GENERATION AND DETECTION OF HYPERPOLARIZED XENON

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ABSTRACT

We present the experimental results of detection of detection of hyperpolarized Xenon obtained by 4.7 T, 200 MHz magnetic resonance (MR) system. Xenon 129 was hyperpolarized by the spin-exchange with Rubidium pumped by extended cavity laser system based on a tunable high-power laser diode optimized for maximum efficiency of the optical pumping process. The application of the laser system is oriented to employment in an experimental arrangement for production of hyperpolarized gasses (HpG), namely Xenon. It is designed to operate in medical and industrial applications to come.

1. INTRODUCTION

Hyperpolarized noble gasses (HpG) have found a steadily increasing range of applications in nuclear magnetic resonance imaging (MRI). They can be regarded as a new class of magnetic resonance contrast media or as a way of great enhancement of the temporal resolution in measurements of processes relevant to areas such as material science and biomedicine [1]. The hyperpolarized Xenon (^{129}Xe) plays a major role in the study of microporous materials like zeolites. The study and application is based on the chemical shift in Xenon gas. At very low pressures of the hyperpolarized Xenon and at the room temperature, the chemical shift is sensitive to the interaction of Xenon atoms with the walls.

The production of HpG, predominantly the ^{129}Xe became attractive for its potential applications in medicine as well. The powerful technique of magnetic resonance imaging of human body has a limited ability to examine organs with low water content and/or with air spaces, such as colon or lungs. An introduction of a highly contrasting ingredient would significantly extend its potential. Gaseous Xenon is normally not present in the body, so the experiments do not suffer from unwanted background signals. More, the hyperpolarized Xenon acts as a source of very strong nuclear magnetic resonance (NMR) signal which can even lead to introduction of specialized simple MRI apparatuses with significantly less powerful magnets.

The phenomenon of angular momentum transfer by the exchange of spin between optically pumped Rb atoms and nuclear spins of ^{3}He was first reported by [2] and theoretically described in [3]. With the higher efficiency of the polarization process that the spin-exchange technique namely of ^{129}Xe can offer, this technique became the mainstream in HpG production and experiments [4].

The output radiation of most lasers is linearly polarized and this is absorbed by both magnetic substates m = ± 1/2 of the Rb 5s $^2S_{1/2}$ ground state. Unlike for the production of hyperpolarized noble gasses (namely ^{129}Xe) the light absorption by the one magnetic substate is necessary. This is ensured by the circularly polarized light which can be generated by introduction of a quarter-wave plate. For example, right circularly polarized light selectively excites population from the m = - 1/2 ground state to the m = 1/2 excited state. Relaxation of the exited state brings population down to both ground states, m = 1/2 and m = - 1/2. Under continuous radiation, the m = - 1/2 ground state will be depleted and population will subsequently accumulate in the m = 1/2 ground state, leaving the Rb electrons spin-polarized. The Rb polarization is subsequently transferred to ^{129}Xe nuclear spins through spin-exchange collisions. For Zeeman splitting of ground state to substates m = ± 1/2 is necessary to apply a homogenous magnetic field, which is generated by a set of Helmholtz coils.

2. EXPERIMENTAL ARRANGEMENT

2.1. VACUUM PART

The target cell has to be evacuated to avoid a rubidium oxidation process. The main part of the arrangement for the target cell evacuation is the Turbomolecular Drag Pumping Station TSH 071 E which consists of diaphragm Pump MVP 015-2 (≤ 400 Pa) and Turbomolecular Drag Pump TMH 071 P (< 1×10^{-5} Pa). Single Gauge Control Unit TPG 261 and combination of cold cathode and Pirani gauge - Vacuum Gauge PKR 251 (10 Pa - 5×10^{-7} Pa) are used for vacuum measurement. The minimum pressure in the vacuum manifold which could be achieved is approximately 10^{-5} Pa. In case of use of Teflon tubes and plastic parts which are necessary for continuous regime of optical pumping, the apparatus is evacuated down to the pressure 10^{-3} Pa only.

A target cell is made from Simax glass with Borofloat windows. The cell is a 100 mm long cylinder with the inner diameter of 35 mm. The cell is sealed and filled with a small amount of rubidium, 200 kPa of N_2 and 100 kPa of natural Xenon.

