

Laser Pumped Rubidium Vapor Polarizer

by

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Abstract

The purpose of this work is to irradiate rubidium vapor mixed with deuterium gas inside a heated glass sphere with finely tuned laser light produced by a high power solid state laser diode. The goal of this project is to produce nuclear spin polarized deuterium nuclei. The laser will be operated at high power and the rubidium vapor will be produced by heating an ampoule containing a rubidium pellet to a sufficient temperature to produce the desired vapor pressure. Data regarding the temperature of the deuterium gas, laser diode operating parameters, and rubidium vapor characteristics will be recorded and analyzed. The object of this effort is the successful operation of the polarization cell and production of polarized deuterium gas.

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Laser Pumped Rubidium Vapor Polarizer

A strongly anisotropic beam of high energy neutrons may be generated by the fusion of spin polarized deuterium and tritium nuclei. The polarization of these nuclei is accomplished by collision with polarized rubidium vapor atoms. The rubidium vapor is polarized by a high power near infrared diode laser. The efficient production of polarized rubidium vapor is a critical component to the polarization of deuterium and tritium nuclei for the production of a concentrated neutron beam. The prospect of such a concentrated neutron beam offers many medical treatment possibilities currently not available with standard neutron generators, which produce their neutron flux isotropically, or equally, in all directions.

One of the most useful inventions that could be created would be a treatment for glioblastomas. These are brain tumors that are essentially inoperable because of the manner in which they spread their octopus-like tentacles throughout the volume of brain tissue surrounding them within the cranial cavity. Complete surgical removal of the tumor is impossible because of the collateral damage to adjacent brain tissue. Early detection of the cancerous tumor is impossible without frequent x-rays of the skull. Currently, glioblastoma has the worst prognosis of any cancerous tumor related to the central nervous system. In most cases, when diagnosed by a doctor, the patient is simply told they have only a few months to live.

A potentially promising treatment for glioblastoma, along with many other cancerous tumors, exists in the invention of a neutron generator which produces a high intensity collimated beam of neutrons. All current neutron generators produce neutrons similar to the way an incandescent light bulb shines light. The light is produced equally in all directions. A neutron generator with polarized nuclei would produce neutrons similar to a laser pointer; the entire beam is produced in a single, narrow direction. A treatment using neutrons for cancerous tumors, such as glioblastomas, has already been proven and is called Boron Neutron Capture Therapy (BNCT). This treatment involves injecting a tumor with an organic dye that has attached to it the isotope boron 10. The borated organic dye is absorbed by and spreads preferentially throughout the tumor and not the surrounding brain tissue. The tumor is then irradiated with neutrons, which pass through the brain tissue with little interaction. This isotope of boron rapidly absorbs the neutrons to produce an alpha particle. These high energy alpha particles have been clinically proven to be very effective at killing cancer cells. The unique

feature of this therapy is that the organic dye spreads completely throughout the malignant tumor and essentially none of the adjacent brain tissue, allowing the alpha particles from the neutron irradiated boron 10 to destroy all of the malignant cancer tissue with very little damage to brain tissue.

The efficacy of this cancer therapy has already been clinically proven. The current problem with administering this BNCT treatment is that it requires a full size nuclear reactor to produce a neutron flux sufficient to make the treatment effective. This is currently operationally and financially prohibitive. A neutron generator using polarized ions for this therapy is possible. If successful, the operation of this neutron beam will provide the medical community with a powerful tool in the treatment of cancer.

Deuterium or tritium nuclei maybe be accelerated to energies greater than 100 keV and strike other deuterium or tritium nuclei. When this happens, a nuclear fusion reaction between the two nuclei occurs and a high energy neutron is produced.

According to work performed by J. A. Wheeler in the early 1960's (Ref. 1) and further described by R. Vandebosch and J. R. Huizenga (Ref. 2), when a neutron strikes a fissile nucleus, the resulting fission fragments are not emitted in random directions. Instead, the direction the fragments separate is uniquely determined according to the quantum mechanical laws of conservation of linear and angular momentum, along with intrinsic spin. The fragments separate along the nuclear symmetry axis with the directional dependence of the fission fragments uniquely determined by the quantum numbers J , K , and M of the transition state.

This concept is contrary to ordinary observation, since, in a typical critical nuclear assembly, fission fragments, neutrons, and gamma rays are emitted randomly in all directions. However, this isotropic emission from the assembly is the result of the random orientation of the nuclear spin axis of the nuclei prior to neutron impact and the random direction of the neutron impact into the nucleus with respect to the axis of nuclear symmetry. On an individual nucleus basis, the fission fragments are always produced in a deterministic direction.

