Экспериментальное и теоретическое изучение спиновой динамики водорода в магнитных полях

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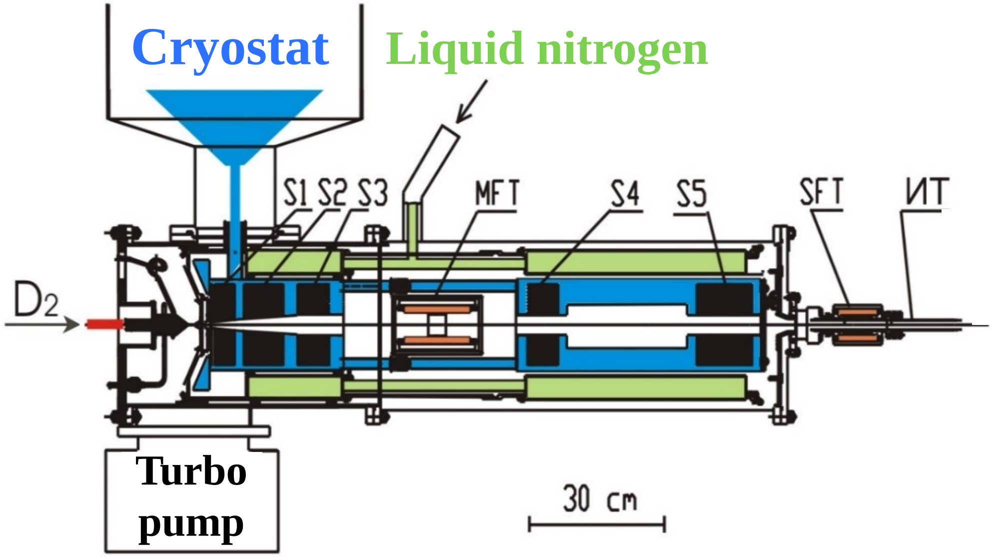
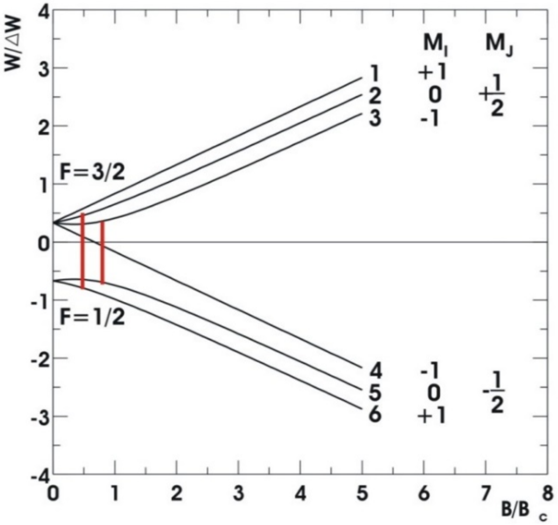
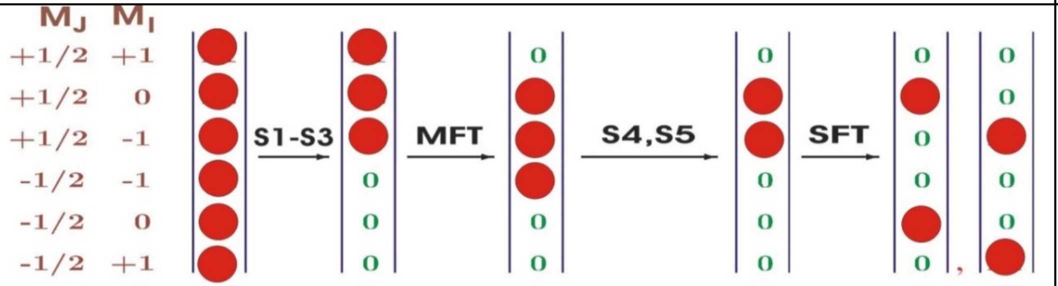
Polarized target at VEPP3 :: Cryogenic Atomic Beam Source

Stern-Gerlach method + adiabatic rf transitions

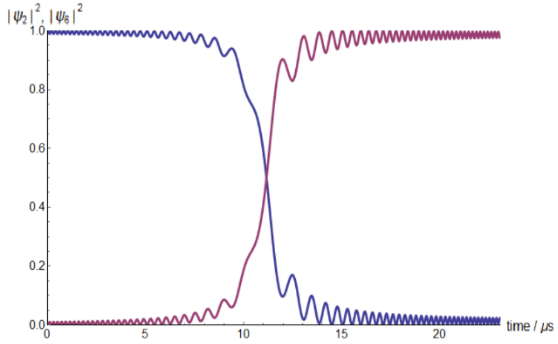






Tensor polarization $P_{zz}=1-3n_0= -2,+1.$

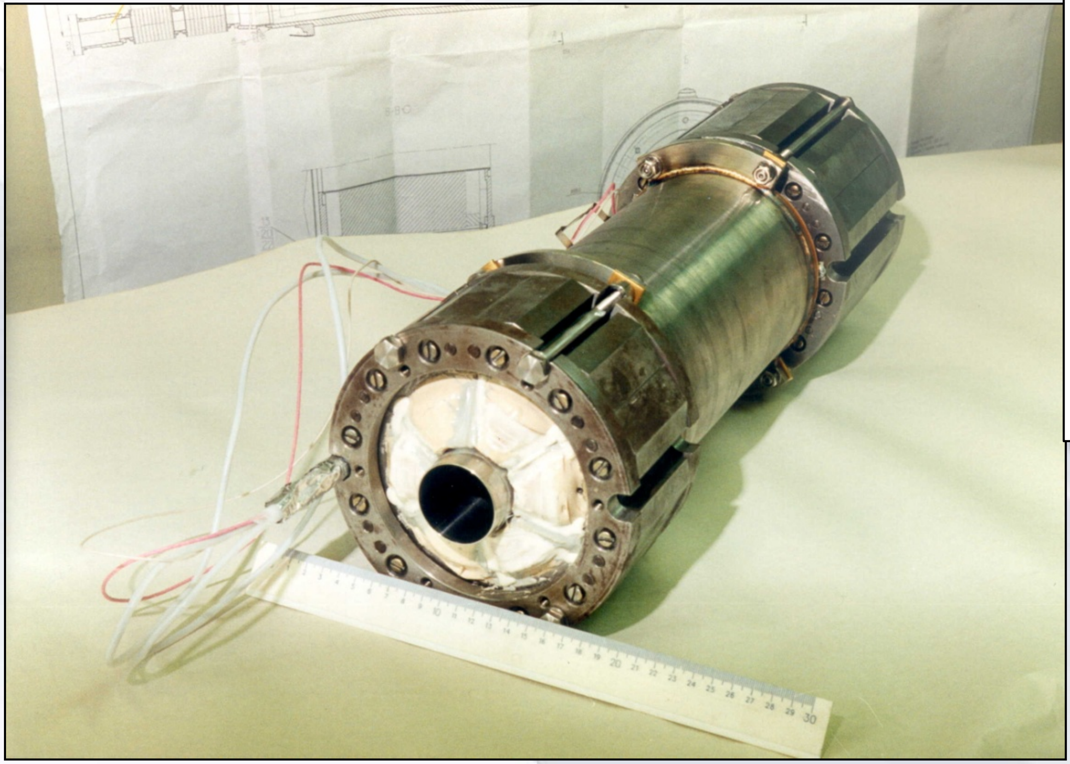
Vector polarization $P_z=n_+-n_- = 0.$

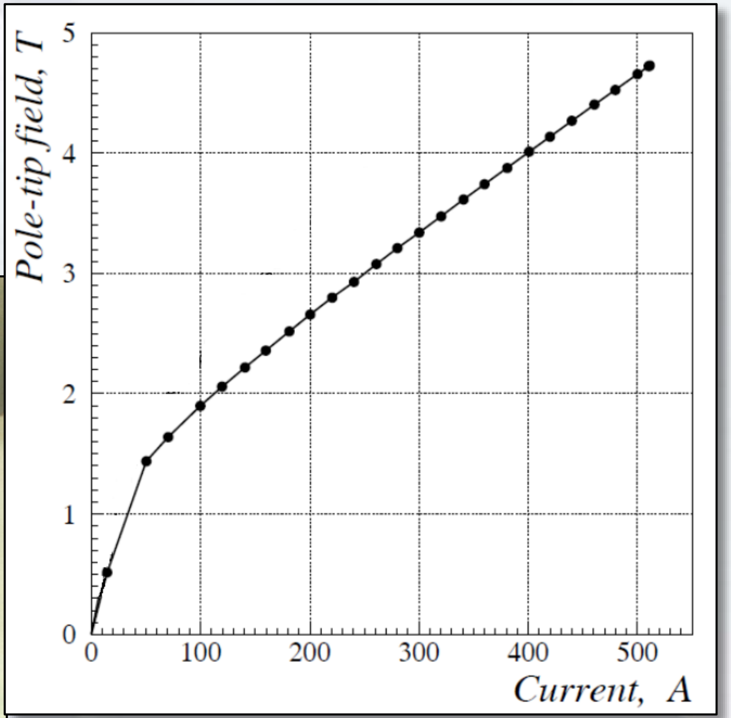


Cryogenic Atomic Beam Source :: Superconducting magnets

Pole tip field of magnets is up to 4.8 T.

Surface of magnets is used as a cryopump.





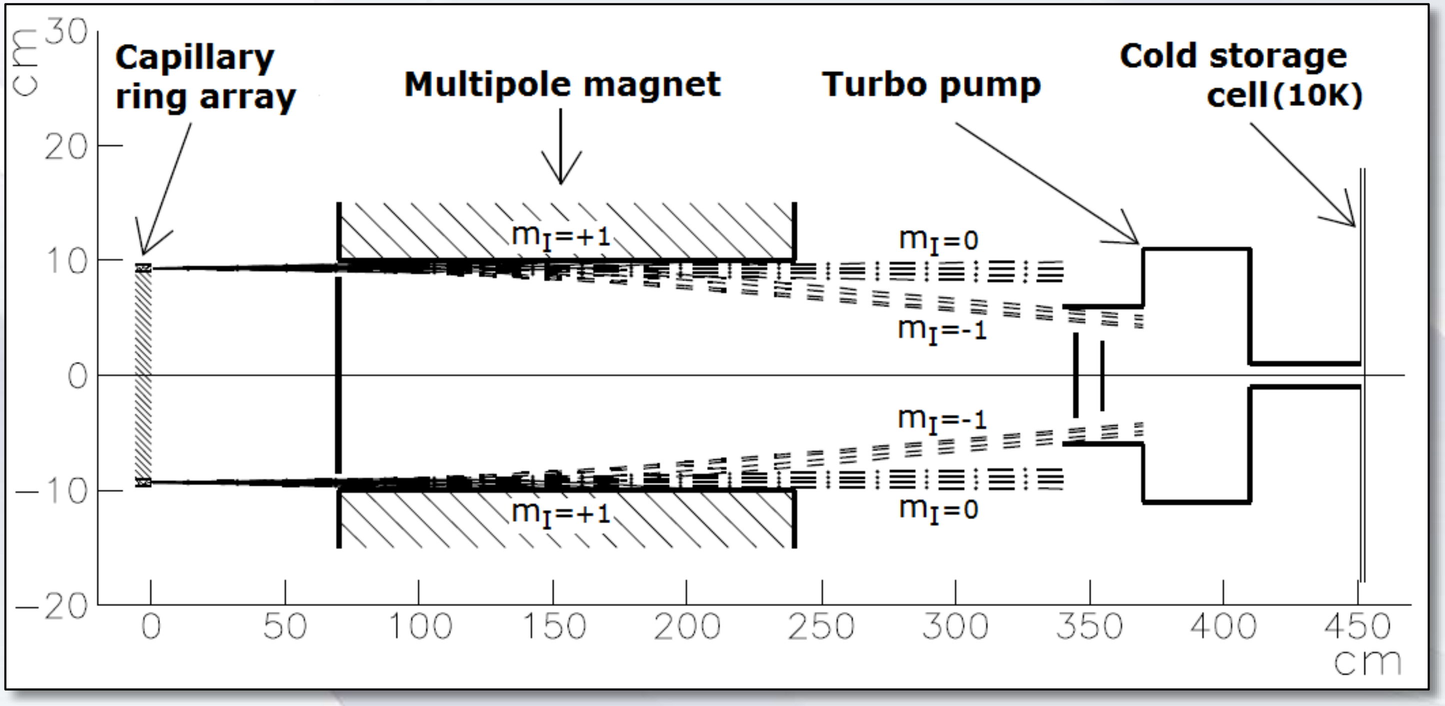
Max. flux = 8.2*10^{16} at./sec.