2.2. LASER SYSTEM AND OPTICAL PART

First experiments with optical pumping of Rb were performed with a Titanium:Sapphire (Ti:Sa) laser [5]. For medical and industrial applications, a simple high-power laser system with narrow linewidth and wide wavelength tuning range is necessary. Hence we concentrated on the design of the external cavity laser (ECL) system based on a high-power laser diode (LD) [6]. The ECL laser is based on the broad-stripe laser diode S-λ-3000C-200-H. Its maximum output CW power is approximately 2.5 W, the selected central wavelength is 797 nm at the temperature 25°C and the LD emission linewidth is about 700 GHz. The original emission linewidth is reduced by diffraction grating used in the Littrow configuration as a wavelength selective feedback. The optical feedback level is optimized by retardation half-wave plate exploiting the polarization sensitivity of the grating. The optimum polarization angle was found in our case 40° and gives the power spectral density enhancement about 3 times compared to the LD itself. Then the ECL emission linewidth was approximately 40 GHz and the power loss is about 40%, from 2.49 W to 1.48 W. The central laser wavelength is stabilized to the D_1 Rubidium absorption line (794.76 nm) to eliminate the ECL thermal drift. The diffraction grating holder was designed to cover the thermal drift of the ambient temperature in the range ±5°C by the piezoelectric transducer. In result it is be able to cover the tuning range up to 232 GHz (±8°C). The experimental setup is shown in Figure 1.

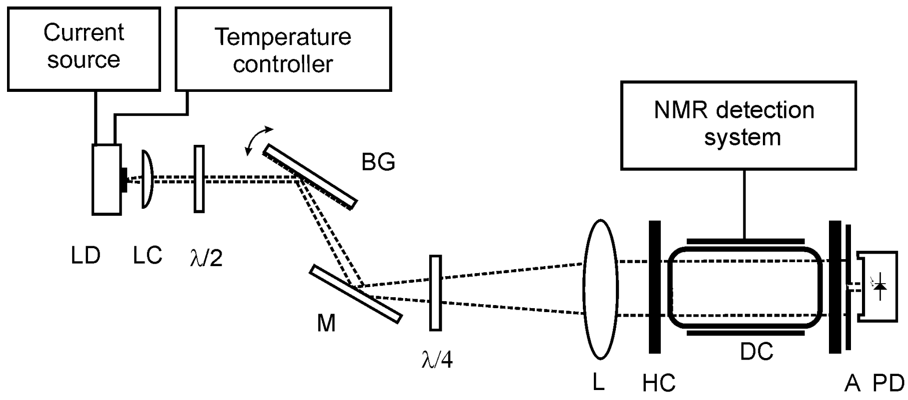

Figure 1: Experimental arrangement for Xenon hyperpolarization. LD is high-power laser diode. LC is aspheric collimating lens, λ/2 is retardation half-wave plate, BG is diffraction grating 2400 lines/mm in Littrow configuration and M is a mirror. λ/4 is retardation quarter-wave which transforms the linear polarization of the laser radiation to the circular one, L is lens, HC are Helmholtz coils, DC are detection coils, A is an aperture and PD is photodetector.

2.3. NMR PART AND EXPERIMENTAL PROCEDURE

To obtain the experimental results, the 4.7 T, 200 MHz MR system was used. The detection part of the MR system was tuned to Xenon resonance frequency 54.2691 MHz. The target cell was placed into the 16 mT scattered field of the MR system. The scattered magnetic field of the 4.7 T magnet proved to be comparable in homogeneity to the set of Helmholtz coils and in the further experiments we exploited the simplicity of the setup. The cell was enclosed in a Delrin box and heated by hot-air flow up to 110°C. After one period of the optical pumping process, the RF pulse is applied and the MR image is constructed from the signal induced in receiver coil.

3. EXPERIMENTAL RESULTS

Figure 2 shows the dependence of spectral line amplitude of hyperpolarized Xenon on duration of laser optical pumping (by ECL system). The optimal duration of the optical pumping process is about 10 minutes.

In the second experiment, we investigated the influence of laser emission linewidth, resp. it’s power spectral density to the Xenon spectral line amplitudes. The experimental results are shown in Table 1 and Figure 3. In the first column is the value related to thermally polarized Xenon. The cell was placed in the magnet of the NMR system for about 24 hours. The values in the next 3 columns are related to hyperpolarized Xenon with free-running laser diode with output power 2.49 W. The last four columns shows the experimental results for hyperpolarized Xenon obtain by ECL system with lower overall output power 1.48 W, but with enhanced power spectral density.

