Status of polarized molecular source

Dmitriy Toporkov

Budker Institute of Nuclear Physics,
Novosibirsk State University
Novosibirsk, Russia.
World Primary Energy Consumption (Million Tons of Oil Equivalent, 1950-2050)


~ 20 Tw up to now
The most important thermonuclear reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma_m$(b)</th>
<th>$E_m$(keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D + T \rightarrow n(14.1) + ^4He(3.5)$</td>
<td>5.0</td>
<td>107</td>
</tr>
<tr>
<td>$D + D \rightarrow \begin{cases} n(2.45) + ^3He(0.85) &amp; 50% \ p(3.02) + T(1.01) &amp; 50% \end{cases}$</td>
<td>0.1</td>
<td>1500</td>
</tr>
<tr>
<td>$D + ^3He \rightarrow p(14.7) + ^4He(3.6)$</td>
<td>0.71</td>
<td>430</td>
</tr>
</tbody>
</table>
Full polarization of the deuteron and He$^3$ would enhance the fusion cross section by 50%. Such a strong polarization effect has been confirmed experimentally to a good accuracy.

The relatively good knowledge about these two reactions allows the conclusion that with polarized beams and targets an enhancement of the fusion yield close to a factor of 1.5 may be expected.

Sources of polarized atoms

The sources of polarized atoms (ABS) has been developed from the early 50\textsuperscript{th}. Clausnitzer was the first who got a polarized proton beam using an ABS with quadrupole focusing magnets. The intensity of polarized atomic beam was approximately $10^{11}$ at/sec.

\[\text{G. Clausnitzer, R. Fleischman, H. Shopper, Zs. F. Physik 144 (1956) 336}\]


Since there fast developing of this technique now reached the limit in the intensity of polarized atoms. The best sources deliver about $10^{17}$ at/sec.
Novosibirsk Cryogenic Atomic Beam Source

Tensor polarization
Vector polarization

$P_{zz} = 1 - 3n_0 = -2, +1$
$P_z = n_+ - n_- = 0$
Ortho and parahydrogen

Spin isomers of molecular hydrogen

Orthohydrogen

Parahydrogen

Covalent bond

Proton spin

Proton spin
Energies of $H_2$ states as a function of magnetic field.

Only molecules in the states $A$, $B$, $C$ with $m_I = -1$, which are focused by the field can enter the CT.
Superconducting sextupole magnets with constant aperture 42 mm inner diam. used in ABS
Geometry selection

\[ F = m \ddot{r} = -\nabla W = \mu \cdot \partial B / \partial r = C \]
\[ \dot{r} = v_r = C \cdot t / mu \]
\[ t = L / u \]
\[ u_r = C \cdot L / (m \cdot u) \]
\[ \alpha = u_r / u = C \cdot L / (m \cdot u^2) \approx C \cdot L / (k \cdot T) \]

For our case \( \mu = 2.5 \times 10^{-3} \mu_B, T \approx 8K, L=19.5 \text{ cm}, \frac{\partial B}{\partial r} = 32 \text{ kG/cm}, \)

\[ \alpha = 1.3 \cdot 10^{-3} \text{ rad} \]
Polarized molecules source based on existing cryogenic ABS

Ring source
diam. 41 mm
width 0.1 mm

Entrance slit
outer diam. 42 mm
inner diam. 40 mm
width 1 mm

Compression tube
L 200 mm, diam. 30 mm

L 36.5 cm
L 87 cm
L mag 12.5 cm

L 150 cm
The source of polarized hydrogen molecules at the test bench
Monte Carlo simulation of the spatial distribution of the molecules at the location of the inlet receiver tube.
Source of cold hydrogen molecules

ring slit 0.1 mm width
diameter 41 mm

Copper block
The entrance slit to a focusing magnet

Cold surface up to 2.5 K

1 mm width ring slit
outer diameter 42 mm
inner diameter 40 mm
Photo of the nozzle and diaphragm made from the exit of the magnet
No beam intensity should be measured at the beam axis in the assumption that molecules touched the cold surface are pumped.
Profile of the molecular jet measured by the compression tube

Flux through the nozzle:
- 6.5$\times$10$^{-2}$ Torr l/s
- 2.6$\times$10$^{-2}$ Torr l/s
- 1.0$\times$10$^{-2}$ Torr l/s

Pressure, $\times$10$^{-6}$ Torr

X, cm
Correlation between the magnetic field and the intensity of the focused beam
Experimental results :: comparison of focusing efficiency $H_2$ and $D_2$

The flux of the focused deuterium molecules is lower since the magnetic moments of $D_2$ molecules are much smaller than those of $H_2$ molecules.