Intrabeam scattering limits the intensity. (*D.K.Toporkov, Phys. of Part. and Nucl. (2014) v.45, No1, 338-340*)

How to increase the intensity of polarized beam ?

Large aperture → Low beam density → Avoidance of intrabeam scattering

Yu.V.Shestakov et al., “Possibility to obtain a high density polarized ortho-hydrogen gas target”. Proc. of 13th Inter. Symp. on High Energy Spin Phys., Pronvino (1998) p.415 (*Calculated $I \approx 10^{17}$mol./s, yielding $t \approx 10^{15}$mol./cm^2*)



m_I – projection of molecular nuclear spin I. Under normal condition hydrogen is a mixture of 3/4 ortho- (I=1) and 1/4 para- (I=0) states. Total electron spin S=0.

Joint Russian-German project within the RSF-DFG cooperation

“Towards a Molecular Source for Polarized Deuterium Fuel in Nuclear Fusion Research and other Applications”
(2016-2018)

Applicants

on the Russian side:	*on the German side:*
Dr. Dmitri Toporkov, *Budker Institute of Nuclear Physics of Siberian Branch RAS, Novosibirsk*	*Prof. Dr. Markus Buscher,* *Institute of Laser and Plasma Physics, Heinrich Heine University, Dusseldorf.*

The joint project involves the study of the possibility of obtaining of nuclear spin polarized molecules of hydrogen isotopes by their separation in a nonuniform magnetic field.

Polarized fuel for thermonuclear fusion

Enhancement on fusion cross section

The primary reaction for fusion $\mathbf{D+T \rightarrow {}^5He^* \rightarrow {}^4He+n}$ *is dominated by spin 3/2 resonance that is just above the particle decay threshold in compound nuclei* $^5He^*$. *=> Only the 3/2 spin channel contributes to the cross section:*

$$\sigma_{unpol} = \frac{\sum_s (2s+1)\sigma_s}{\sum_s (2s+1)} = \frac{2\sigma_{1/2} + 4\sigma_{3/2}}{6} = \frac{2}{3}\sigma_{3/2}$$

If the incoming particles are both polarized: $gain = \dfrac{\sigma_{pol}}{\sigma_{unpol}} = \dfrac{\sigma_{3/2}}{2/3\sigma_{3/2}} = 1.5$

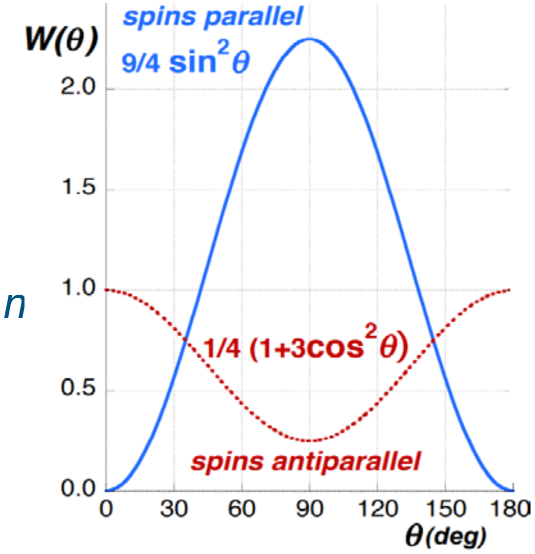
Control of angular distribution of reaction products

Maxwell-averaged cross section for $\mathbf{D + T \rightarrow {}^4He+n}$:

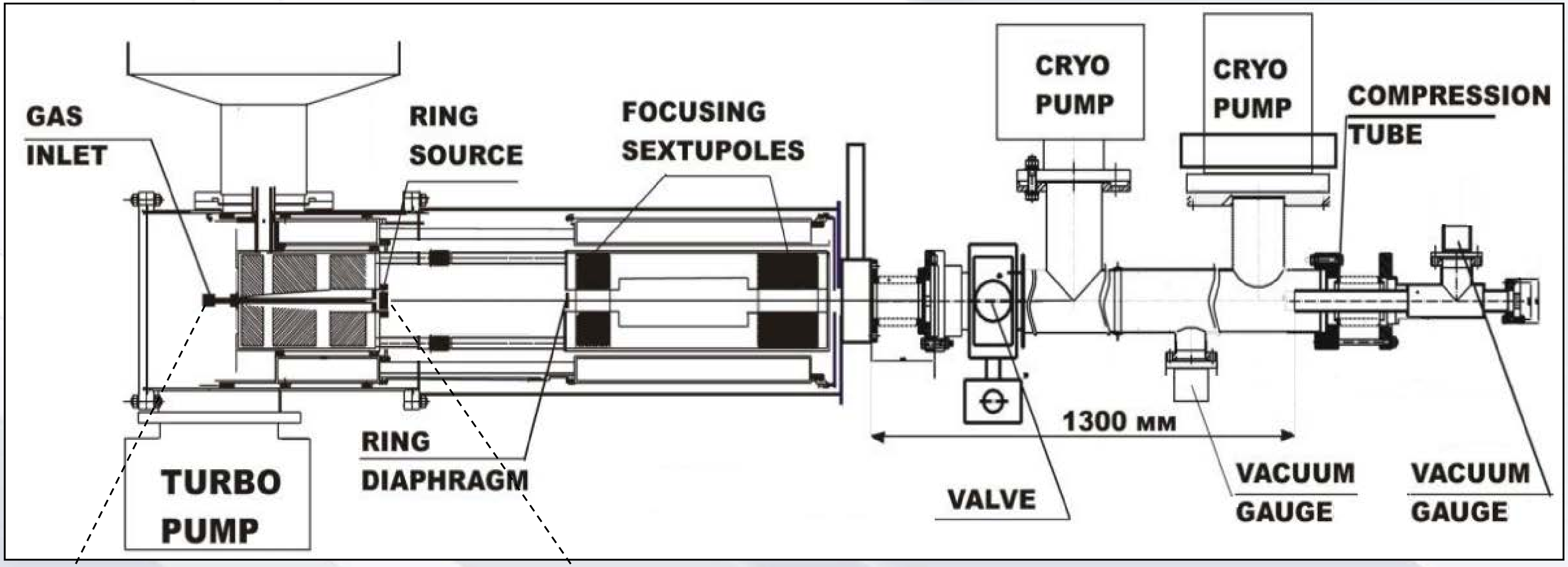
$$\langle d\sigma(\theta)v\rangle = \frac{1}{4\pi}\langle\sigma_0 v\rangle W(\theta) = \frac{1}{4\pi}\langle\sigma_0 v\rangle\Big\{1 - \frac{1}{2}P_D^V P_T + \frac{1}{2}\big[3P_D^V P_T \sin^2\theta + \frac{1}{2}P_D^T(1-3\cos^2\theta)\big]\Big\}$$

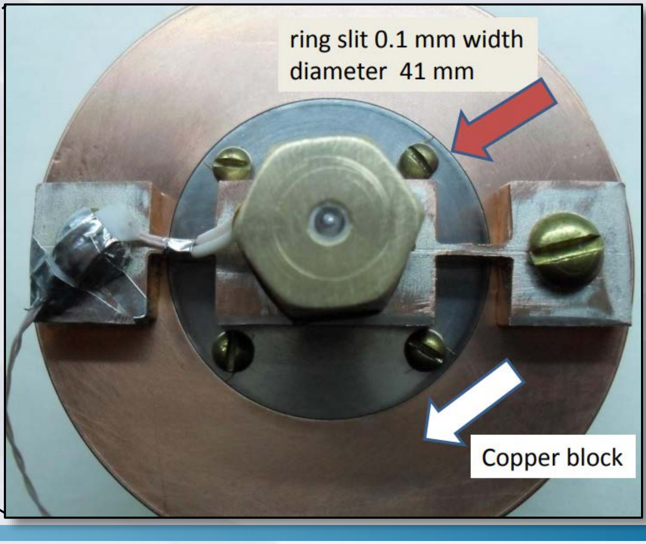
P_T *is the triton polarization,* P_D^V *and* P_D^V *are the deuteron vector and tensor polarizations, angle* θ *is measured relative to magnetic field.*

(A.M.Sandorfi, et al., arXiv:1703.06165v1 [physics.plasm-ph] 2017)

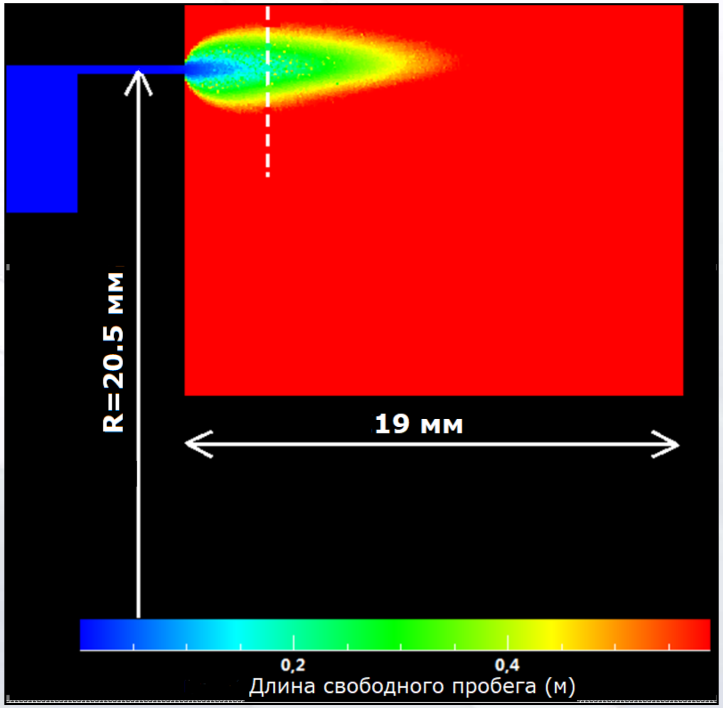


Experimental setup to obtain polarized molecules





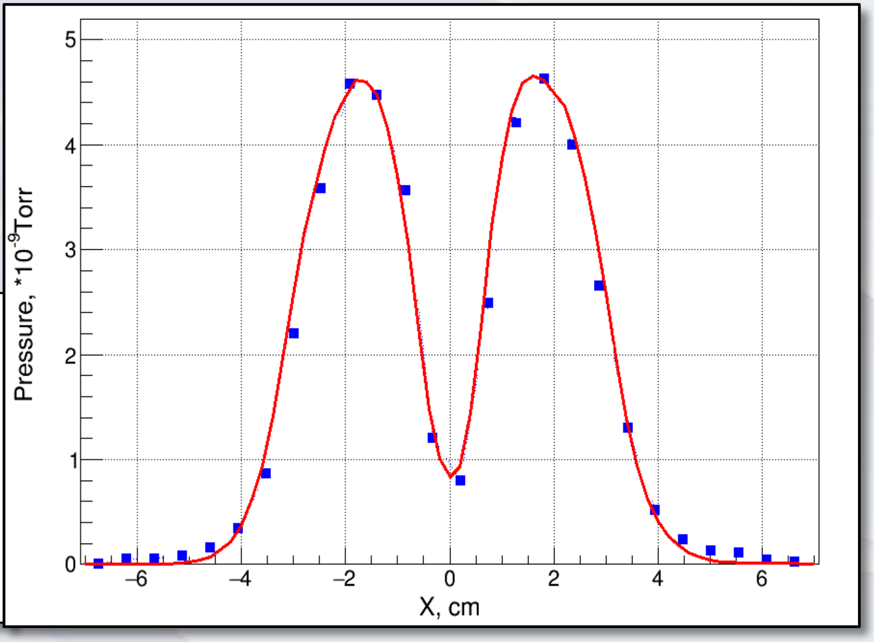
Profile of the molecular beam



The DSMC method was used to calculate the dynamics of the H_2 outflow through a ring nozzle.

