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Technical notes

Source of polarized hydrogen molecules

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ABSTRACT

A novel source of polarized hydrogen and deuterium molecules has been tested. The use of sextupole superconducting magnets allows us to select molecules with the nuclear spin projection −1 for hydrogen and −2 for deuterium. The measured beam intensity of polarized hydrogen molecules for the nozzle temperature range of 6.5–30 K and a gas flow rate up to $5 \cdot 10^{-2}$ Torr · l/s is presented. The measured flux of polarized hydrogen molecules of $\approx 3 \cdot 10^{12}$ mol/s is in reasonable agreement with estimations. The obtained results can be used as a basis for the development of a high-intensity source of polarized molecules.

The sources of polarized particles are widely used for the production of polarized high energy ion beams and polarized gas targets internal to storage rings of charged particles [1,2]. An additional interest in polarized sources is connected with the idea of using polarized fuel for thermonuclear fusion [3]. The use of polarized fuel makes it possible to significantly increase the energy production in d-t and ^{3}He-d reaction. If both particles are polarized, an enhancement of the fusion yield close to a factor of 1.5 may be expected. Such a strong polarization effect has been confirmed experimentally [4].

Starting with the intensity of polarized beam 10^{11} atoms/s more than 50 years ago [5], now atomic beam sources (ABSs) of highly polarized hydrogen and deuterium atoms have reached a limit of $\approx 10^{17}$ atoms/s which is explained in terms of intrabeam scattering. The produced atoms are also extremely reactive radicals, which does not allow one to accumulate and store them for a long time. Research to obtain polarized molecules in the process of recombination of polarized atoms from the ABS is now underway in Juelich [6,7]. However, this method of obtaining polarized molecules has a limitation in the intensity, as well as a decrease of the degree of polarization during the process of recombination.

In [8] a conventional Stern–Gerlach separation of hydrogen molecules was proposed to produce a beam of polarized protons. In [9] we have suggested and in [10] demonstrated the possibility to obtain polarized hydrogen and deuterium molecules using the superconducting sextupole magnets of cryogenic ABS [11]. Here we present and discuss the results of a more extensive study of this source for different nozzle temperatures and gas flow rates.

Both hydrogen and deuterium exist in two spin isomer states—ortho-state, when spin wave function is symmetric, and the para-state, when spin wave function is anti-symmetric. Under normal conditions, hydrogen is a mixture of 3/4 ortho- and 1/4 para-states, while deuterium contains 2/3 ortho- and 1/3 para-states. At low temperatures, the ortho-deuterium and the para-hydrogen are thermodynamically stable. Spontaneous ortho–para transformation at low temperatures is very slow. Having different projections of the magnetic moment, molecules of hydrogen can be spatially separated in an inhomogeneous magnetic field, which was first demonstrated in [12]. Since the molecules have small magnetic moment of the order of a nuclear magneton, the gradient of the separating magnetic field must be large.

The hyperfine energy structure of a hydrogen molecule in a magnetic field is shown in Fig. 1 [13]. Molecules in states A, B and C have a projection of the spin moment $m_I = -1$ and in an inhomogeneous magnetic field they are driven away from the high-field region. The operating principle of the source is illustrated in Fig. 2. Two magnets, 7.0 and 12.5 cm in length, separated by a gap of 31 cm, were used to focus the molecules. The inner diameter of the vacuum chamber of 42 mm determines the available aperture of the magnets. The magnetic field at a radius of 21 mm from the axis of the magnet, with a current in the magnets of 350 A, has a magnitude of 34 kG and a field gradient of 32 kG/cm. When working with hydrogen, the temperature of liquid helium was lowered to 2.5 K by reducing its vapor pressure to increase pumping speed for H_2. A nozzle was mounted at a distance of 33 cm from the magnet entrance and could be cooled down to liquid helium

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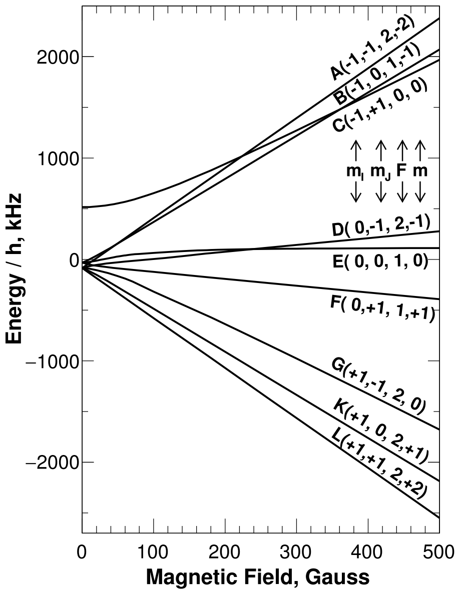

Fig. 1. Energies of H_2 states as a function of magnetic field [13]. Here m_I, m_J, m are projection of spin I, orbital J and total F moments, respectively.

