe the ω_0 frequency (and closely around because of the Heisenberg uncertainty and Doppler effect if the system is not static). In other words the spin-flip induces an energy absorbtion at a well determined frequency, characteristic of the system. This is the Magnetic Resonance. When the spin system is a nucleus or a system of nuclei, the phenomenon is called Nuclear Magnetic Resonance.

If the system is more complex than a couple of nuclear levels, it has several resonance frequencies. We can determine the position of the levels by studing the NMR frequencies and also the effects of the environment that cause shifts on the resonance frequency positions and thus give information on the system structure. This is the NMR spectroscopy.

Another application of the NMR is the measurement of a magnetic field knowing the gyromagnetic ratio γ of a system (the system being a NMR probe for example) : by sweeping with the RF field and finding the resonance frequency of the system, one can deduce the field amplitude $B_0 = \frac{\omega_0}{\gamma}$ surrounding the system. It's the principle of the NMR probes used, for example in the magnets of the TJNAF's spectrometers.

The application of interest for the polarized target is the polarization measurement. On the contrary of the two first applications, the resonance frequency ω_0 is known and fixed and it's the magnetic field amplitude that is swept.

2.2 Polarimetry Measurement

Let's consider n_0 systems, each of spin μ. The definition of the system polarization is:

$P = \frac{n^+ - n^-}{n_0}$

where $n^+$is the number of states $|\uparrow>$ and n^- the number of states $|\downarrow>$

The magnitude of the system's magnetic moment is the resultant of all the spins of the systems :

$< \mu > = \frac{n^+ - n^-}{n_0} \mu = P\mu$ (1)

The effect of the radio frequency field is to induce a precession of $< \overrightarrow{\mu} >$around an axis determined by $\overrightarrow{B_{eff}}$, the effective field seen from a frame rotating around $\overrightarrow{B_0}$ with the angular frequency ω_0. If the $\overrightarrow{B_0}$ magnitude variation is slow enough to allow the magnetic moment to follow the direction of the effective field $\overrightarrow{B_{eff}}$, but fast enough in front of the spin thermic relaxation characteristic time, we are under the so called "Adiabatic Fast Passage" and the magnetic moment of the system always remains aligned with $\overrightarrow{B_{eff}}$: $< \overrightarrow{\mu} > = \frac{<\mu>}{|\overrightarrow{B_{eff}}|} \overrightarrow{B_{eff}}$

The magnetization of the system is proportional to the magnetic moment of the system :

$\overrightarrow{M} = \alpha < \overrightarrow{\mu} >$ (2)

One has only to consider the transverse part of $\overrightarrow{M}$, called $\overrightarrow{M_T}$, since the NMR signal is detected in the Pick Up Coils which axis is perpendicular to the radio frequency coils (refer to paragraph 3).

From the equations (1) and (2) we see that the polarization is proportional to the magnetization :

$P(t) = \frac{M_T(t)}{\alpha\mu}$

The transverse magnetization gives rise to a transverse oscillating magnetic field proportional to the magnetization : $\overrightarrow{B_T(t)} = \alpha' M_T(t) \overrightarrow{u_T}$ that induces a signal in the Pick Up coils. The Lenz law gives the induced voltage :

$\epsilon = -\frac{d\phi}{dt} = -\frac{d}{dt}\int_{S_{pu}} \overrightarrow{B_T(t)} d\overrightarrow{s}$

where S_{pu} is the Pick Up coils surface. Under the Adiabatic Fast Passage condition, we have $\frac{dM_T(t)}{dt} \simeq 0$ thus :

$\epsilon = -M_T \frac{d}{dt}\int \alpha' \overrightarrow{u_T} d\overrightarrow{s} = -P(t)\mu\alpha\alpha' \frac{d}{dt}\int \overrightarrow{u_T} d\overrightarrow{s}$

So the signal induced in the Pick Up coils is proportional to the polarization of the target and thus provides a polarization measurement .

The factor $\alpha\alpha'\mu\frac{d}{dt}\int \overrightarrow{u_T} d\overrightarrow{s}$ could be computed but several phenomenons tough to estimate make this computation difficult and not accurate. We rather avoid it by calibrating the system with water.

