Magnetic resonance and relaxation of polarized beta-active nuclei.

Modern state and visible trends

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β-NMR=magnetic resonance and relaxation of polarized β-active nuclei.

- NMR is powerful method to study the structure and internal processes in substance on atomic scale.
- β-NMR is based on the correlation between nuclear polarization $\boldsymbol{P} = \langle \boldsymbol{I} \rangle$ and direction $\boldsymbol{k}$ of β-irradiation for β-active nuclei

  - $W(\vartheta) \sim 1 + a \cdot P(t) \cdot \cos\vartheta, \qquad \cos\vartheta = \boldsymbol{kP}/kP,$

  - $\varepsilon = (W(0) - W(\pi))/(W(0) + W(\pi)) = a \cdot P(t),$

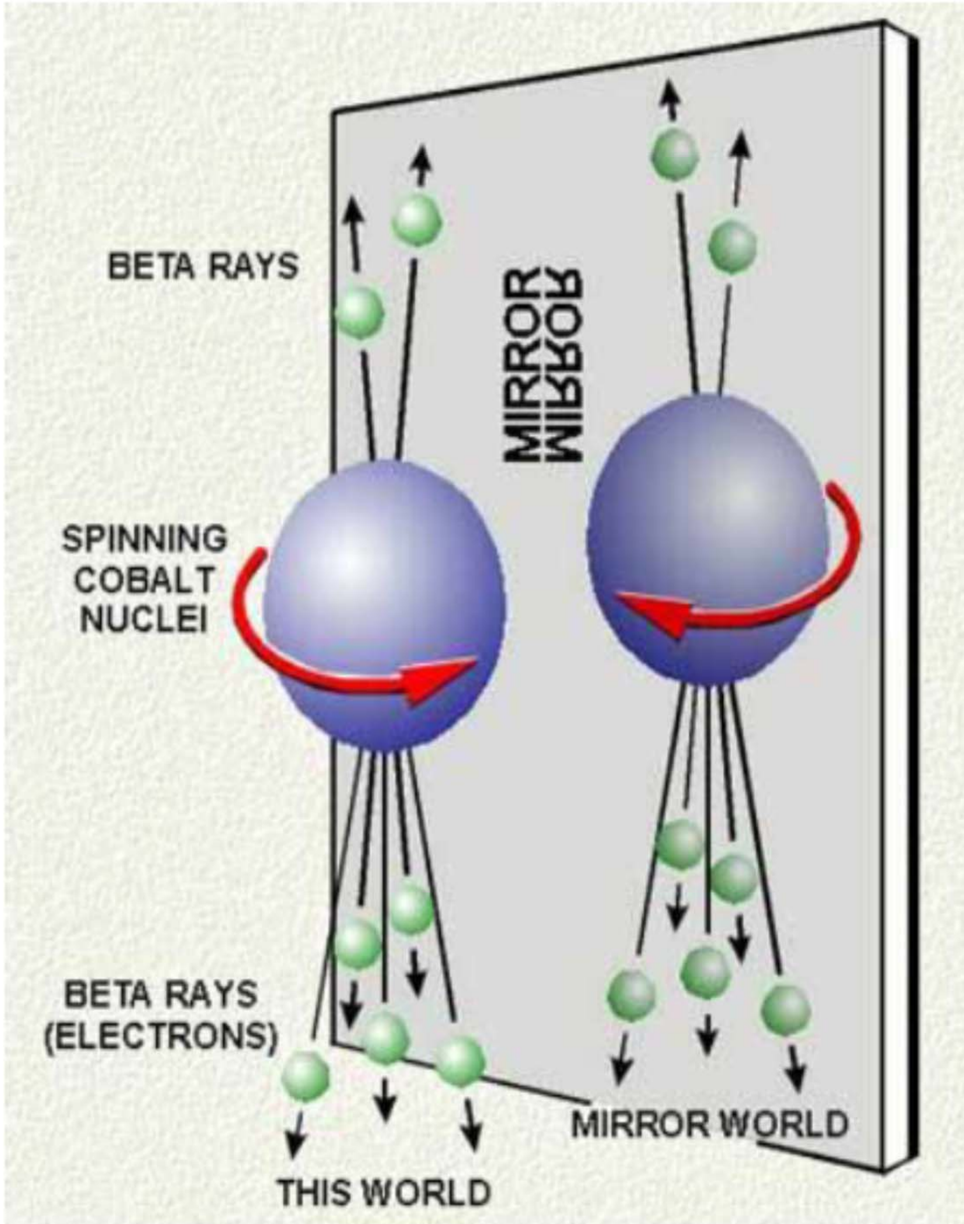
- Here $a \sim 0.1$ is nuclear constant. Time $t=0$ corresponds to the moment of β-active nucleus creation.

Parity Violation

ß emission is correlated with the spin direction of the decaying nucleus,

violating mirror symmetry

Lee and Yang 1957



A picture of W.A. MacFarline and G.D. Morris, Canada beta-NMR team, 2010.

The method was invented by F.L. Shapiro (FLNF, JINR, Dubna) soon after discovery of parity nonconservation in beta-decay: Usp. Fiz. Nauk 65, 133 (1958).