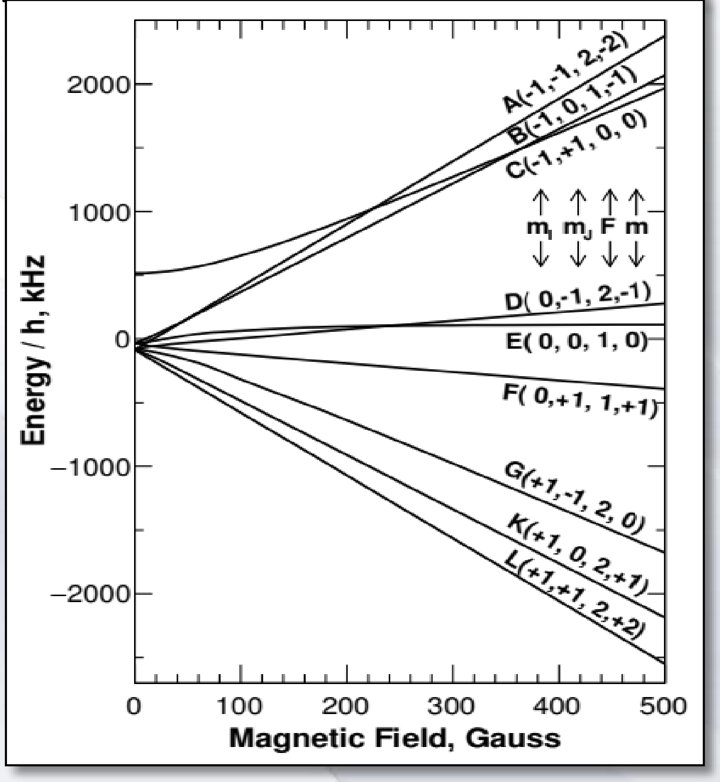
*Molecules interacting with the inner surface of the magnets, subject to **2 h sin(Θ) « λ**, are reflected specularly.*

Right figure shows the pressure (blue points) measured by the CT as a function of the CT position. The position of compressing tube is changed in the direction perpendicular to the molecular jet. Red curve is the results of simulation.

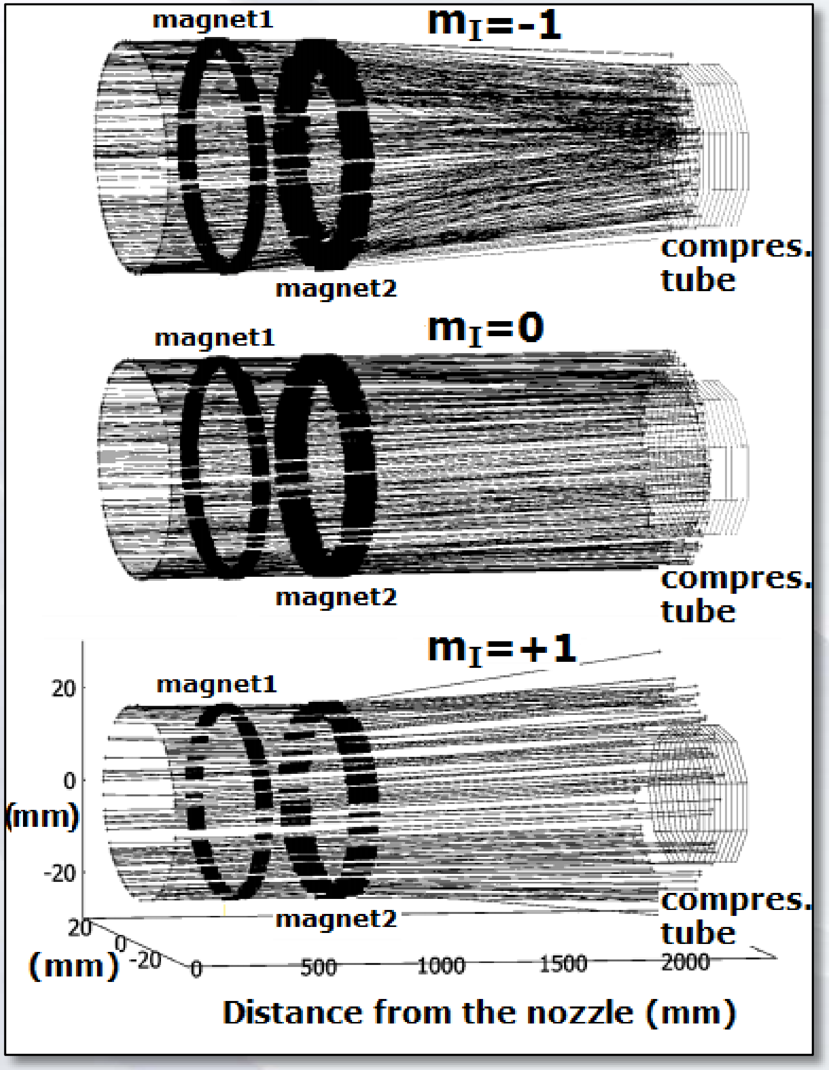


Monte Carlo ray tracing simulation

Energies of H_2 states as a function of magnetic field.



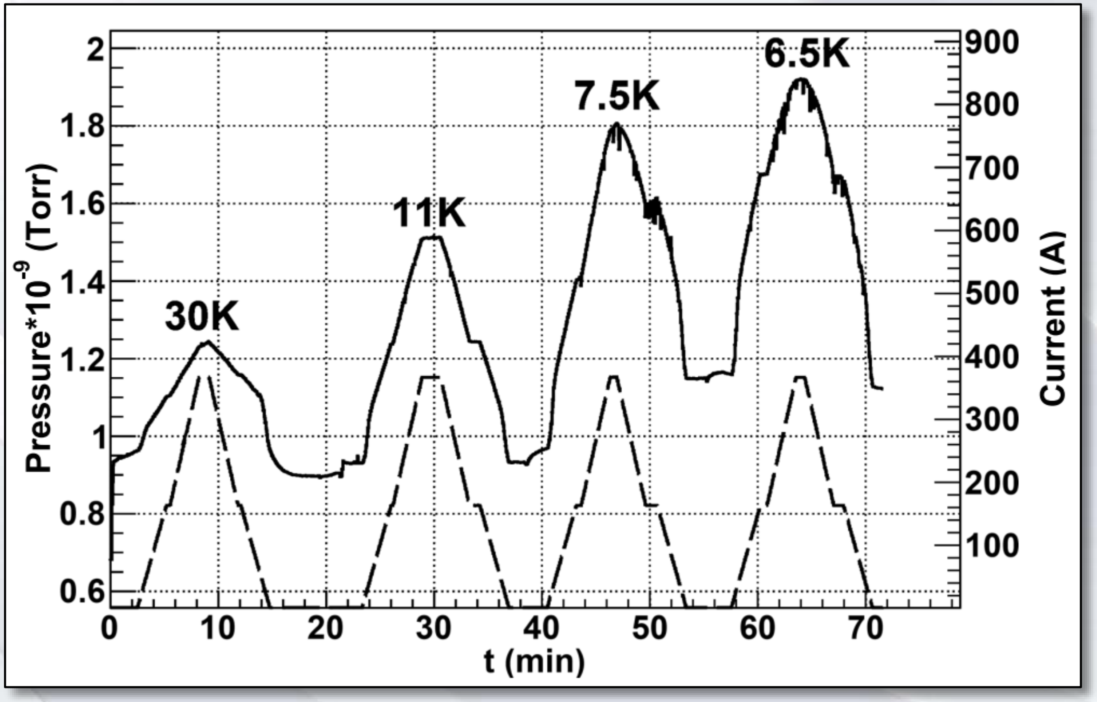
Only molecules in the states A,B,C with $m_I=-1$, which are focused can enter the CT.



Experimental setup to obtain polarized molecules

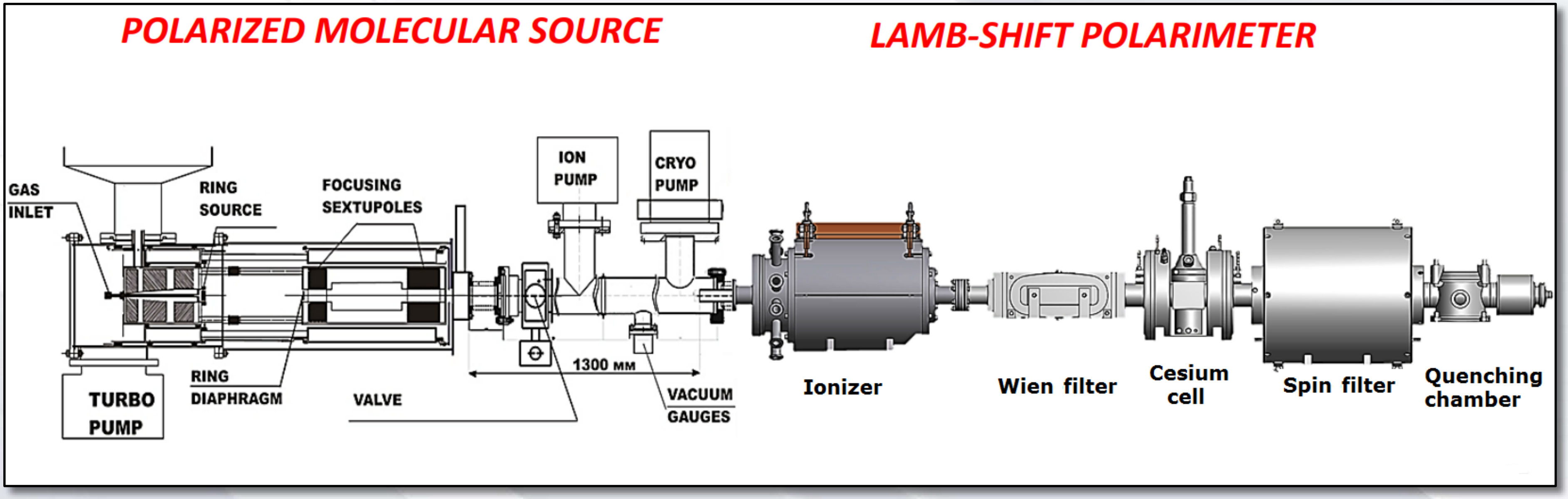
Experimental results :: Intensity of H_2 beam while ramping the magnet

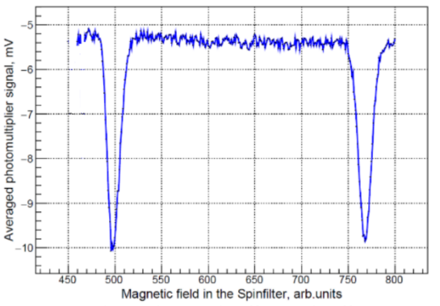
Figure shows the experimental result on the pressure change in the CT for a H_2 molecular beam, when the current through the magnets was turned on and off. The measurements were done at different temperature of the nozzle.



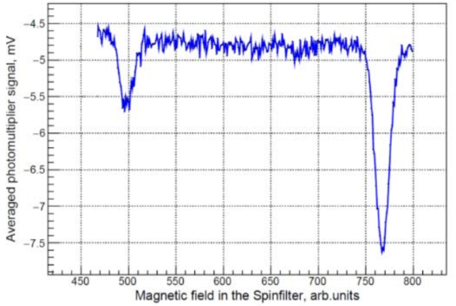
The conductance of the CT and the sensitivity of the vacuum gauge to the given gas are known. => It is possible to determine the flux of focused (polarized) molecules. $I_{max} \approx 3\cdot10^{12}$ mol./sec.

Polarization measurement with the LSP

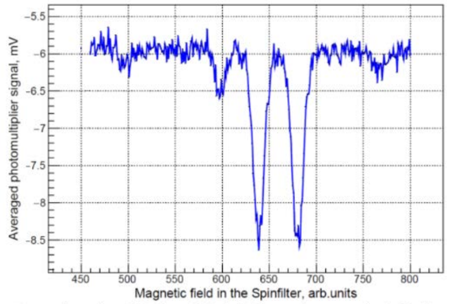




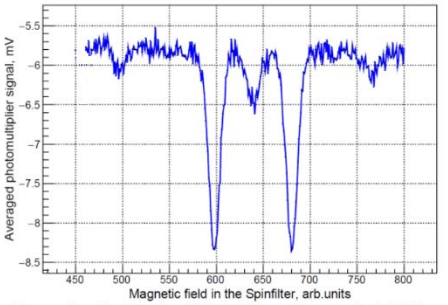
Hydrogen jet. WF is off, MFT is off



Hydrogen jet. WF is off, MFT is on (current is 0.17A).