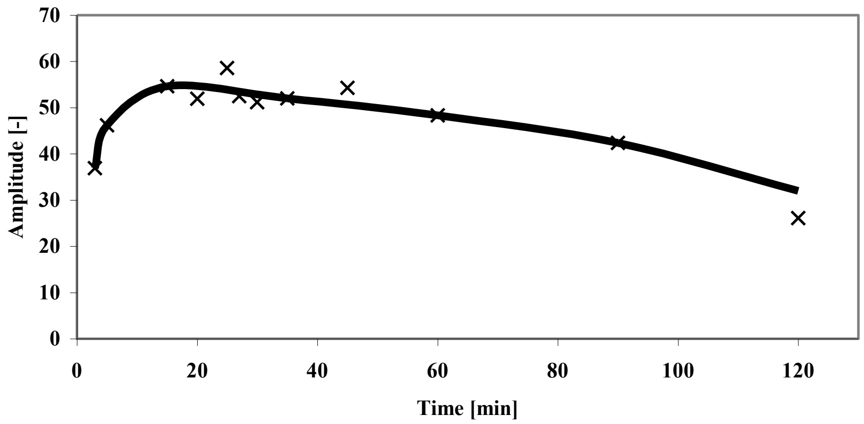

Figure 2: Dependence of amplitude of hyperpolarized xenon spectral line on the optical pumping duration

Xenon 129		thermally polarized	hyperpolarized, free running LD			hyperpolarized, ECL		
FID amplitude	[-]	290	15898	14873	14662	28242	27060	28322
Spectral line amplitude	[-]	3.9	182.3	170.5	166.5	348.6	322.2	320.6
Spectral line halfwidth	[Hz]	38.5	42.6	42.7	43.3	38.9	42.1	44.3
Spectral line center	[Hz]	10008.3	10095.2	10097.7	10095.2	10097.7	10097.7	10095.2
Temperature	[°C]	16	23	23	24.4	19.4	19.6	19.6

Table 1: Data comparison of thermally polarized xenon 129, and hyperpolarized xenon 129 by free running LD and ECL system

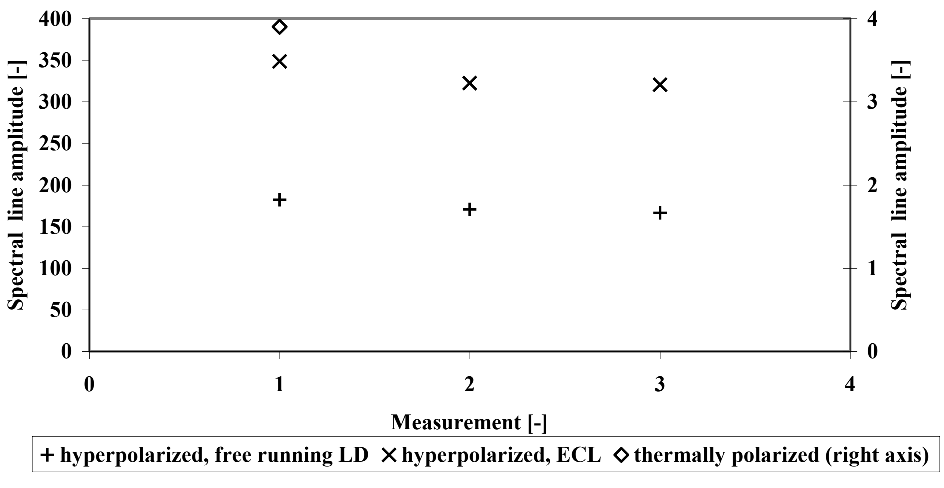

Figure 3: Spectral line amplitude comparison of thermally, hyperpolarized by free running LD and ECL system

4. CONCLUSIONS

We realized the experimental arrangement for Xenon hyperpolarization based on 4.7 T NMR system and high-power pumping laser system. To achieve Xenon hyperpolarization, the free running laser diode and the ECL system was used and their efficiency compared and evaluated. We found out that the efficiency of the optical pumping process is significantly higher for the ECL system because of the higher power spectral density at the wavelength of desire. The influence of the optical pumping duration to the ^{129}Xe spectral line amplitude was investigated as well.

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