1958 г. Май *Т. LXV, вып. 1*

УСПЕХИ ФИЗИЧЕСКИХ НАУК

НЕКОТОРЫЕ ВОЗМОЖНОСТИ ИСПОЛЬЗОВАНИЯ ПОЛЯРИЗОВАННЫХ ТЕПЛОВЫХ НЕЙТРОНОВ, СВЯЗАННЫЕ С НЕСОХРАНЕНИЕМ ЧЕТНОСТИ ПРИ β-РАСПАДЕ

Ф. Л. Шапиро

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VOLUME 3, NUMBER 9 PHYSICAL REVIEW LETTERS NOVEMBER 1, 1959

MEASUREMENT OF THE NUCLEAR g FACTOR OF Li^8[*]

Donald Connor
Argonne National Laboratory, Lemont, Illinois
(Received October 12, 1959)

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Nuclear Physics **34** (1962) 505—509, © *North-Holland Publishing Co, Amsterdam*

BETA DECAY ASYMMETRY OF Li^8, Ag^{108} AND Ag^{110} NUCLEI PRODUCED IN THE CAPTURE OF POLARIZED THERMAL NEUTRONS

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Theoretical and Experimental Physics Institute, Academy of Sciences, Moscow, USSR

First beta-NMR study at helium temperatures was carried out in ITEP giving the start for investigation of condensed media.

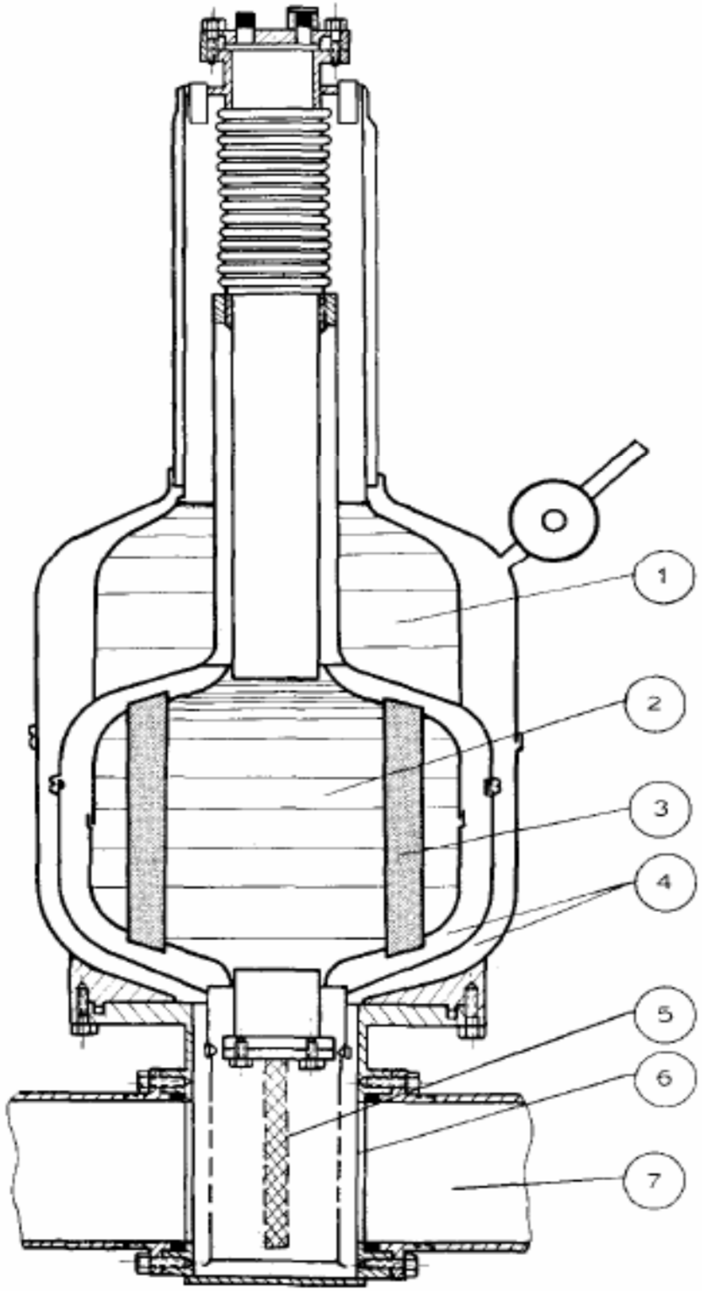


Fig. 1. Schematic representation of helium cryostat for asymmetry measurements of beta decay of polarized nuclei 1: liquid nitrogen. 2: liquid helium. 3: activated carbon. 4: vacuum. 5: sample. 6. scintillation plastic. 7: light pipe.

β-NMR is different from conventional NMR in two important properties.

1) Polarized nuclei in β-NMR are produced in nuclear reactions like

$^{7}Li(n,\gamma)^{8}Li$, $^{11}B(n,\gamma)^{12}B$, $^{19}F(n,\gamma)^{20}F$, $^{7}Li(d,p)^{8}Li$, $^{11}B(d,p)^{12}B$, $^{109}Ag(n,\gamma)^{110}Ag$, $^{115}In(n, \gamma)^{116}In$, …,

and they have polarization P~1 contrary to application of stable nuclei having $P \sim \mu H/T \sim 10^{-5}$ in conventional NMR.

2) The polarization in β-NMR is measured with high efficiency via significant beta-decay anisotropy ε instead of measuring of small free induction signal in conventional NMR.