The process of fusion is analogous to fission. Deuterium and tritium first undergo fusion, then fission into a neutron and an alpha particle. The direction of emission of the neutron and alpha particle is constrained by the same set of quantum mechanical parameters J , K , and M as in

fission. In a neutron generator, this direction of emission is primarily determined by the rotational angular momentum of the accelerated deuteron projectile nucleus prior to impacting the triton target nucleus. Most fortunately, the ground state of a deuteron is mostly the $L=0, S=1$ state, where there is no angular momentum and the total angular momentum is just the spin. With the ground state of the triton target nucleus in the $L=0, S=1/2$ state and the spins of the deuteron and triton aligned, the possibility for the directions of fission, or neutron and alpha particle emission, is reduced to a single directional plane perpendicular to the nuclear axis of symmetry. When the linear momentum of the deuteron is accounted for, the direction of the beam is biased in the forward direction, as shown in Figure 1.

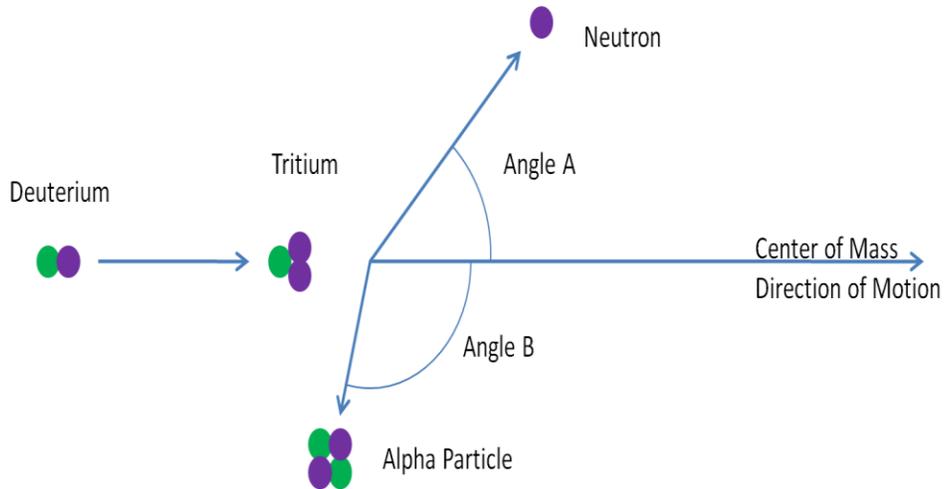


Figure 1. Fusion of Deuterium and Tritium Conservation of Momentum

When this process occurs in normal neutron generators, the nuclear spins of the deuterium and tritium nuclei are completely randomly oriented at the moment the fusion reaction occurs, thus producing the neutrons with an isotropic direction distribution. If the nuclei are polarized by collision with laser polarized rubidium atoms prior to the fusion reaction, conservation of linear and spin angular momentum may cause the neutrons to be emitted with a high degree of anisotropy. This could only occur if the deuterium and tritium nuclei exhibit a high degree of nuclear spin polarization at the moment of fusion.

The critical technical issue for this concept is the production of a beam of highly spin polarized deuterium ions and highly spin polarized tritium atoms. Production of a highly spin polarized beam of atomic deuterium has been performed at a number of nuclear physics

facilities for more than 15 years (Ref. 3). Atomic beam sources with intensities of 1×10^{16} to 1×10^{17} polarized deuterium atoms per second are common. However, these atomic beam sources with such large outputs are large, heavy devices with large power requirements, and are not suitable for medical radiological treatment systems.

The physics of the angular distribution of emitted neutrons based on initial conditions of spin, angular, and linear momentum is well known and understood. Also, the physics of nuclear magnetic spin alignment is very well known and practiced everyday by the nuclear magnetic resonance imaging industry. However, the magnetic fields of the MRI machines spin align only a very small fraction of the hydrogen nuclei in the patient undergoing observation. MRI machines observe the spin of normal hydrogen with a spin of $\frac{1}{2}$. Tritium also has a spin of $\frac{1}{2}$, which splits into two magnetic sublevels: $m_I = +1/2$ and $-1/2$. Deuterium, on the other hand, has a spin of 1, with magnetic sublevels: $m_I = +1, 0,$ and -1 . To generate the beam of neutrons in a preferential direction, the deuterium and tritium nuclei must have parallel or anti-parallel spins, $(+1, +1/2)$ or $(+1, -1/2)$, at the moment the deuterium nuclei strike the tritium nuclei and undergo fusion.