2.3 The Experimental Setup

The experimental setup for the NMR polarimetry is shown on **Figure 3.1**.

The nature and the roles of numbered devices are :

1- **Function generator HP 3225B** used to remove the Radio-frequency noise in the Pick Up coils. The induced RMN signal detected in the Pick Up coils has the same frequency as the inducing RF signal, which can also be detected by the Pick Up coils and swamp the induced signal. In that purpose, the Pick Up coils are mounted perpendicular to the RF coils. Nevertheless this perpendicularity is not perfect and the coils are not infinitely flat (and also the field lines of the RF field are not straight and perpendicular to the RF coils) so we pick up a component of this RF field. To cancel the RF signal we send to the device #2 a signal with the same frequency but opposed phase. The cancelling signal frequency is given by the device #3. The 92.000 kHz shown on the device's screen is the water resonance frequency.

2- **Amplifier SR 830** is used as a thin pass-band filter (it performs the Fourier transform and takes the Fourier component at a frequency given by the device #3). The addition of the cancelling signal and the pick up signal is also performed by the device. It is not used as an amplifier.

3- Lock the frequency given by device #4

4- This **SR DS345 function generator** sets the reference frequency for devices #1 and #2 and generates the RF signal.

5- Sets the time reference for device #1 (since the RF noise signal and the cancelling signal must be in opposite phases, we have to define a zero time reference).

6- Attenuator to protect the device #7 wich cannot withstand an input signal superior to 1 volt.

7- **Power amplifier ENI 2100L** for the RF coils alimentation.

8- Set of capacitors to form a LC circuit with the RF coils. We choose the capacitor to work at the resonance frequency ($\frac{1}{2\pi\sqrt{LC}} = f_{resLC} = f_{RMN}$).

9- Ampermeter for the RF coils current.

10- **Preamplifier SR 560** (actually used as a an amplifier since device #2's role is not to amplify the signal). Takes the two Pick Up coils's cell resonance signal, adds them (in fact substract the signal since they have opposed sign). Acts also as a pass band filter.

11- **Power supplies KEPCO** for the main coils.

12- RF coils

13- Pick Up coils

14- main coils (also in dashed line)

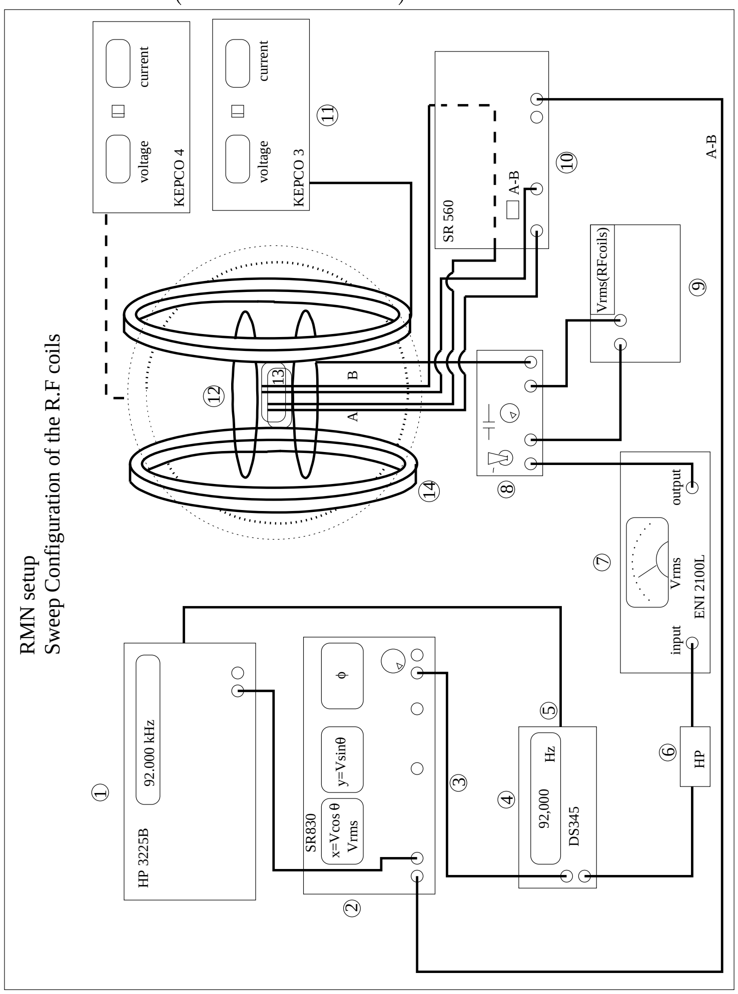

Figure 2.3 : The experimental RMN setup.