The β-NMR has following advantages relative to conventional NMR:

a) very high sensitivity, admitting to work with 10^6-10^8 β-nuclei in the sample;

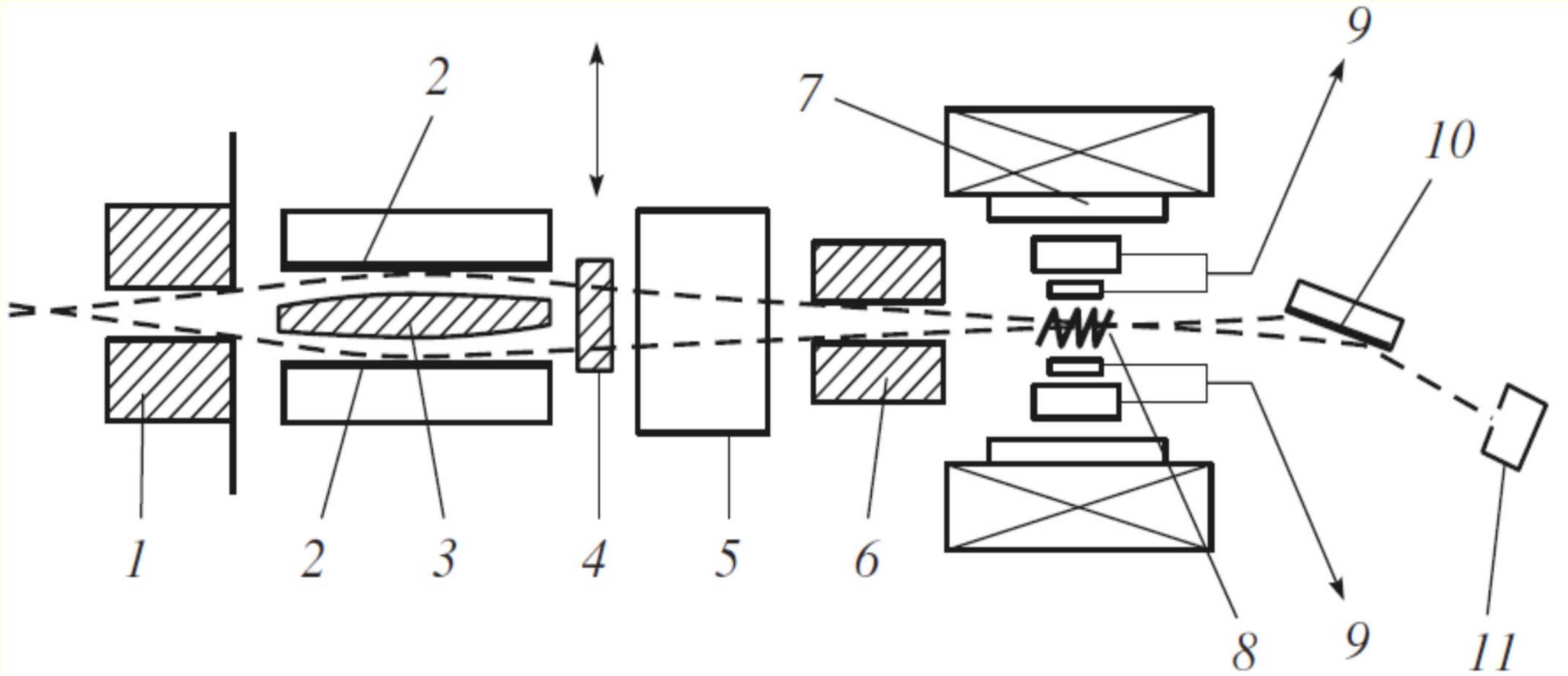
b) independence of the sensitivity on external magnetic field, that gives a possibility to study the relaxation at any (including small) fields;

c) relaxation studies can be carried out without application of alternating fields, that is very important for metallic samples, and for samples in metallic containers;

d) such β-nuclei, as ^{20}F, ^{108}Ag, and ^{110}Ag for example, have quadrupolar moments contrary to their stable isotopes possessing spins ½; they admit to measure quadrupole interactions; and

e) the method is sensitive to fast processes of motion of defects, produced by β-nucleus on time scale of hyperfine frequency just after the β-nucleus creation in the sample; it gives the information about defects evolution up to time $t \sim T_{1/2}$.

Reactor based β-NMR set up (ITEP)



1 - neutron collimator

2 – polarizer of neutron beam, 3 - direct-beam absorber,

4 - chopper, 5 - spin-flipper, 6 - magnet-collimator,

7 - electromagnet, 8 - sample with rf-coil, 9 - β-counters,

10 - analyzer of neutron beam, 11 - neutron counter.

Typical reactions

$$^{7}Li\left(\vec{n},\gamma\right)\,^{8}\overrightarrow{Li},\quad ^{19}F\left(\vec{n},\gamma\right)\,^{20}\vec{F},\quad ^{109}Ag\left(\vec{n},\gamma\right)\,^{110}\overrightarrow{Ag}$$

For students.

The method is based on a miracle – parity noncoservation, and on three brilliant inventions:

1) Neutron polarizer (nuclear attraction is substituted by effective repulsion due to QM s-scattering, and by effective repulsion potential inside the substance, that in combination with internal magnetic field produces splitting and polarization of neutron beam).