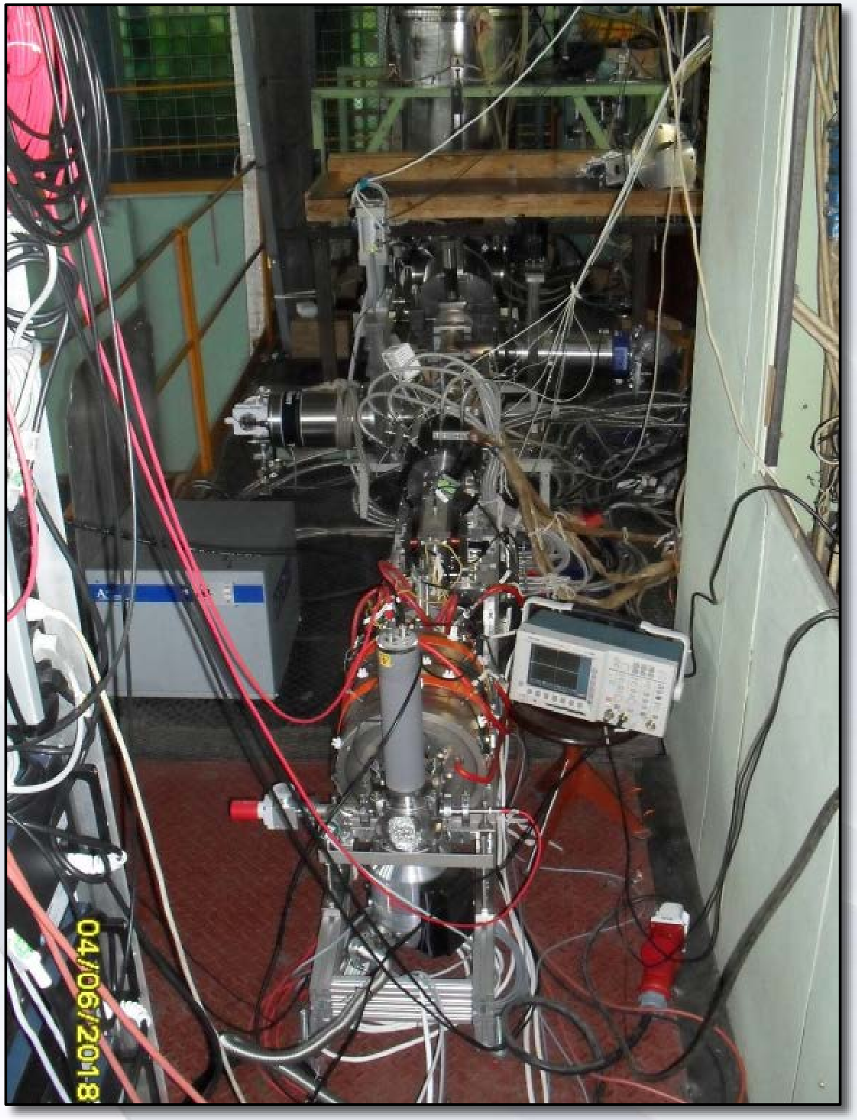


Deuterium jet. WF is off, MFT is on (current is 0.32A).



Deuterium jet. WF is off, MFT is on (current is 0.25A).

Photo of the Lamb-Shift Polarimeter in Novosibirsk



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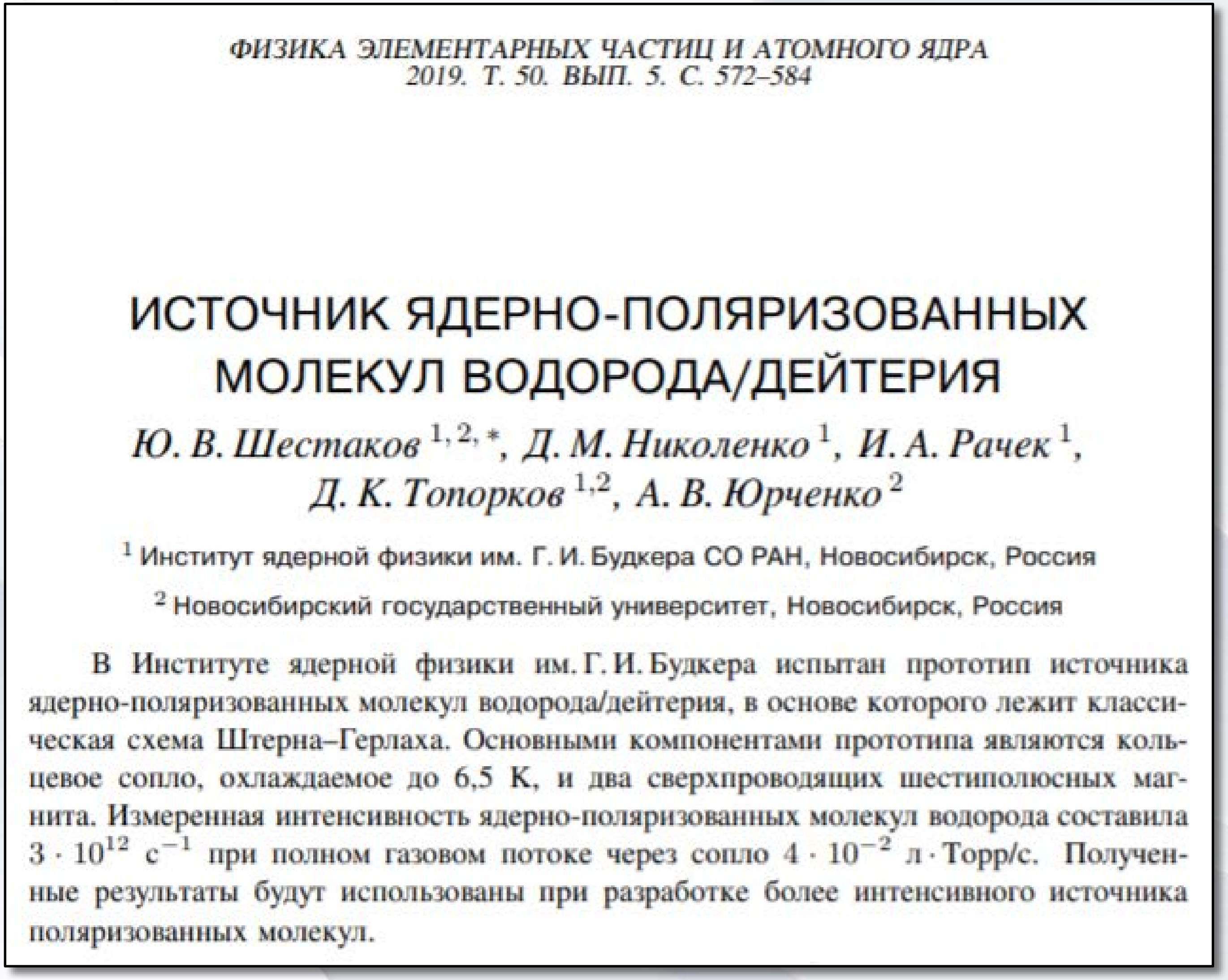

ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2019. Т. 50. ВЫП. 5. С. 572–584

ИСТОЧНИК ЯДЕРНО-ПОЛЯРИЗОВАННЫХ МОЛЕКУЛ ВОДОРОДА/ДЕЙТЕРИЯ

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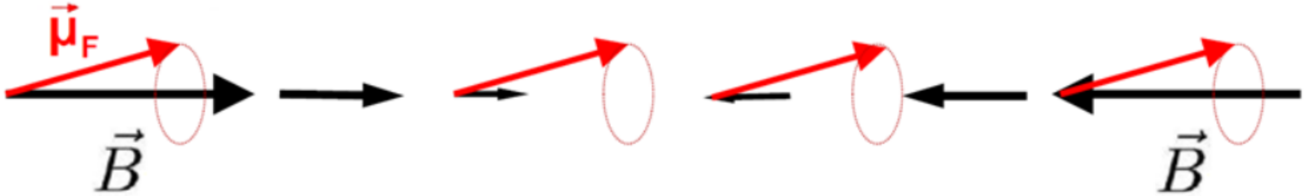
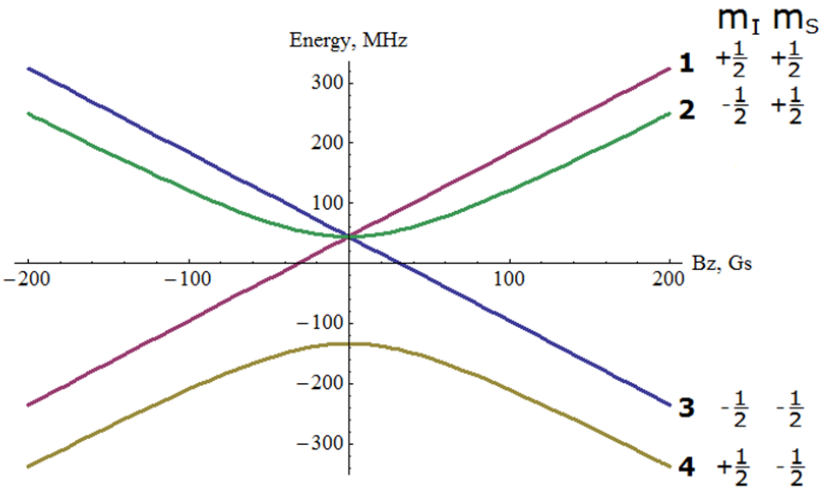
В Институте ядерной физики им. Г. И. Будкера испытан прототип источника ядерно-поляризованных молекул водорода/дейтерия, в основе которого лежит классическая схема Штерна–Герлаха. Основными компонентами прототипа являются кольцевое сопло, охлаждаемое до 6,5 К, и два сверхпроводящих шестиполюсных магнита. Измеренная интенсивность ядерно-поляризованных молекул водорода составила $3 \cdot 10^{12}$ с$^{-1}$ при полном газовом потоке через сопло $4 \cdot 10^{-2}$ л · Торр/с. Полученные результаты будут использованы при разработке более интенсивного источника поляризованных молекул.

Квантовый интерферометр на основе ИПА и Сона-переходов

Переход между энергетическими уровнями при прохождении области с нулевым магнитным полем (Сона-переход).

Идеальный случай





Реальный пучок атомов имеет поперечный размер => возникает B_r

$$div(B)=0 \quad => \quad B_r=-(dB_z/dz)r/2$$

Квантовый интерферометр на основе ИПА и Сона-переходов

$$\begin{pmatrix}1\\0\end{pmatrix} \longrightarrow \begin{pmatrix}\mathrm{Cos}\left[\frac{\theta}{2}\right]\\ e^{i\delta}\,\mathrm{Sin}\left[\frac{\theta}{2}\right]\end{pmatrix} \longrightarrow \begin{pmatrix}e^{\frac{-iE1t}{\hbar}}\,\mathrm{Cos}\left[\frac{\theta}{2}\right]\\ e^{\frac{-iE3t}{\hbar}}\,e^{i\delta}\,\mathrm{Sin}\left[\frac{\theta}{2}\right]\end{pmatrix} \to \begin{pmatrix}\mathrm{Cos}\left[\frac{\theta}{2}\right] & e^{-i\delta}\,\mathrm{Sin}\left[\frac{\theta}{2}\right]\\ e^{i\delta}\,\mathrm{Sin}\left[\frac{\theta}{2}\right] & -\mathrm{Cos}\left[\frac{\theta}{2}\right]\end{pmatrix} \cdot \begin{pmatrix}e^{\frac{-iE1t}{\hbar}}\,\mathrm{Cos}\left[\frac{\theta}{2}\right]\\ e^{\frac{-iE3t}{\hbar}}\,e^{i\delta}\,\mathrm{Sin}\left[\frac{\theta}{2}\right]\end{pmatrix} =$$