3 A few words on EPR

The EPR polarimetry is another independent way to measure the polarization of the target. The setup is currently on preparation and will not be precisely described.

3.1 EPR principle

The EPR, Electron Paramagnetic Resonance, is based on the Zeeman effect, that is to say the interaction between a system and a magnetic field. Lets label this field B_0 and takes the more simple system : an Hydrogen atom. The magnetic field couples the nuclear spin $\overrightarrow{\mu}$ ($\mu = 1/2$) and the electronic spin $\overrightarrow{s}$(s=1/2). So the Zeeman Hamiltonian can be written, defining the quantum axis $\overrightarrow{u_z}$ following $\overrightarrow{B_0}$:

$H_z = \frac{1}{2\pi} g\mu_B B_0 s_z + \hbar\gamma B_0 + a\overrightarrow{s}\,\overrightarrow{\mu}(3)$

where the last term is a pertubative term called Contact Term (or Fermi Term) arising from the nucleus field and the electron (Hyperfine structure).

As the $a\overrightarrow{s}\,\overrightarrow{\mu}$ term is perturbative, the system can be described at a first order with the state functions $|\alpha>$|a>, where $|\alpha>$ is an eigenvector of μ and |a> an eigenvector of s. In comparison with the electronic transition characteristic time, the nuclear state seems stable thus we will care only of the electronic spin transitions $\triangle m_s = \pm 1$.

(3) gives the frequencies of the emitted photon during an electronic transition :

$\nu_{EPR} = \frac{1}{h}\triangle E = \frac{1}{2\pi h} g\mu_B B_0 \pm \frac{1}{2h}a$

Sweeping the magnetic field induces electronic transitions at the values :

$B = \frac{h\nu \mp \frac{1}{2}a}{g\mu_B/2\pi}$

that means we have two absorption resonance frequencies, caracterising of the hydrogen atom system, shown on **Figure 3.1** :

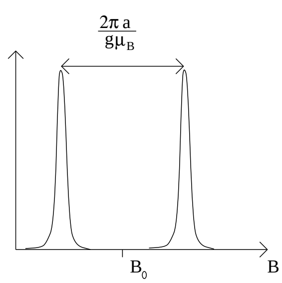

Figure 3.1 : the two EPR resonances for the Hydrogen atom.

Like in NMR, if the system is more complex, several couples of resonance frequencies arise and the gap inside a couple is system structure dependent, thus we can extract information on the system structure. This is EPR spectroscopy.

3.2 EPR Polarimetry

The EPR polarimetry is based on the shift of the Rubidium Zeeman resonance, due to, in one hand the magnetic field arising from the Helium 3 polarization, and on the other hand from the Rb-He spin exchange interaction.

The part of the shift due to the spin exchange is proportional to the nucleon spin while the part of the shift due to the Helium 3 polarization is proportional to the polarization $\overrightarrow{P} = \frac{<\overrightarrow{\mu}>}{<\mu>}$.

$\triangle\nu_{spin-exchange} = \alpha \frac{d\nu_{EPR}}{dB} < \overrightarrow{\mu} >$

$\triangle\nu_{polarization} = \beta \frac{d\nu_{EPR}}{dB} \frac{<\overrightarrow{\mu}>}{<\mu>}$

In adding the two contributions, we have the total frequency shift :

$\triangle\nu_{EPR} = \alpha' \frac{d\nu_{EPR}}{dB} \overrightarrow{P}$

where we define $\frac{d\nu_{EPR}}{dB} = \frac{\mu_B g_s}{h(2\mu+1)}$at low magnetic field, with $\mu = 5/2$ for Rubidium 85.

As in NMR, the constant α' can be computed but not with sufficient accuracy and so have to be experimentaly measured.