2) Adiabatic transmission of polarized neutrons in presence of scattered external fields:

$$\left|\frac{d}{dt}\frac{\mathbf{H}}{H}\right| = \varepsilon\gamma H = \varepsilon\omega_L, \;\; \varepsilon \ll 1 \to \Delta P/P \sim \exp(-C/\varepsilon),$$

$C \sim 1.$

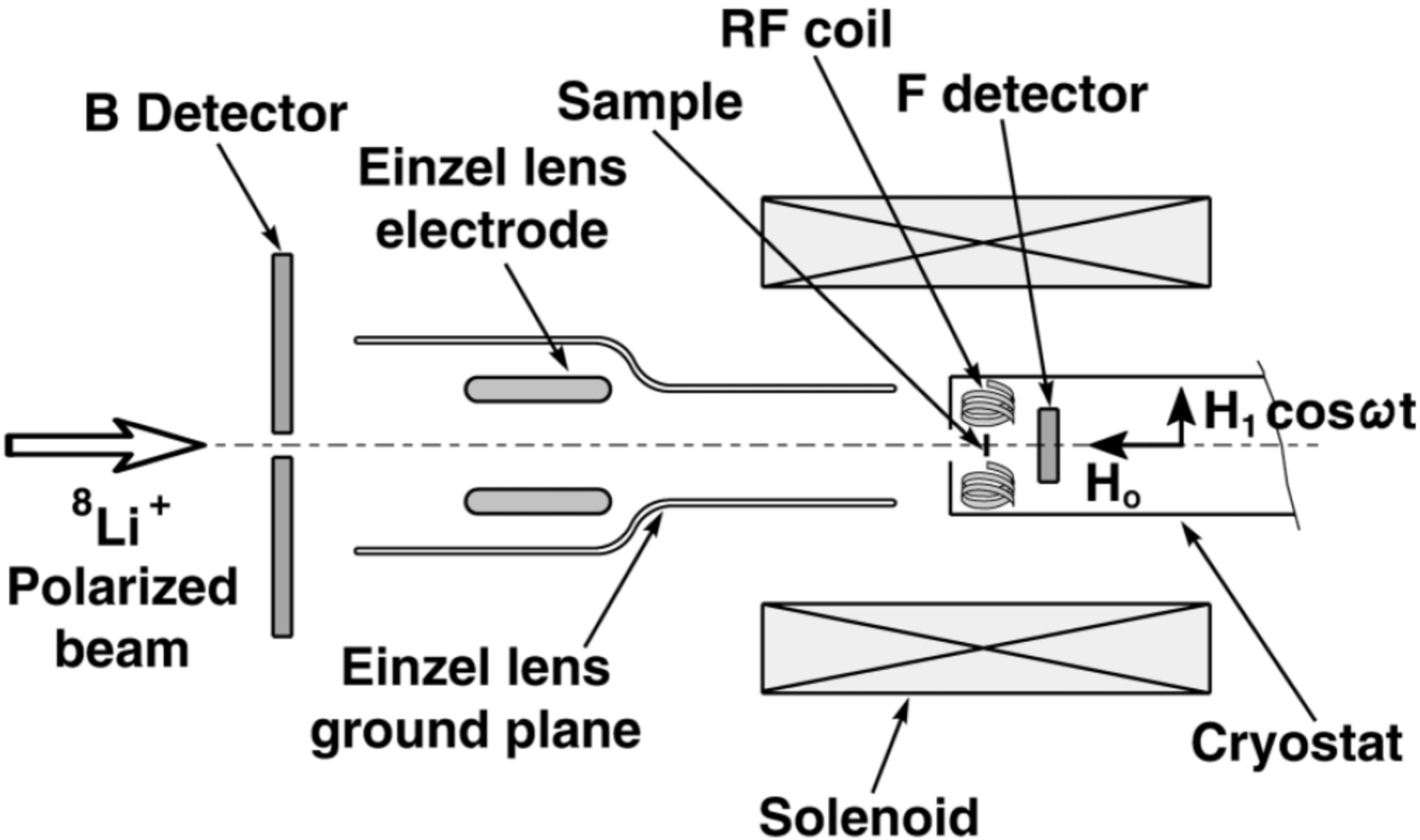
3) Spin flipper – fast and effective reversion of neutron polarization relative to guiding magnetic field

Accelerator based β-NMR (TRIUMF, Canada)

VOLUME 93, NUMBER 15 PHYSICAL REVIEW LETTERS week ending 8 OCTOBER 2004

Depth-Controlled β-NMR of ^{8}Li in a Thin Silver Film

G. D. Morris,[1] W. A. MacFarlane,[2,3] K. H. Chow,[4] Z. Salman,[3] D. J. Arseneau,[3] S. Daviel,[3] A. Hatakeyama,[3] S. R. Kreitzman,[3] C. D. P. Levy,[3] R. Poutissou,[3] R. H. Heffner,[1] J. E. Elenewski,[5] L. H. Greene,[5] and R. F. Kiefl[3,6]



Observables

$$\varepsilon=[N(\pi) - N(0)]/[N(\pi)+N(0)]$$

If, as usual, $H_Z=\omega_0 I_z$, $H_{RF}=2\omega_1 I_x cos(\omega t)$, then for **pulse neutron irradiation**

$$\varepsilon(t)= \varepsilon(0)exp(-t(w(\omega)+1/T_1)), \quad \varepsilon(0)= \varepsilon(H_0,T);$$

and for **continue neutron irradiation**

$$\varepsilon_c= \varepsilon(0)\,\lambda\,/[\lambda+w(\omega)+1/T_1].$$

λ – beta-decay rate. These relations are valid as **first approximation at time scale** $\boldsymbol{t \sim 1/\lambda}$**.**

Main information about structure and processes in the sample is concentrated in dependences of $\varepsilon(0)$, T_1, and spectrum $w(\omega)$ on all controllable parameters.

Main controllable parameters are external static magnetic field H_0, magnitude ω_1 and frequency ω of alternating field, and temperature T.

High developed theory of nuclear relaxation is necessary for data processing. The theory of nuclear magnetic resonance and relaxation is most developed part of nonequilibrium statistical mechanics.