The nuclear polarization of deuterium atoms may be accomplished by colliding unpolarized deuterium atoms with polarized rubidium atoms. The polarization of the rubidium atoms is achieved by irradiation with a narrow linewidth laser diode source operating at a wavelength of 895 nm. The high power 30 watt laser used in this experiment was manufactured by Coherent Lasers, Inc. The valence electron of a rubidium atom is easily and efficiently spin polarized by pumping with circularly polarized light while in a strong uniform magnetic field. The electrons in the vapor are spin polarized by optical pumping with a circularly polarized laser tuned to the $n=3$ to 2 transition of the valence electron in the rubidium vapor. The deuterium atoms pick up an electron primarily into the $n=2$ excited state.

To preserve the polarization state after collisions, the rubidium vapor cell is contained in a magnetic field. This magnetic field preserves the spin polarization as the deuterium atom decays to the ground state after the charge exchange has occurred. As the spin polarized deuterium atoms emerge from the vapor cell, the atoms flow from the polarizer into the main accelerator to allow acceleration into the target. The nuclei first pass through an inhomogeneous magnet field to separate the spin states according to the Stern-Gerlach principle. The polarized

deuterium atoms are then stripped of an electron and accelerated into the polarized tritium target. As the polarized deuterium nuclei impact the polarized tritium nuclei, the resulting nuclear fusion produces the neutrons in a strongly anisotropic manner. The spread of the neutron beam is largely determined by how accurately the polarized nuclear spins are aligned.

Either potassium or rubidium may be used to spin polarize deuterium atoms. Rubidium and potassium have a relatively high charge exchange cross section with deuterons, and the readily available tunable diode lasers with high power at the required wavelength. However, for this experiment, rubidium is chosen over potassium because to achieve the desired vapor pressure in the polarization cell of 1 to 10 mTorr, potassium must be heated to approximately 260 degrees Celsius, while rubidium needs only to be heated to about 160 degrees Celsius. This 100 degree Celsius difference may not appear to be significant. However, in the laboratory, the difference is significant since the entire polarization cell must be heated to more than this temperature to prevent condensation of the rubidium vapor on the walls of the cell.

This diode laser pumping technique transfers angular momentum from the laser beam to a vapor of rubidium atoms. The electrons of the deuterium or tritium atoms are polarized through spin exchange collisions with the polarized rubidium atoms. After many collisions between the deuterium gas atoms and the rubidium vapor atoms, the deuterium atom electrons become highly polarized. Through spin-orbit coupling and hyperfine interactions, the nuclei of the deuterium atoms become highly spin polarized and approach spin temperature equilibrium.

The purpose of this project is to irradiate rubidium vapor mixed with deuterium gas inside a heated glass sphere with finely tuned laser light produced by a high power solid state laser diode. The goal of this project is to produce highly nuclear spin polarized deuterium nuclei. The laser is operated at 10 to 30 watts and the rubidium vapor is produced by heating the ampoule containing the rubidium pellet to a sufficient temperature to produce the desired vapor pressure. Data regarding the temperature of the deuterium gas, laser diode operating parameters, and rubidium vapor temperature characteristics is recorded and analyzed. The ampoule containing the rubidium metal pellet with the heating cover removed is shown in Figure 2. This picture displays the ampoule connected to the double walled polarization chamber through a glass tube. As can be seen from the picture, the polarization chamber is inside another glass chamber.

The outer glass jacket wall is to contain hot air at a temperature of approximately 200 degrees Celsius to prevent the rubidium vapor from condensing on the inner glass wall. This is a major experimental constraint, since rubidium vapor condensing on the inner glass wall acts as a mirror to the laser beam and seriously reflects a significant part of the beam and prevents the vapor from being irradiated by the beam. The diameter of the inner glass wall chamber is approximately 5 centimeters, while the laser beam diameter is approximately 3 centimeters. Thus, the laser beam irradiates the glass wall at close to normal incidence over the central portion of the beam and is not highly reflected. The reflected part of the high power beam could be a serious eye safety concern, even though laser safety goggles are worn during all laser operation. However, the convex curved surface of the glass spherical walls act as divergent mirrors and rapidly diverge the reflected laser beam.