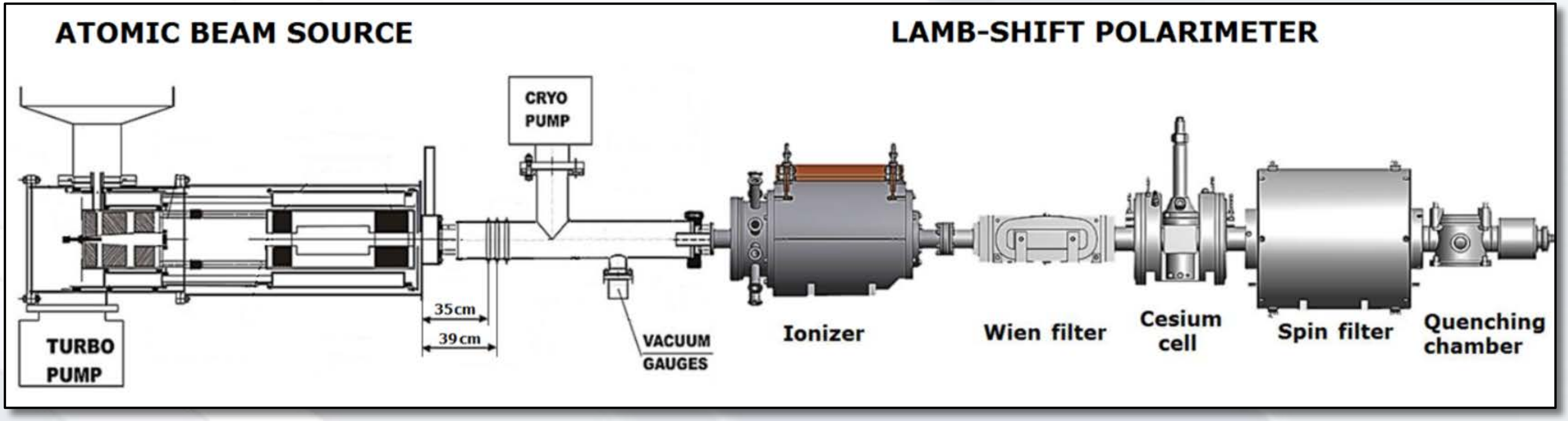
$$= \begin{pmatrix}e^{\frac{-iE1t}{\hbar}}\,\mathrm{Cos}\left[\frac{\theta}{2}\right]^2 + e^{\frac{-iE3t}{\hbar}}\,\mathrm{Sin}\left[\frac{\theta}{2}\right]^2\\ e^{i\delta-\frac{iE1t}{\hbar}}\,\mathrm{Cos}\left[\frac{\theta}{2}\right]\mathrm{Sin}\left[\frac{\theta}{2}\right] - e^{i\delta-\frac{iE3t}{\hbar}}\,\mathrm{Cos}\left[\frac{\theta}{2}\right]\mathrm{Sin}\left[\frac{\theta}{2}\right]\end{pmatrix}$$

Если $\theta = \frac{\pi}{2} \Longrightarrow \mathrm{Cos}\left[\frac{\theta}{2}\right] = \mathrm{Sin}\left[\frac{\theta}{2}\right] = \frac{1}{\sqrt{2}}$ *и*

$$\mathrm{W1} = \frac{1}{2}\left(1 + \mathrm{Cos}\left[\frac{\Delta E t}{\hbar}\right]\right) = \frac{1}{2}\left(1 + \mathrm{Cos}\left[\frac{2\,\mu_B\,B}{\hbar}\,t\right]\right);$$

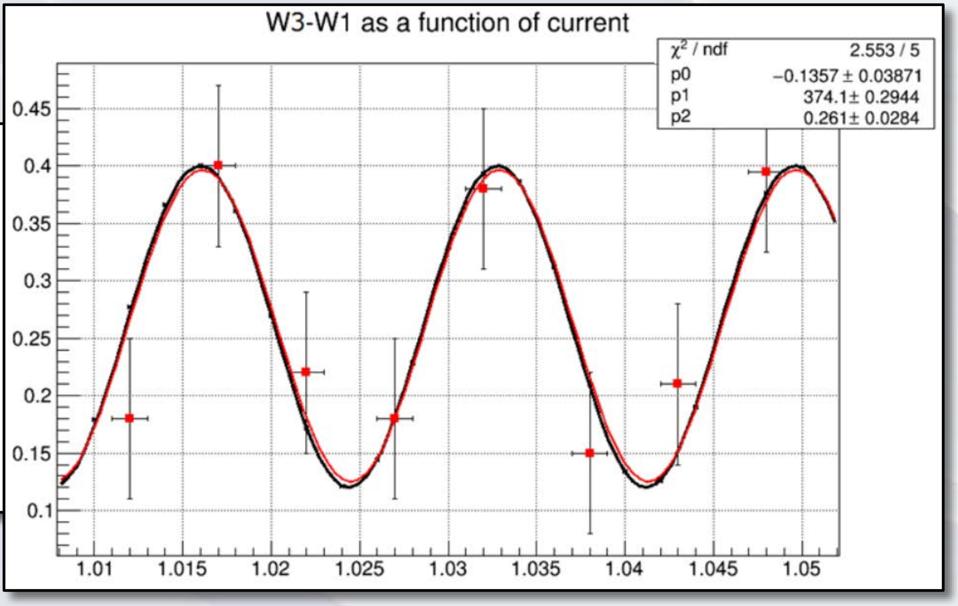
$$\mathrm{W3} = \frac{1}{2}\left(1 - \mathrm{Cos}\left[\frac{\Delta E t}{\hbar}\right]\right) = \frac{1}{2}\left(1 - \mathrm{Cos}\left[\frac{2\,\mu_B\,B}{\hbar}\,t\right]\right).$$

Квантовый интерферометр на основе ИПА и Сона-переходов

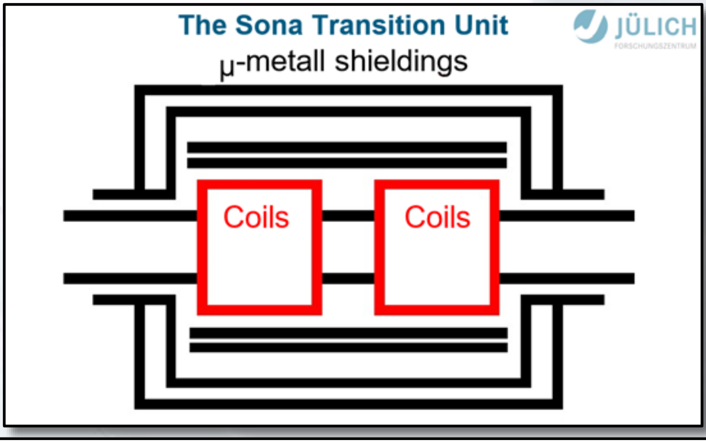


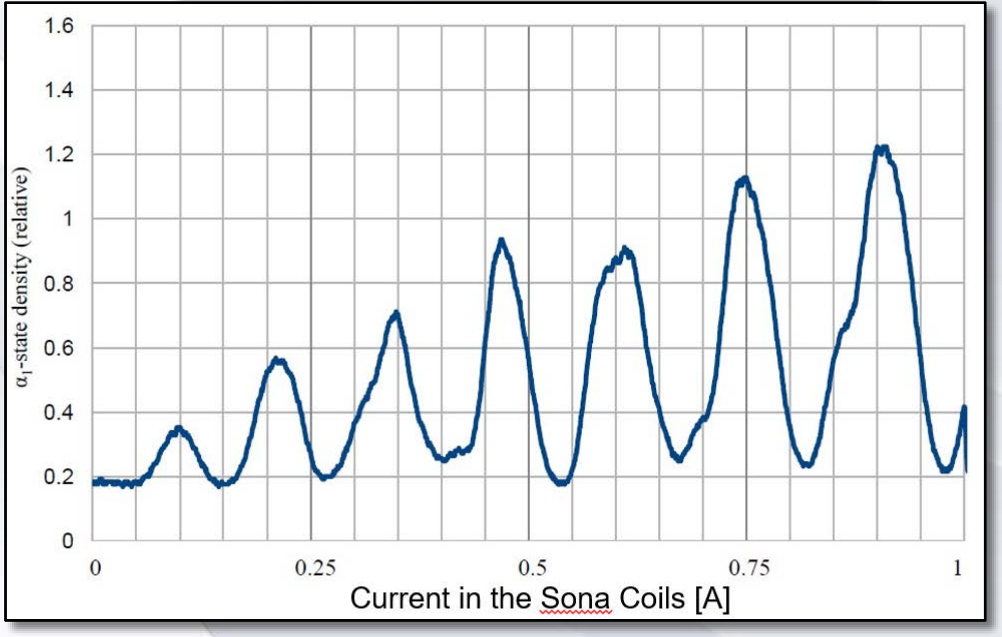
Результаты первых измерений:

- низкая чувствительность поляриметра;
- плохая экранировка от внешнего магнитного поля;
- магнитные свойства нержавеющей трубы влияют на проникновение магнитного поля.



Наблюдение осцилляций в Юлихе (Германия)





См. http://hepd.pnpi.spb.ru/hepd/events/abstract/2018/Talk.LSP.PNPI.2018.pdf

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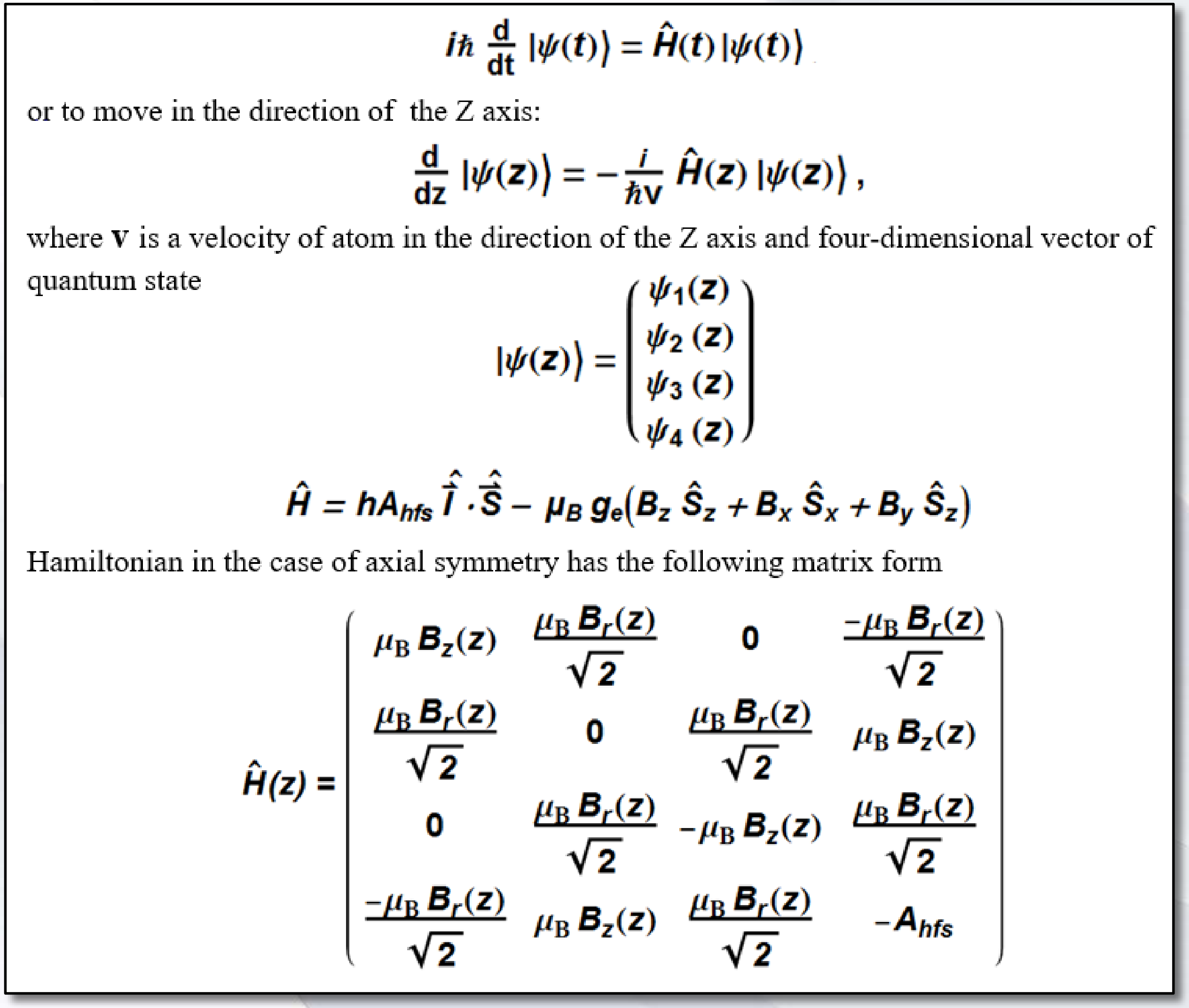


$$i\hbar\frac{\mathrm{d}}{\mathrm{dt}}|\psi(t)\rangle = \hat{H}(t)\,|\psi(t)\rangle$$

or to move in the direction of the Z axis:

$$\frac{\mathrm{d}}{\mathrm{dz}}|\psi(z)\rangle = -\frac{i}{\hbar v}\hat{H}(z)\,|\psi(z)\rangle\,,$$

where **v** is a velocity of atom in the direction of the Z axis and four-dimensional vector of quantum state