The dependence $\varepsilon(t=0)= \varepsilon(H_0,T)$ is initial for **slow processes**. It contains the information about **fast processes**, which are finished to time $t\sim 1/\lambda$.

Main interactions.

Magnetic hyperfine interaction, the simplest forms is

$$H_M=A\mathbf{IS},$$

Electrical quadrupole hyperfine interaction,

the simplest forms is

$$\mathrm{H_Q}=\beta[(\mathbf{In})^2 - \mathrm{I(I+1)/3}],$$

Dipole-dipole interactions:

$$\mathrm{H_d}=\gamma_i\gamma_j[\mathbf{I}_i\mathbf{I}_j - 3(\mathbf{I}_i\mathbf{n}_{ij})(\mathbf{I}_j\mathbf{n}_{ij})]/r_{ij}^{3}.$$

Beta-decay asymmetry ε

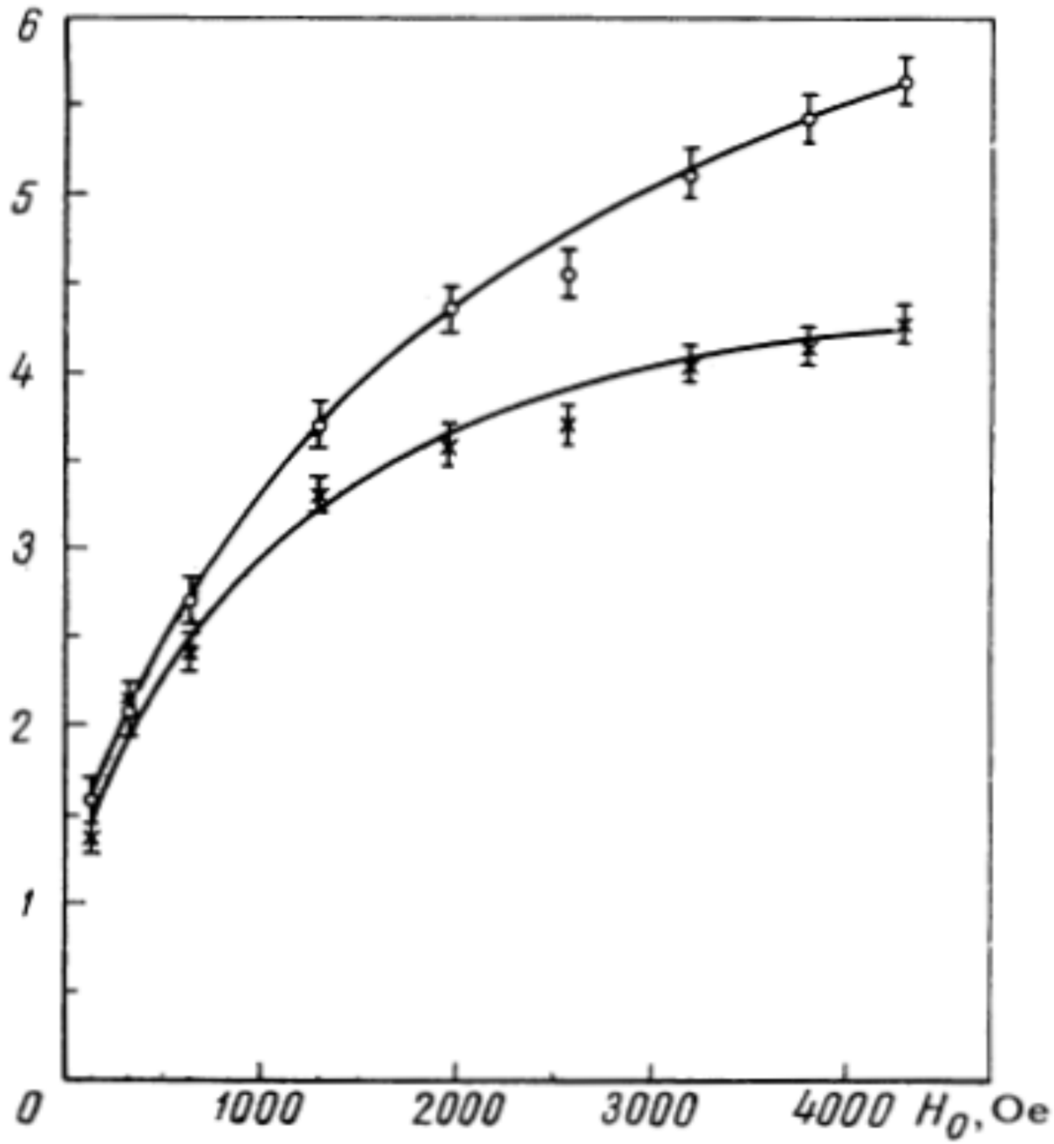
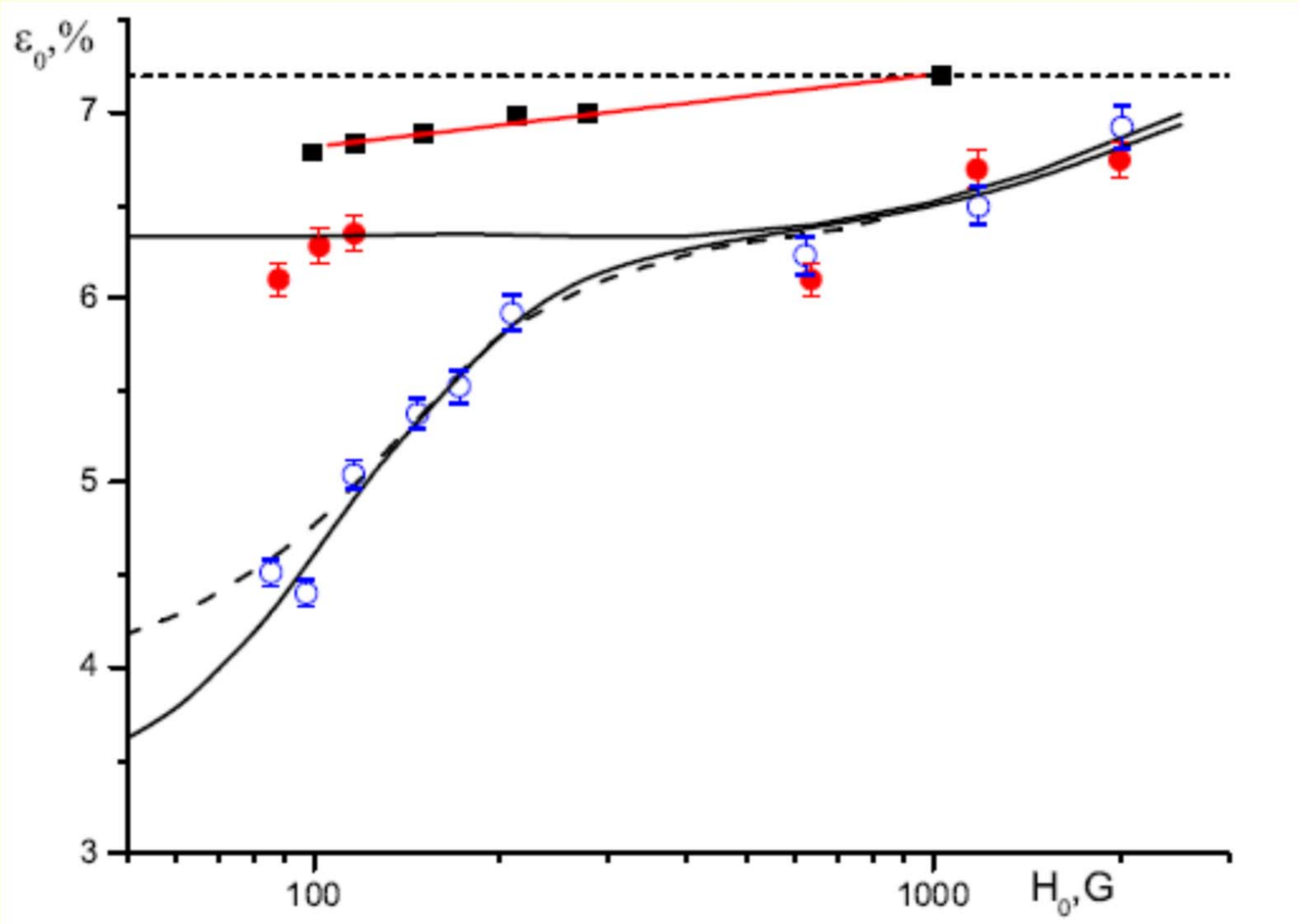