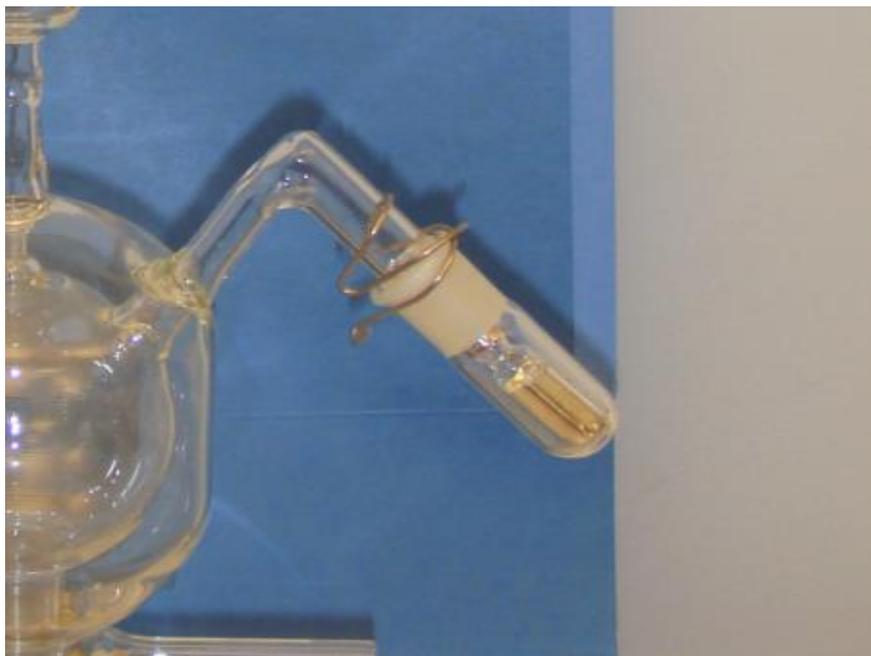


Figure 2. Ampoule Containing Rubidium Pellet with heating element removed.

No direct method is available for this experiment to measure the pressure of the rubidium vapor as the pellet is heated. A Pfeiffer Full Range Compact Vacuum Gauge is used to measure the pressure inside the main part of the system. This vacuum gauge covers the entire range from atmospheric pressure to high vacuum with a digital readout. However, as soon as the hot rubidium vapor leaves the heated part of the polarization chamber, it condenses on the room

temperature vacuum lines and the contribution of its partial pressure to the total system pressure is lost. The vapor pressure of rubidium as a function of temperature is well known from several references. Thus, for the purposes of this experiment, the vapor pressure of the rubidium is determined by measuring its temperature and then referring to data Figure 3.

The rubidium ampoule is wound with 25 gauge nichrome wire and connected to a 12 volt 5 ampere DC power supply through a 14 Ohm rheostat to control the current through the nichrome wire. The ampoule is then wound with glass heating tape for insulation and to hold the nichrome wire in place.

	Vapor Pressure					
P (Pa)	1	10	100	1 k	10 k	100 k
P (Torr)	.0075	.075	.750	7.5	75	750
at T (C)	161	213	279	368	496	685
at T (K)	434	486	552	641	769	958

Figure 3. Rubidium Vapor Pressure vs. Temperature

A picture of the rubidium ampoule mounted in place inside the large Helmholtz coil is shown in Figure 4. Close examination of the picture reveals the 25 gauge nichrome wire wound around the ampoule. In operation, this wire not only surrounds the ampoule, but also is wound around the glass arm leading into the chamber. The glass arm must be kept at the same or higher temperature as the ampoule to prevent the rubidium vapor from plating out onto the glass walls. To this wire are attached alligator clips connecting the wire to the rheostat and DC power supply. Glass insulation tape is wound around the entire ampoule and glass arm. Great care is taken to keep the entire arm up to the outer glass wall heated to prevent condensation of the vapor on any cool section of the apparatus.

The principle objective of this project was to develop a data set of rubidium ampoule temperature as a function of current through the nichrome wire. This was performed by wrapping the ampoule and arm with glass insulation and increasing the current through the wire and measuring the temperature of the bottom of the ampoule. The glass heating tape was wound sufficiently thick enough such that even at high current operation, the outside of the glass insulation was essentially at room temperature.