Magnetic moment of $H_2$ is $2.5 \cdot 10^{-3} \mu_B$

Magnetic moment of $D_2$ is $6.5 \cdot 10^{-4} \mu_B$

The measured flux of polarized deuterium molecules is about 7 times smaller than the flux of hydrogen molecules. The geometry of the source was not optimized to get the highest flow of $D_2$. 
Intensity of the H2 beam while ramping the magnet for different nozzle temperature (computer screen)

Temperature dependence of focusing beam

![Graph showing temperature dependence of focusing beam](image-url)
Background pressure in compression tube and pressure change due to magnetic field vs the flux through the nozzle \(T_{\text{nozzle}}=7.3\ \text{K}\).
Flux of focused molecules into the compression tube and the ratio of fluxes vs the flux through the nozzle.

T nozzle = 7.3 K.

Flux of polarized molecules into compression tube due to magnetic focusing (10**-7 Torr*l/s)

Ratio of flux into compression tube to the flux through the nozzle (10**-5)

Monte Carlo simulation predict 0.21*10**-5
**PROBLEM**

Why the intensity of the focused beam is going down with the increasing of the flux through the nozzle while the background signal is increasing?

- **Attenuation of the beam by the residual gas**
- Directivity of the flow from the nozzle is falling down with increasing of flux
- **Probably at higher pressure in the nozzle clusters of molecules are produced which not focused by the magnetic field**
ATTENUATION OF THE BEAM BY RESIDUAL GAS

The pumping speed is about 18000 l/s. $S \sim (950 \text{ cm}^2)$
Flux of molecules $4 \cdot 10^{-2} \text{ Torr} \cdot \text{l/s}$.
Pressure $P=2 \cdot 10^{-6} \text{ Torr}$.
Density $2.5 \cdot 10^{11} \text{ mol/cm}^3 (T \sim 70K)$.
Thickness of the residual gas is $n \cdot L = 0.09 \cdot 10^{14} \text{ mol/cm}^2$.
The cross section of $\text{H}_2-\text{H}_2$ scattering is $\sigma = 3 \cdot 10^{-14} \text{ cm}^2$

\[ I=I_0 \cdot \exp(-n \cdot L \cdot \sigma) = I_0 \cdot \exp(-0.27) = I_0 \cdot 0.76 \]
Collision energy distribution

Beam temperature 7 K, gas temperature 77 K

\( \frac{dn}{dE} \) vs. \( E_{\text{c.m.}}, \text{ meV} \)

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Elastic cross section as a function of collision energy.

Future prospect

• Measurement of the nuclear polarization of molecules using Lamb-shift polarimeter
• Understanding the process of the beam attenuation by the residual gas and the reflection of molecules from the cold surface
• Working on the directivity of the molecular beam
• Design the prototype of a new source
MOLECULAR SOURCE WITH LAMB-SHIFT POLARIMETER

POLARIZED MOLECULAR SOURCE

LAMB-SHIFT POLARIMETER

Production and Storage of Polarized H2, D2, and HD Molecules
Presented by Dr. Ralf ENGELS on 10 Sep 2018 at 15:30
Turning of the polarimeter
Conclusion

• The measured flux of focusing molecules is close to the expected one
• More investigation should be done to get optimal molecular flux from the CMBS
• This investigation has been done under the joint RSF-DFG grants № 16-42-01009 and № BU 2227/1-1
A team working on polarized molecular source
Geometry of the proposed 60 pole magnet

$S_{\text{coil}} = 3.92 \text{ cm}^2$

*dimensions are in (mm)*
Possible setup of future polarized hydrogen molecules source

Capillary ring array
area ~ 6000 mm$^2$

Multipole magnet

Turbo pump

Storage cell

D 40 cm

100 cm

200 cm