FIG. 2. Dependence of the asymmetry coefficient a on the magnetic field H_0 for $Ag^{107}Cl$ and $Ag^{109}Cl$ samples: ○ – Ag^{108}, × – Ag^{110}; T = 4.2°K.

A.D.Gulko, S.S.Trostin, A.Hudoklin. Sov. Phys. JETP **25**, 998, 1967

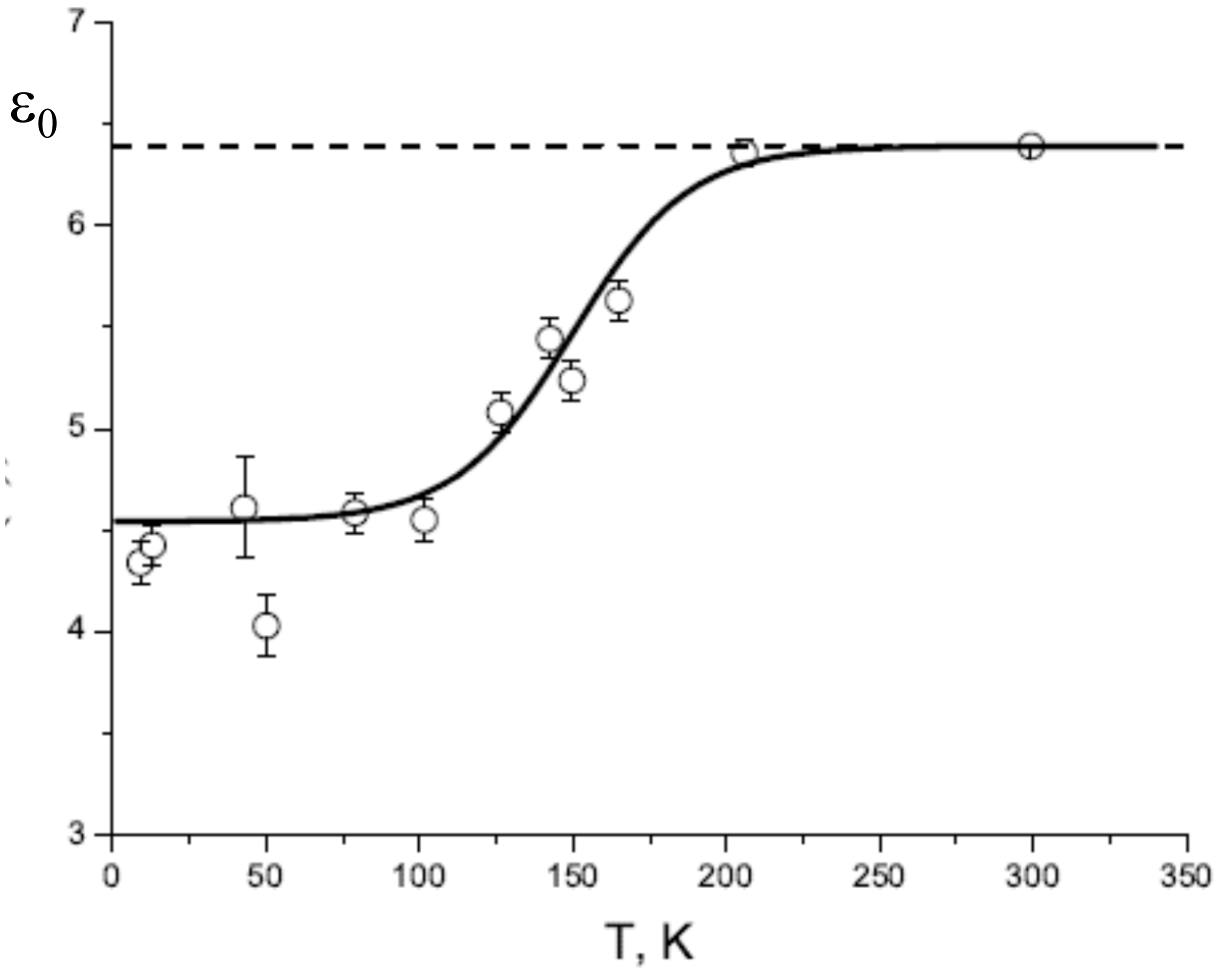
Studies of radiation damages induced by β-nuclei creation in (n,γ)-reaction.