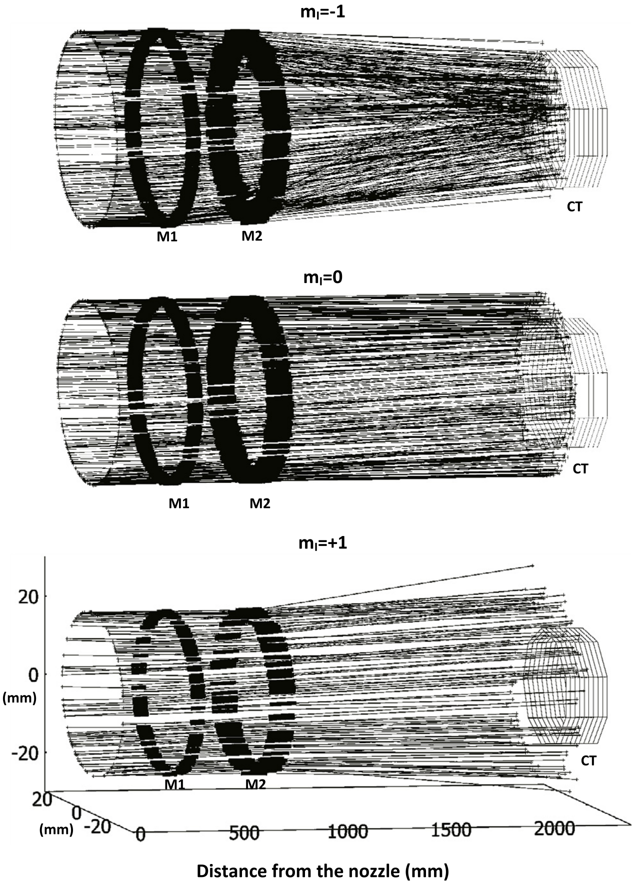

Fig. 2. Illustration of the operating principle of the source: M1, M2— sextupole magnets, CT—compression tube, lines—Monte Carlo simulation of molecules trajectories for different projection of spin moment.

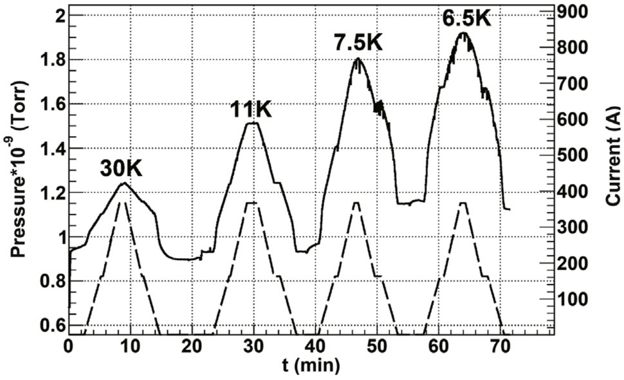

Fig. 3. Dynamics of hydrogen pressure in the compression tube (solid line) and current through the coils of the magnets (dashed curve) for the fixed gas flow through the nozzle and various nozzle temperature.

temperature. The nozzle is a copper block having a circular slit, with outer and inner diameters of 41.9 and 41.7 mm (slit width, respectively, is equal to 0.1 mm). Nozzle is installed coaxially with the sextupole magnets. The nozzle temperature can be varied over a wide range with the use of a heater. A disk with a diameter of 40 mm was placed at the entrance of the magnets, forming a circular diaphragm with an outer diameter of 42 mm and a width of 1 mm. In this geometry the molecules are passing near the poles of the magnet, where the field gradient is maximal. At a distance of 135 cm from the end of the magnets a compression tube (CT) for molecules 30 mm in diameter and 20 cm in length is placed on the axis. In such a geometry the direct ballistic flux of molecules cannot reach the CT. Hydrogen molecules in the ortho-state ($I = 1$, $m_I = -1$, both proton spins are anti-parallel to the magnetic field axis) are slightly focused to the beam axis. Molecules in the state ($I = 1$, $m_I = 1$) are defocused in opposite direction and hit the cold surface of the magnets where they are frozen out. Molecules in the state $I = 1$, $m_I = 0$ and the para-state $I = 0$, $m_I = 0$ are not influenced by the magnetic field and, therefore, they follow their ballistic trajectories and miss the entrance of the CT. Only molecules in the state with $I = 1$, $m_I = -1$, which are focused by the strong gradient can enter the CT. A vacuum gauge is installed in the volume of CT to determine the pressure change during the magnet ramping. A differential pumping system including two cryopumps was implemented to get ultra high vacuum in the vicinity of the CT. When the magnetic field is turned on, the molecules in substates with negative spin projection (A, B, C on Fig. 1) are directed toward the axis and enter the tube, increasing the pressure in it.

A Monte Carlo simulation of the trajectories of hydrogen molecules moving through the magnets has been performed for different projections of the spin moment. It was assumed that the gas follows the Maxwell velocity distribution and the cosine angular distribution at the nozzle exit. It was also supposed that if a molecule touched a cryogenic surface, it is adsorbed with a probability equal to one. A flux of polarized molecules focused into the CT predicted by Monte Carlo modeling was determined as: $Q_{MC} = 2.1 \cdot 10^{-6} Q_0$, where Q_0 is the total flux of molecules from the nozzle. The magnetic moment was considered the same for all three substates A, B and C.

Fig. 3 shows the experimental result on the pressure change in the CT for a hydrogen molecular beam, when the current through the magnets was turned on and off. One can easily see a strong correlation between the hydrogen pressure in the CT and current through the magnets. The measurements have been performed at different temperature of the nozzle as indicated in Fig. 3. If the temperature of the nozzle goes down below 6.5 K a condensation of gas in the nozzle occurs. Considering that the conductance of the compression tube and the sensitivity of the vacuum gauge to the given gas is known, it is possible to determine the flux of focused (polarized) molecules into the tube. Fig. 4 shows the intensity of polarized beam entering the CT as a function of the temperature of the nozzle for the gas flow of $4 \cdot 10^{-2}$ Torr l/s. The intensity of the focused beam increases more than two times while the