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The Development of a Laser-Driven Spin-Polarized Deuterium Target

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INTRODUCTION

As an alternative to standard techniques for producing a polarized deuterium target, we are developing an optically pumped spin-polarized deuterium gas target for use in the Soviet VEPP-3 electron storage ring. We polarize deuterium through spin exchange with an optically pumped alkali gas in a storage cell. There are many important factors affecting the deuterium polarization, two of which are the phenomenon of radiation trapping, and coverage of the Doppler-broadened absorption peaks of the alkali. A technique for determining the amount of polarization of deuterium in the cell is also mentioned.

PROJECT STAGES AND GOALS

This project is a collaboration between Argonne National Laboratory and the Institute of Nuclear Physics in Novosibirsk, USSR. Its ultimate goal is to develop a high-density flow (4×10^{17} atoms/sec) of polarized deuterium, to be used as a target for high-energy electrons (2 GeV) in the Soviet VEPP-3 electron storage ring. Standard electron scattering experiments (those with unpolarized target nuclei) have not been able to extract measurements of the charge form factor of the deuteron, which essentially describes the distribution of charge in the nucleus, at momentum transfer energies greater than 1 fm^{-1}.[1]

Physicists are very interested in the location of the first zero in the charge form factor of the deuteron; it is sensitive to two opposing structural models of the nucleus: the quark model and the meson-exchange model. The study of high-energy electron scattering off of polarized deuterium, coupled with the results

from unpolarized scattering experiments, allows the extraction of the so called T_{20} parameter and therefore measurement of the charge form factor. Using this new method, our project has produced the only polarized data for electron scattering in the world.[2]

The T_{20} parameter, which is a function of the momentum transfer of the collision, is expected to have a zero at 4 fm^{-1}. No data has yet been obtained at momentum transfer energies this high; the limiting factor is the thickness of the deuterium target. As momentum transfer energies increase, the cross-section for an elastic electron-deuteron collision decreases exponentially. Therefore, much higher densities of deuterium are needed to increase chance of an event; our goal is 1×10^{13} atoms/cm^3.

Work on our project has been divided into three phases, each aimed at increasing the target density. Phase I involved the development of a storage cell, a specially coated elliptical pipe. The density of a jet passing through such a cell is proportional to I/C, where I is the input rate and C is the leak rate. C depends only on the cell dimensions and is proportional to the average radius cubed over the cell length. A very small radius was desirable, but this cell was limited to approximately 1.7 cm because it could not be removed and had to pass the entire electron beam. However, it was successful and gave a gain of a factor of 3 over the free jet; data was obtained at around 3 fm^{-1}.

Phase II, which has just been completed and taken to Novosibirsk, achieves a smaller cell radius by its "clam shell" properties. A motor and chain assembly rotates the half-elliptical tube out of the electron beam (opening the "clam shell") when other tests are to be run. The expected gain is a factor of 10 over phase I. Phase III is the development of the polarized deuterium target using optical pumping and spin-exchange as an alternative to standard techniques. The advantage is the possibility of producing a much greater flux (and therefore greater density) of polarized deuterium than standard techniques can now provide. The whole apparatus will eventually go to Novosibirsk and act as a source for the phase II apparatus.

The standard method involves a Stern-Gerlach type of apparatus.[3] In simple terms, unpolarized atomic deuterium (from a dissociator) flows through an inhomogeneous magnetic field with a large gradient in the field direction which, acting on the intrinsic magnetic moment of the electrons, separates the atoms into two oppositely polarized beams. One beam is defocused leaving the other, consisting purely of deuterium atoms with electrons having an identical spin orientation - either "up" or "down", to be focused and directed into a target area. Because of physical limitations, with our present technology we cannot improve the output of this apparatus.

Our method is inexpensive and easier to implement, and the density of deuterium which can be polarized is approximately proportional to the density of photons which can be pumped into the cell. Therefore, the gain is expected to be a factor of 40. However, the effects of a phenomenon called "radiation trapping" and laser coverage, provide an uncertain limit to the efficiency of this method.