$$\varepsilon(t) = \varepsilon_0 exp(-t/T_1), \quad \varepsilon_0 = \varepsilon(H_0, T)$$



Dependence of initial polarization of beta-nuclei ^{8}Li in LiF single crystal on external static magnetic field H_0||[100] in absence (filled circles and squares, T=300K) and in presence (open circles, T=8K) of radiation damages (fluorine vacancies). Squares – absence of ^{6}Li.
M.I.Bulgakov, S.P.Borovlev, A.D.Gulko, F.S.Dzheparov, I.G.Ivanter, S.S.Trostin.
Preprint ITEP-150, Moscow 1976.

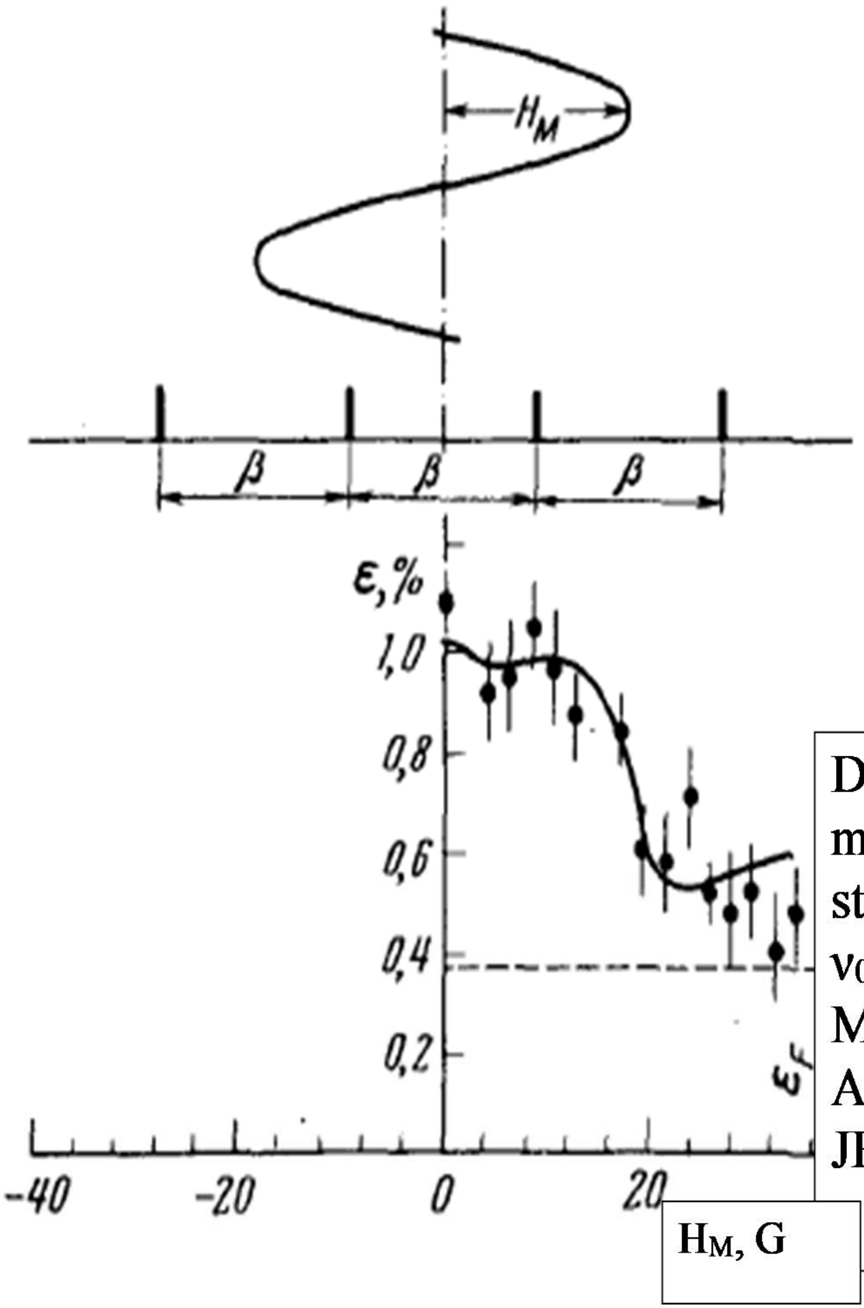
$$\varepsilon(t) = \varepsilon_0 exp(-t/T_1), \quad \varepsilon_0 = \varepsilon(H_0, T)$$