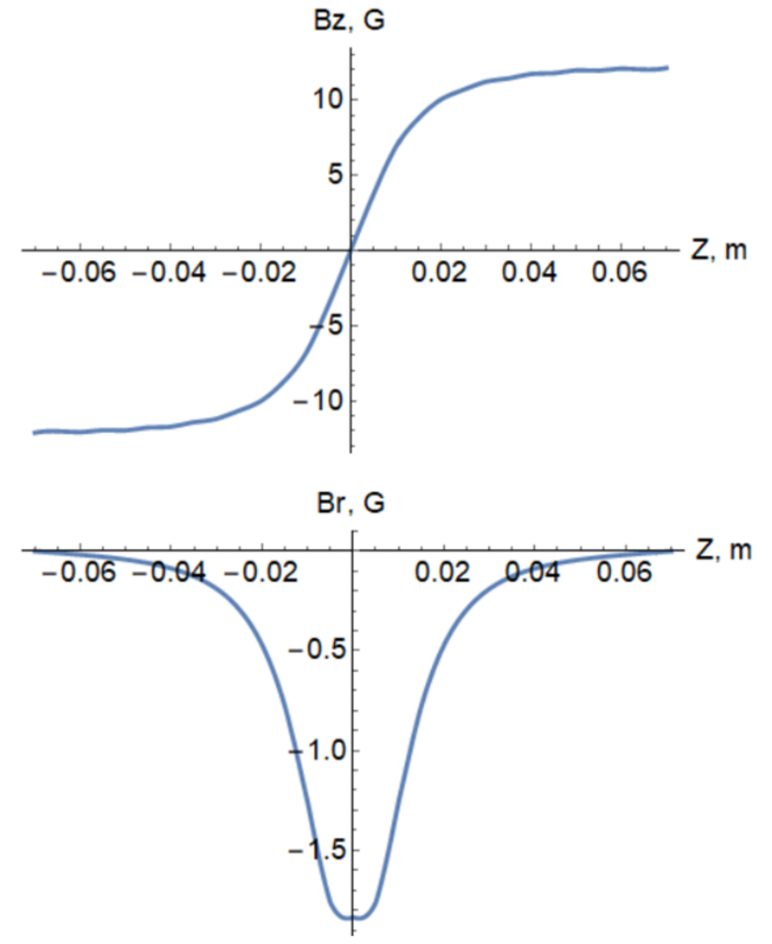
$$|\psi(z)\rangle = \begin{pmatrix}\psi_1(z)\\ \psi_2(z)\\ \psi_3(z)\\ \psi_4(z)\end{pmatrix}$$

$$\hat{H} = hA_{hfs}\,\hat{\vec{I}}\cdot\hat{\vec{S}} - \mu_B\,g_e\left(B_z\,\hat{S}_z + B_x\,\hat{S}_x + B_y\,\hat{S}_z\right)$$

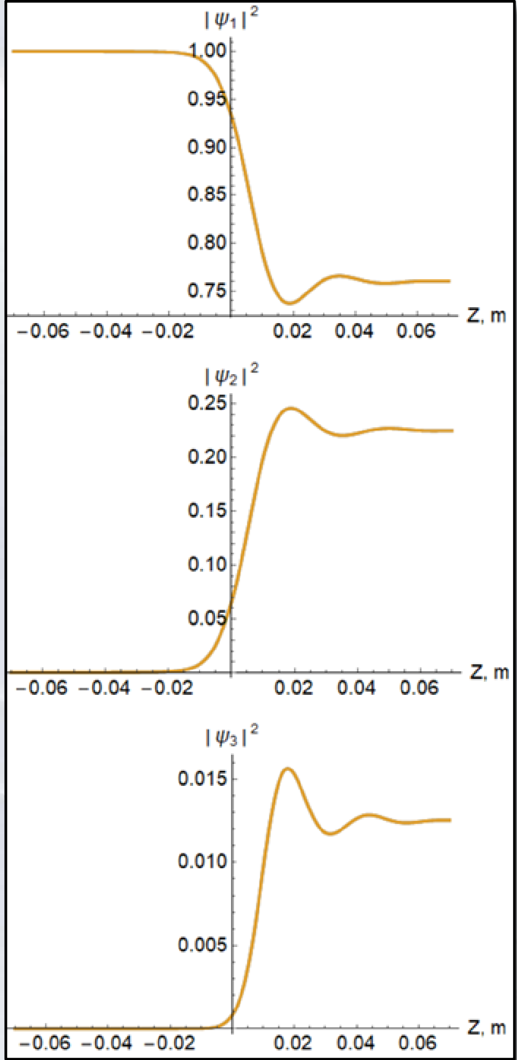
Hamiltonian in the case of axial symmetry has the following matrix form

$$\hat{H}(z) = \begin{pmatrix} \mu_B B_z(z) & \frac{\mu_B B_r(z)}{\sqrt{2}} & 0 & \frac{-\mu_B B_r(z)}{\sqrt{2}} \\ \frac{\mu_B B_r(z)}{\sqrt{2}} & 0 & \frac{\mu_B B_r(z)}{\sqrt{2}} & \mu_B B_z(z) \\ 0 & \frac{\mu_B B_r(z)}{\sqrt{2}} & -\mu_B B_z(z) & \frac{\mu_B B_r(z)}{\sqrt{2}} \\ \frac{-\mu_B B_r(z)}{\sqrt{2}} & \mu_B B_z(z) & \frac{\mu_B B_r(z)}{\sqrt{2}} & -A_{hfs} \end{pmatrix}$$

Наблюдение осцилляций в Юлихе (Германия)



Components of magnetic field vs Z (axis along the motion of atoms) at r=5mm. Current through the coils is 10A.



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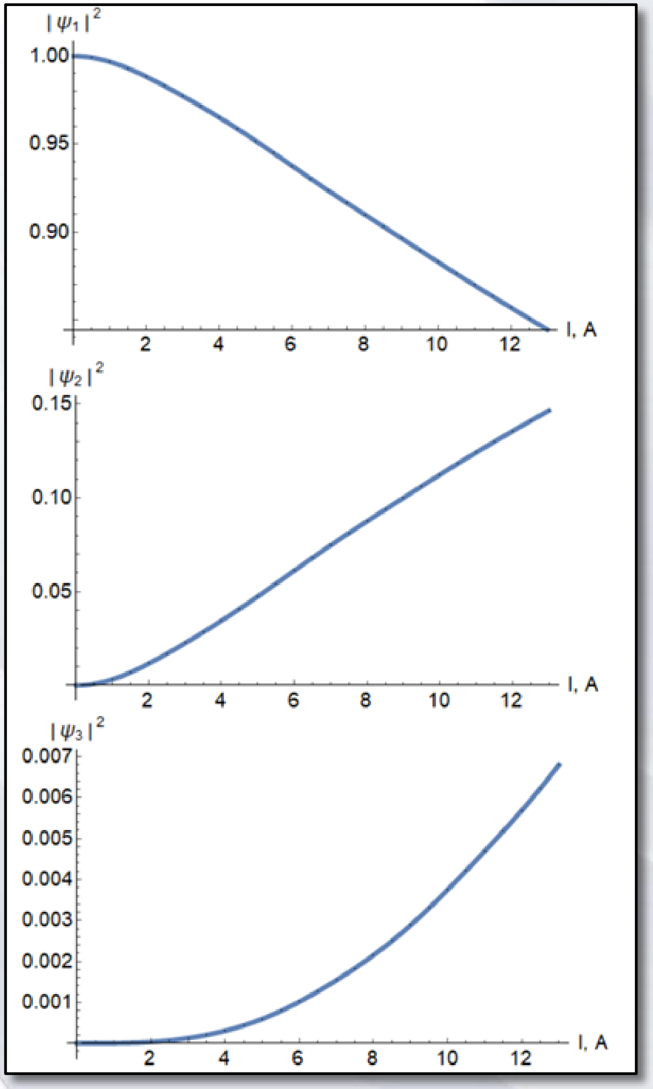

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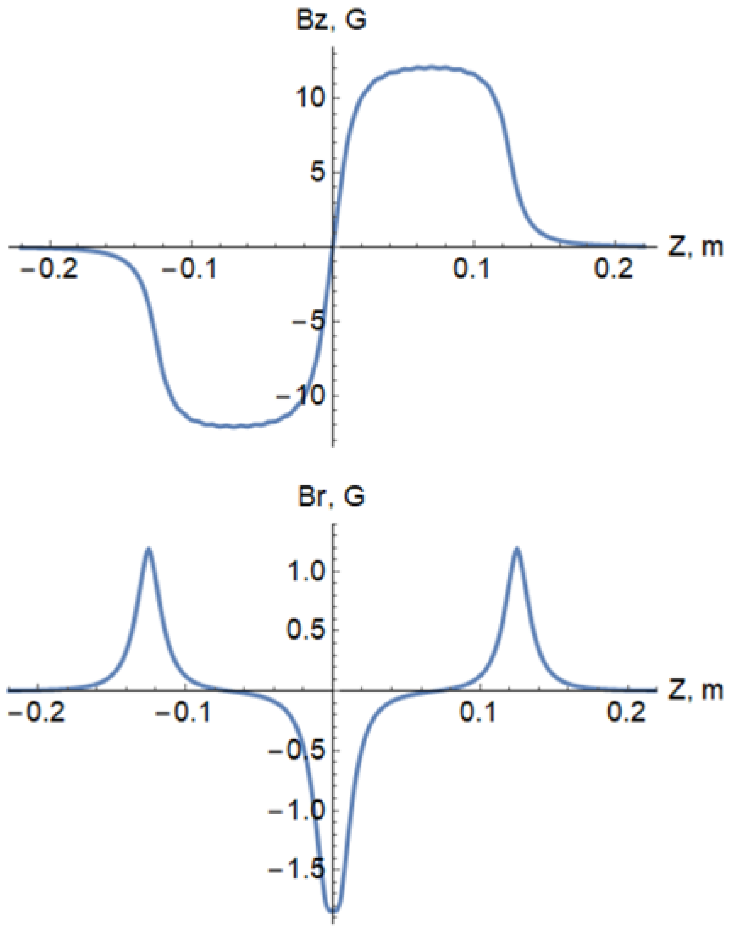