OPTICAL PUMPING AND SPIN-EXCHANGE

The basic claim of optical pumping is the idea that photons can transfer order to electrons. A photon may be absorbed by a valence electron of an atom if the energy of the photon is equal to the energy required to excite the electron to an available and acceptable new energy level. Once the electron has been excited, it may give off a photon and decay back down to the same energy level as before, or a new level. Using a "left" or "right" circularly polarized photon one can direct which level an electron will be excited from, and knowing the chance that the electron will decay back to a certain level, one can force a percentage of the atoms in a volume to have their valence electron in an identical energy level. These atoms are polarized. The order of the photons has been transferred to the gas.[4]

It is not possible to simply optically pump the deuterium because x-ray photons would be needed. Therefore alkali atoms, which require a much lower energy photon are polarized and allowed to spin-exchange with the deuterium. When a deuterium and an alkali atom collide, the spin of the alkali electron

and that of the deuterium electron may be exchanged. The deuterium electron may then exchange its spin with the deuterium nucleus through hyperfine spin interactions. After several such exchanges, the deuterium nucleus and atom will completely polarized.

PHASE III: Set up and Problems

We are currently testing a cell of 1.2 cm radius, 4.8 cm length. Deuterium gas flows at 1.5×10^{17} atoms/sec into a larger tube mounted on top of the cylinder, where it is dissociated from molecular into atomic form. A thin arm, side-mounted, is loaded with sodium. The cell is surrounded by copper plates which can be heated above three hundred degrees celsius, and is in the center of a pair of Helmholtz coils which provide a weak orienting field. The laser light enters the cell along the axis of the coils and in the direction of the magnetic field. The gases flow through the cell and are pumped away. The cell walls are coated with dri-film to prevent depolarization from wall collisions.

Radiation Trapping

During optical pumping, if the density inside the cell becomes too high, a phenomenon called "radiation trapping" can occur. As I described above, an optically pumped electron soon gives off a photon and decays to a lower energy state. Under conditions of high density, a neighboring atom may absorb this unpolarized photon and become depolarized itself. If the depolarization rate overcomes the pumping rate of the lasers, then radiation trapping conditions occur. As a result, since the alkali atoms are not being polarized, deuterium polarization deteriorates.

We are now testing static cells (evacuated and containing only sodium) with different inner diameters. Theoretically, a smaller diameter cell should provide a shorter escape path for the photons we are trying to detect, reducing the chance that they will be absorbed, and therefore increasing the maximum density achievable before significant radiation trapping can occur. The results of these test are not yet available.

Doppler Linewidth Coverage

Because the sodium atoms in the cell are moving around energetically, each atom may see the laser light in a slightly doppler shifted way. For instance, an atom moving directly away from an oncoming photon will see its frequency as slightly red-shifted. The frequency of the photon should originally be slightly blue-shifted from resonance to compensate for this situation. The actually frequency that will be absorbed by the sodium atoms in the cell can be represented by a gaussians. There are two peaks of resonant frequency corresponding to the sodium-D doublet at 5897.56 angstroms. The output of our two dye lasers can be represented by the sum of two gaussians. We would like to know how well the lasers' output covers the sodium absorption curve.

Using curve fitting programs to find the shape of the lasers' output which would provide optimum coverage, we decided to frequency-broaden both laser's output. This is accomplished relatively simply and cheaply with electro-optic modulators (EOMs). These devices contain a crystal which, when driven by a either a specific frequency or simply white noise, will broaden the frequency spectrum of a laser beam passing through it.[5] We are in the process of testing our new EOM's.

Results

Our best results to date show approximately 38% polarization of deuterium with a flow of about 6×10^{16} atoms/sec. We would like to achieve at least 50% polarization at about 4×10^{17} atoms/sec. There should be a considerable improvement resulting from the study of the problems mentioned above. In the future we may obtain a ring-dye laser to increase our power input.

A TECHNIQUE FOR MEASURING POLARIZATION

We extract a signal from the cell which allows us to measure the percent polarization of deuterium or sodium. The relationship between the strength of the external magnetic field and the frequency of the hyperfine splitting of either deuterium or sodium is

hyperfine splitting of either deuterium or sodium is known. Therefore, we pump radio frequency power into the cell at a constant frequency, and then ramp the magnetic field over a short range in which we know we should see excitations between hyperfine levels. The photons from the resulting radiative de-excitations are detected and displayed on an oscilloscope. Deuterium shows three peaks, and sodium four; the ratios of the areas under the peaks is related to the abundances of electrons in each hyperfine level, and therefore to the percent of atoms polarized.

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