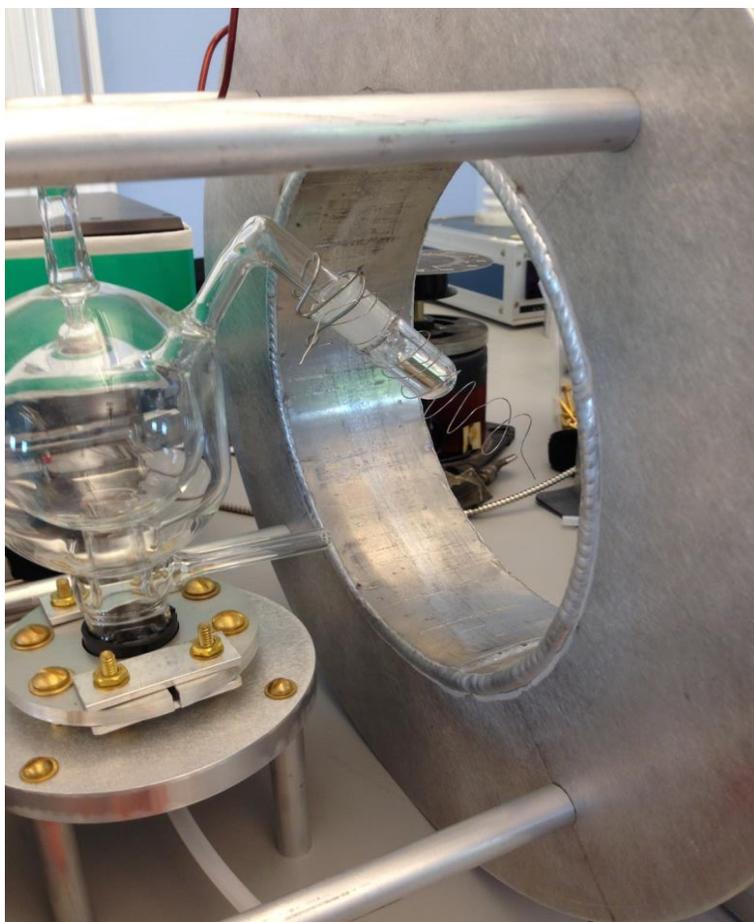


Figure 4. Rubidium Ampoule and Polarization Chamber Inside Helmholtz Coil

To measure the temperature of glass ampoule, the insulation was removed from the bottom of the ampoule while hot and measured with a Klein IR Thermometer. A red laser dot was produced by the thermometer to locate the position of the temperature measurement precisely. This measurement procedure is shown in Figure 5. All measurements were taken after the temperature of the ampoule had reasonably come to equilibrium with the glass, wire, and insulation. This process normally occurred in a few minutes.

Under normal operation, the heated rubidium vapor can be seen filling the inner glass polarization cell. It has a shiny metallic appearance, as would be expected. The outer glass wall surrounding the inner glass wall chamber only serves to allow the inner glass wall to be heated with hot air from an electric blower. The outer wall has inlet and outlet ports to allow the hot air from the blower to pass through the void between the glass chambers and heat the inner chamber. The issue of heating the polarization could be greatly mitigated if insulation could be

placed around the outside. However, insulation cannot be placed over the outside chamber since it would interfere with the passage of the laser through the glass walls to pump the rubidium vapor.

Heating the outside chamber wall to prevent vapor condensation is a significant laboratory challenge. The hot air exhausting from the exit port of the outer chamber presents somewhat of a challenge to the laboratory environment, since it must operate for an extended period to sufficiently heat the chamber. Since many heat loss avenues existed between the hot air blower and the chamber, no measurement of the temperature of the hot air was attempted. The temperature of the blower was simply increased until no rubidium vapor was visually observed to condense on the wall of the inner chamber.



Figure 5. Temperature Measurement of Glass Ampoule

In practical operation, the bottom of the ampoule will remain covered with insulation. The data shown in Figure 6 will allow the ampoule to be heated to a known temperature, and thus produce a vapor pressure that can be interpolated from the data in Figure 3. The data collected below indicate a potential operating point of approximately 1.3 Amps through the nichrome wire to produce a vapor pressure of about 10 mTorr. This is roughly the desired operating point since the pressure inside the polarization chamber must be maintained at approximately 1 mTorr to prevent the dissociated deuterium atoms from quickly recombining back into deuterium molecules by collisions. Once the deuterium atoms are polarized, they will not recombine, since with both atoms polarized in the same direction, the deuterium molecule will not form. The ground state of the deuterium molecule has to have one atom with spin up and the other with spin down to be stable.

Current (Amps)	Temperature (deg C)
0.0	22.5
0.2	44.2
0.4	69.5
0.6	94.8
0.8	115
1.0	141
1.2	165
1.4	186

Figure 6. Nichrome Wire Current vs. Temperature

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