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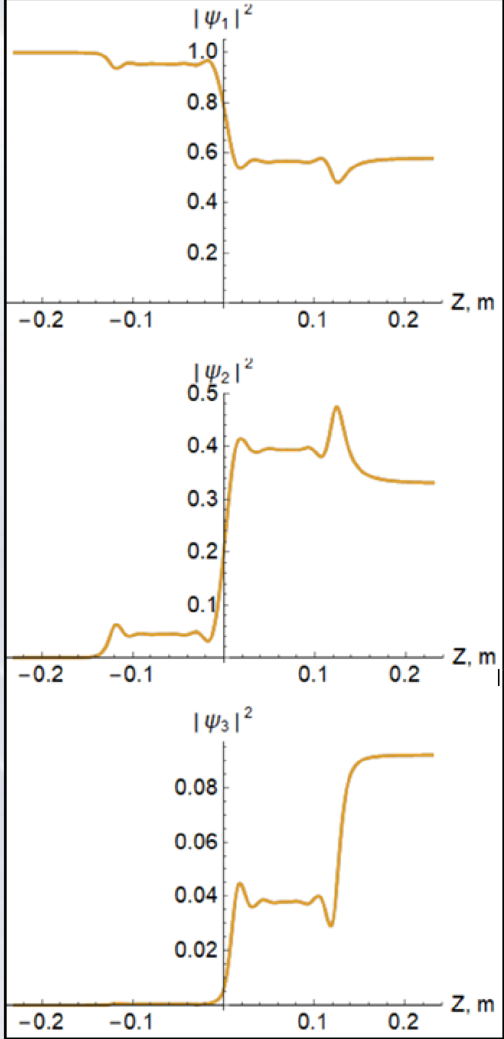
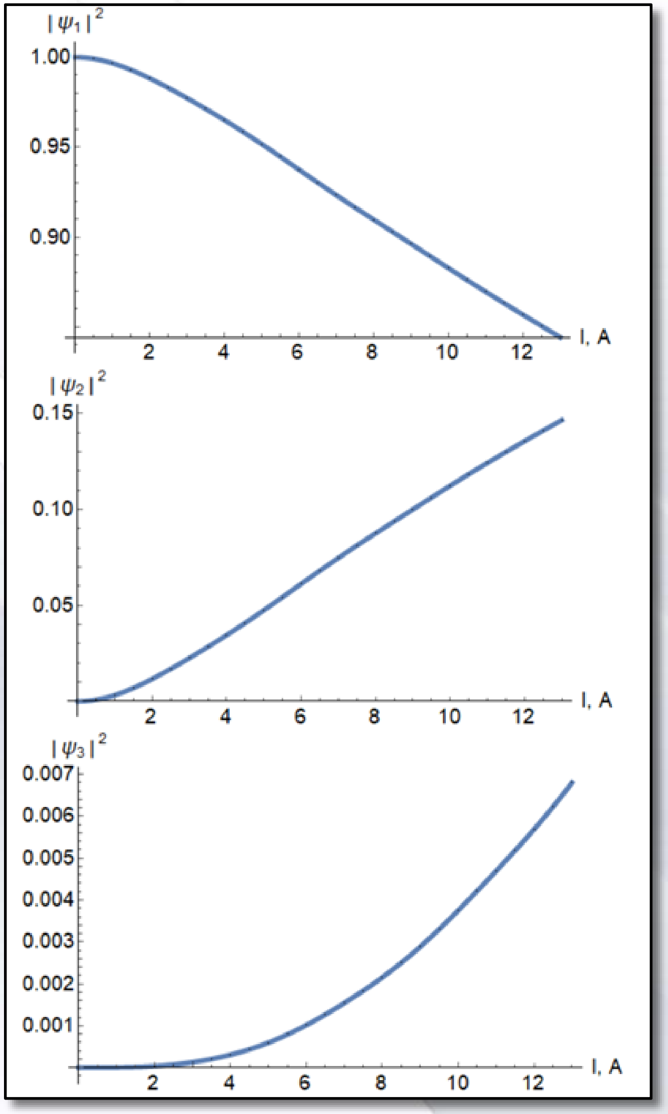
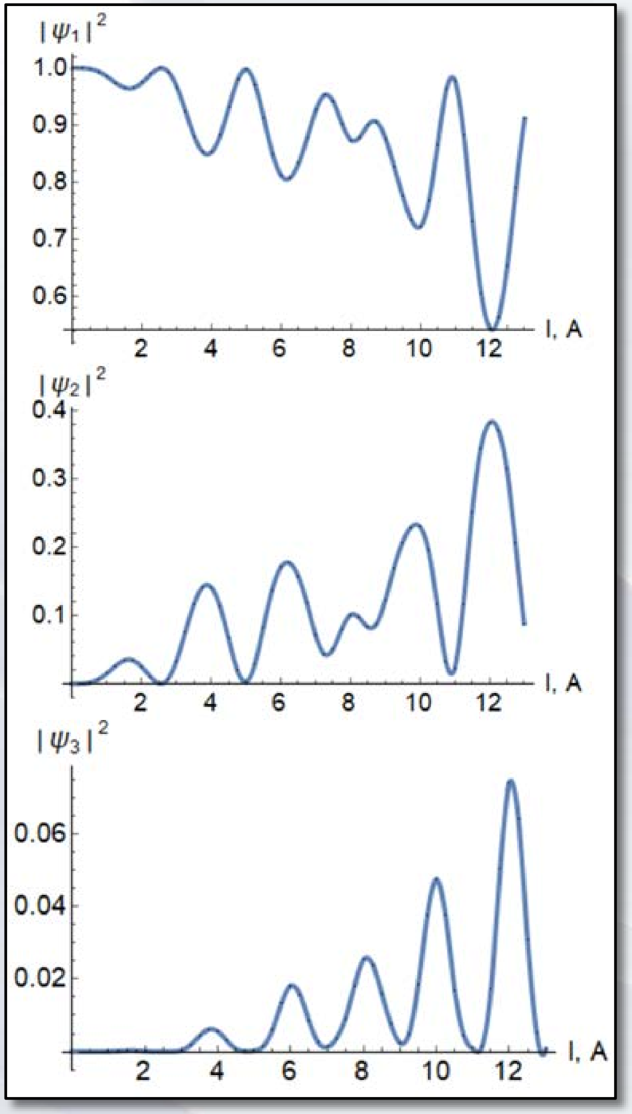


Наблюдение осцилляций в Юлихе (Германия)





Сравнение двух расчетов

Синяя кривая – численное решение ур-ния Шрёдингера.

Оранжевая кривая – матричный расчет по выше описанной схеме квантового интерферометра.

Частица со спином 1 описывается тремя базисными состояниями, соответствующими трем собственным значениям оператора S_z

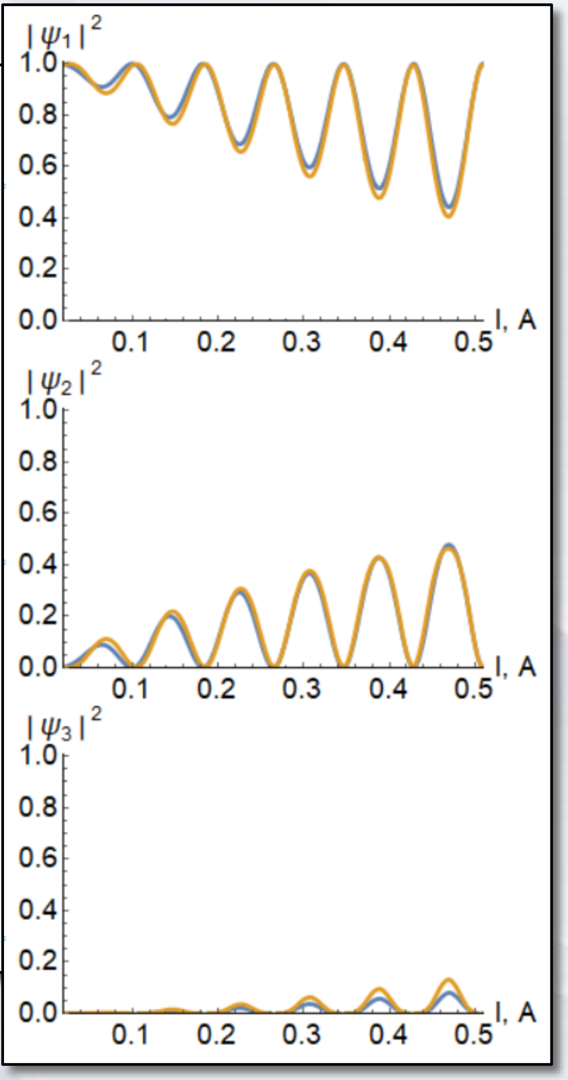
$$\begin{pmatrix}1\\0\\0\end{pmatrix},\ \begin{pmatrix}0\\1\\0\end{pmatrix},\ \begin{pmatrix}0\\0\\1\end{pmatrix}.$$

При этом операторы S_x S_y и S_z задаются матрицами:

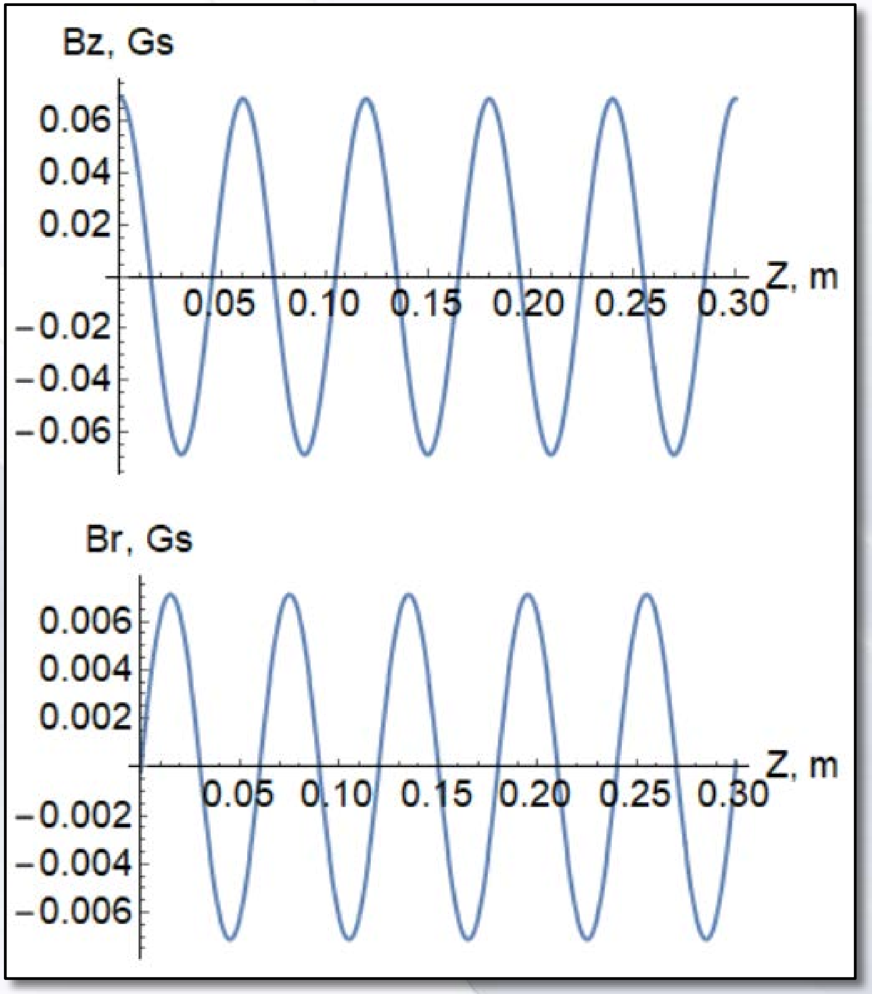
$$S_x = \frac{1}{2^{1/2}}\begin{pmatrix}0&1&0\\1&0&1\\0&1&0\end{pmatrix},\ S_y = \frac{i}{2^{1/2}}\begin{pmatrix}0&-1&0\\1&0&-1\\0&1&0\end{pmatrix},\ S_z = \begin{pmatrix}1&0&0\\0&0&0\\0&0&-1\end{pmatrix}.$$

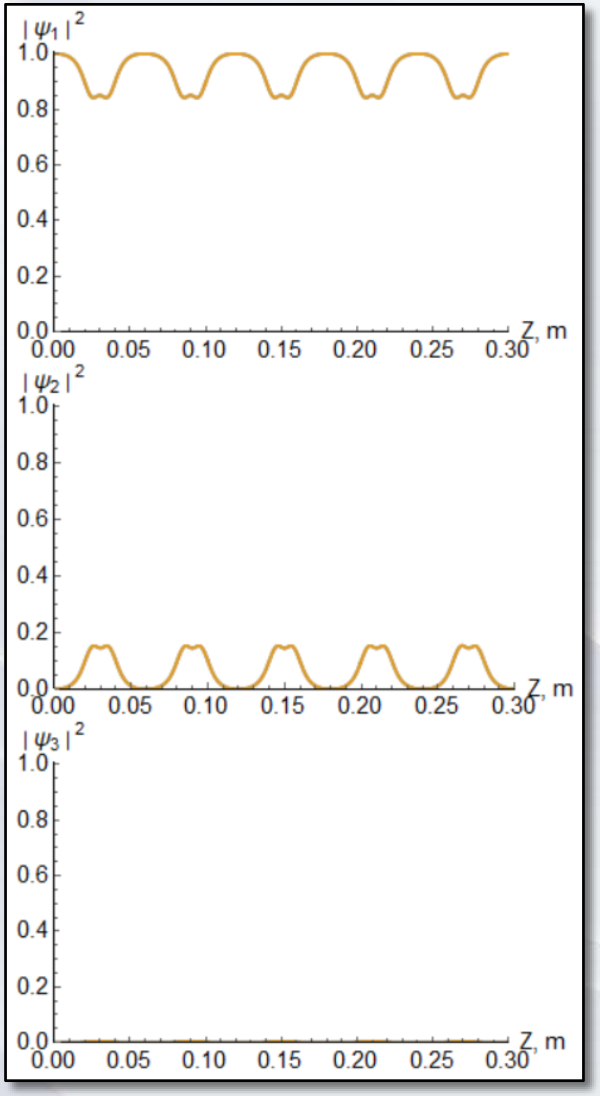
Поворот вектора состояния:

$$\psi' = e^{-i\theta S_j}\,\psi$$

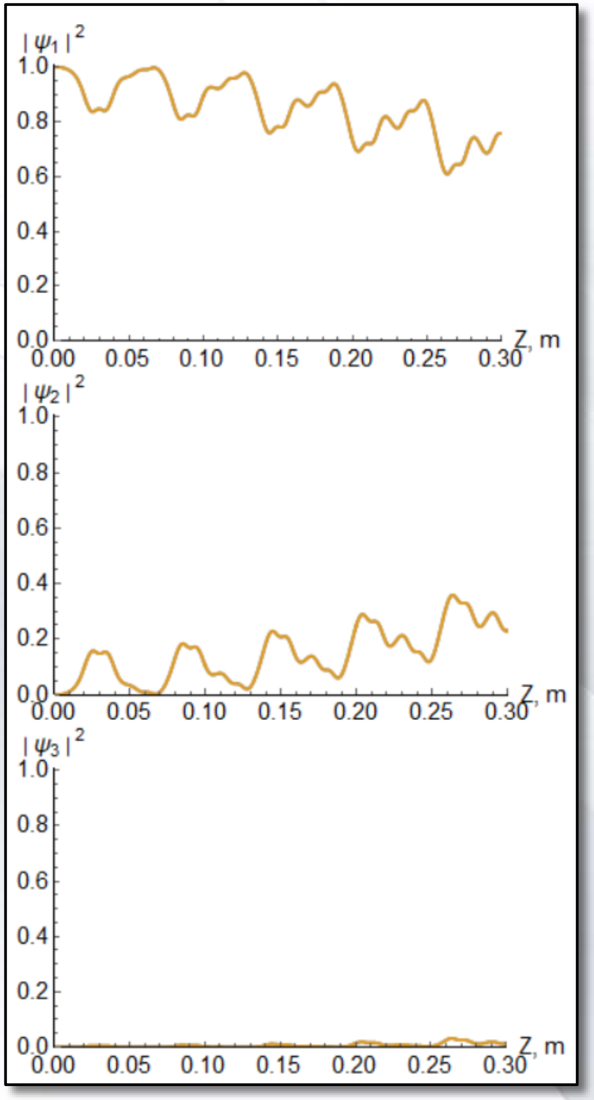


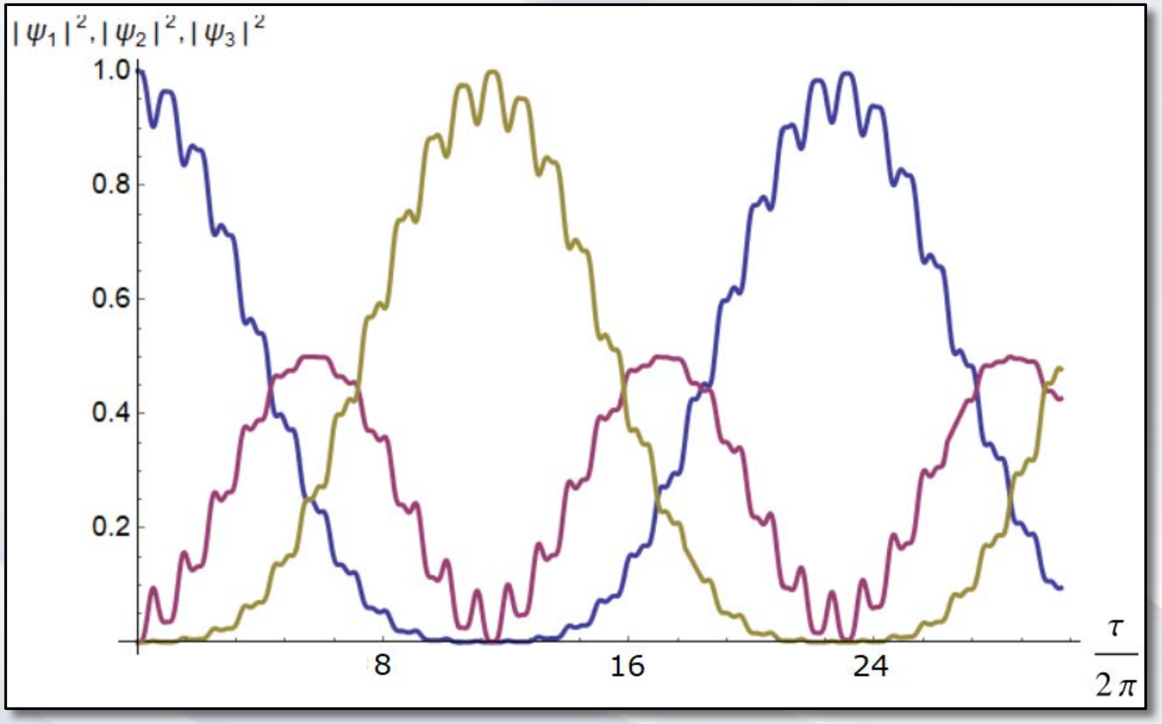
Спиновая динамика H_1 в периодическом магнитном поле





Спиновая динамика H_1 в периодическом магнитном поле





Спиновая динамика H_1 в периодическом магнитном поле

$$H_z(t) = H_0 \sin(kvt)\,, \quad H_\rho = -\frac{1}{2}k\rho\, H_0 \cos(kvt)\,.$$

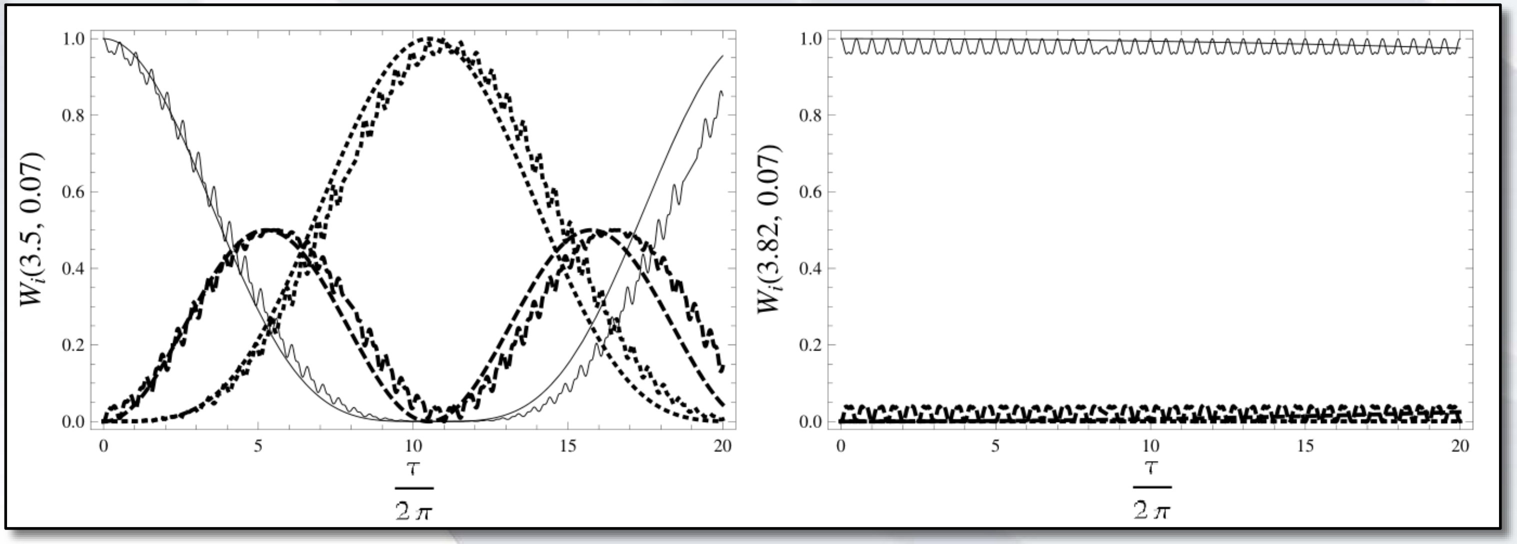
$$i\frac{\partial}{\partial\,\tau}\psi = B[S_z \sin\tau - \sqrt{2}\lambda\, S_x \cos\tau]\psi\,, \quad B = \frac{\mu_B H_0}{\hbar k v}\,, \quad \lambda = \frac{k\rho}{2\sqrt{2}}\,, \quad \psi = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}.$$

Krylov-Bogolyubov-Mitropol'skii method

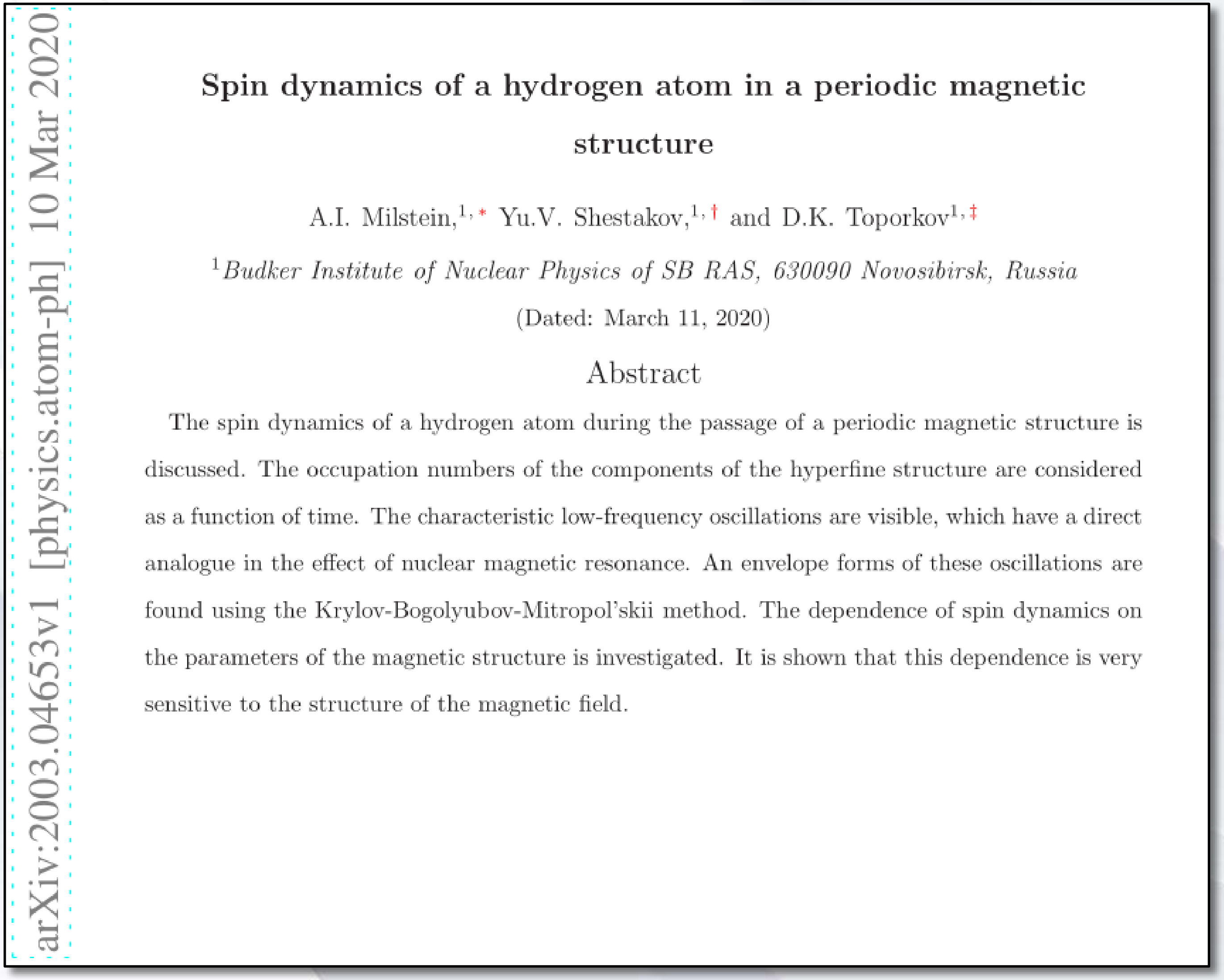
$$\overline{W}_1 = \cos^4(\Omega_0\tau/2)\,, \quad \overline{W}_0 = 2\sin^2(\Omega_0\tau/2)\cos^2(\Omega_0\tau/2)\,, \quad \overline{W}_{-1} = \sin^4(\Omega_0\tau/2),$$

where the oscillation frequency Ω_0 reads $\Omega_0 = \sqrt{2}\lambda B\, J_1(B)\,.$

$$B^* = 3.83,\ 7.02,\ 10.17,\ 13.32...$$



Спиновая динамика H_1 в периодическом магнитном поле



Spin dynamics of a hydrogen atom in a periodic magnetic structure

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Abstract

The spin dynamics of a hydrogen atom during the passage of a periodic magnetic structure is discussed. The occupation numbers of the components of the hyperfine structure are considered as a function of time. The characteristic low-frequency oscillations are visible, which have a direct analogue in the effect of nuclear magnetic resonance. An envelope forms of these oscillations are found using the Krylov-Bogolyubov-Mitropol'skii method. The dependence of spin dynamics on the parameters of the magnetic structure is investigated. It is shown that this dependence is very sensitive to the structure of the magnetic field.

СПАСИБО !