Dependence of initial polarization of beta-nuclei [8]Li in LiF single crystal on temperature T. External field H_0=100G, H_0||[100].

M.I.Bulgakov, S.P.Borovlev, A.D.Gulko, F.S.Dzheparov, I.G.Ivanter, S.S.Trostin. Preprint ITEP-150, Moscow 1976.

Quadrupole splitting of Larmor resonance line by diamagnetic defect (lithium vacancy).



Dependence of β-decay anisotropy on magnitude H_M of modulation of external static field H_0.
ν_0=2404.5 kHz, H_1=0.21G, T=13K.
M.I.Bulgakov, S.P.Borovlev, A.D.Gulko, F.S.Dzheparov, S.S.Trostin. JETP Lett. **27**, 453, 1978.

Application of the resonance at double Larmor frequency for study of dislocations in LiF single crystals

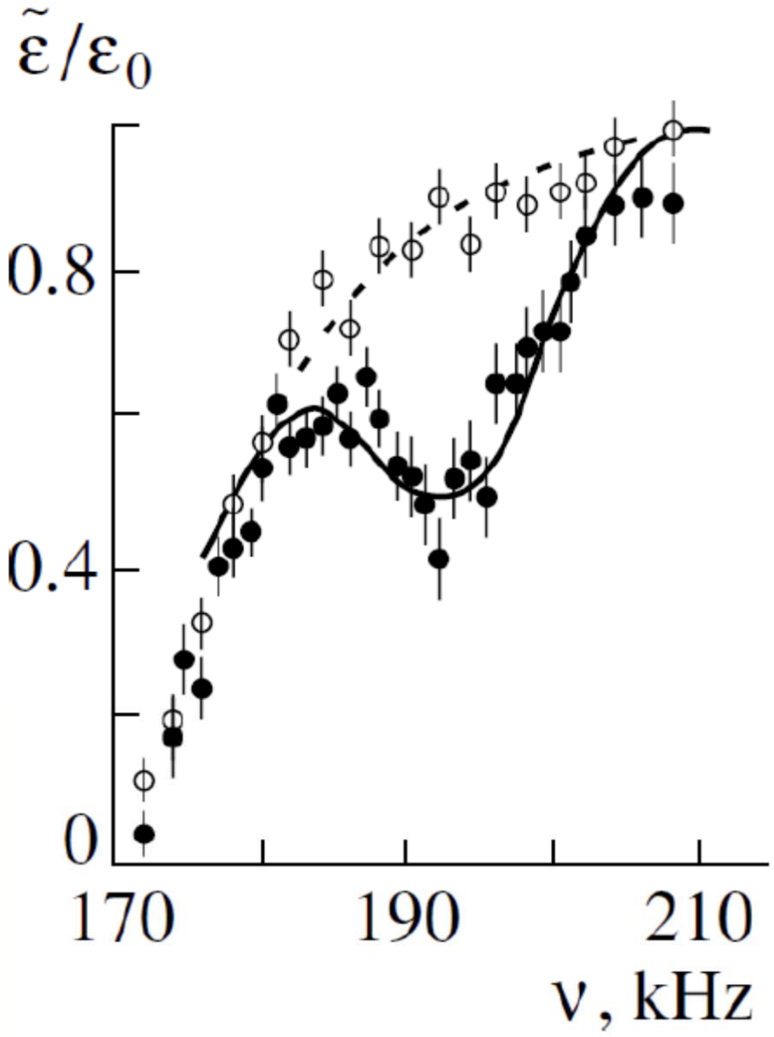


Fig. 2. β-NMR spectra of ^{8}Li nuclei according to measurements in the integral mode for LiF powder samples with respect to the frequency ν of an oscillating radio-frequency field of amplitude $2H_1 = 15$ G. Points represent (∘) the β-NMR spectrum in the powder prior to treating it with an external pressure [these data were used in approximating (dashed curve) the wing of the shape function for the two-spin resonance at the difference of the Larmor frequencies in ^{7}Li and ^{8}Li] and (•) the β-NMR spectrum in the powder treated with an external pressure of 190 MPa. The solid curve was computed by formulas (31)–(34) with allowance for the parameter values of $H_0 = 153.4$ G, $\tau_{\mathrm{irr}} = 2.4$ s, $\tau_{\mathrm{obs}} = 4$ s, and $\varepsilon_0 = 5.86(16)\%$.

Yu.G.Abov, A.D.Gulko, F.S.Dzheparov, S.V.Stepanov, S.S.Trostin. Phys. At. Nucl. **65**, 1999, 2002

Multispin resonances with participation of beta-active nuclei. Yu.G.Abov et al. JETP Lett. 1982

$$\omega = j\omega_8 + f\,\omega_{19} + l\omega_7, \quad j, f, l \text{ are integer}$$

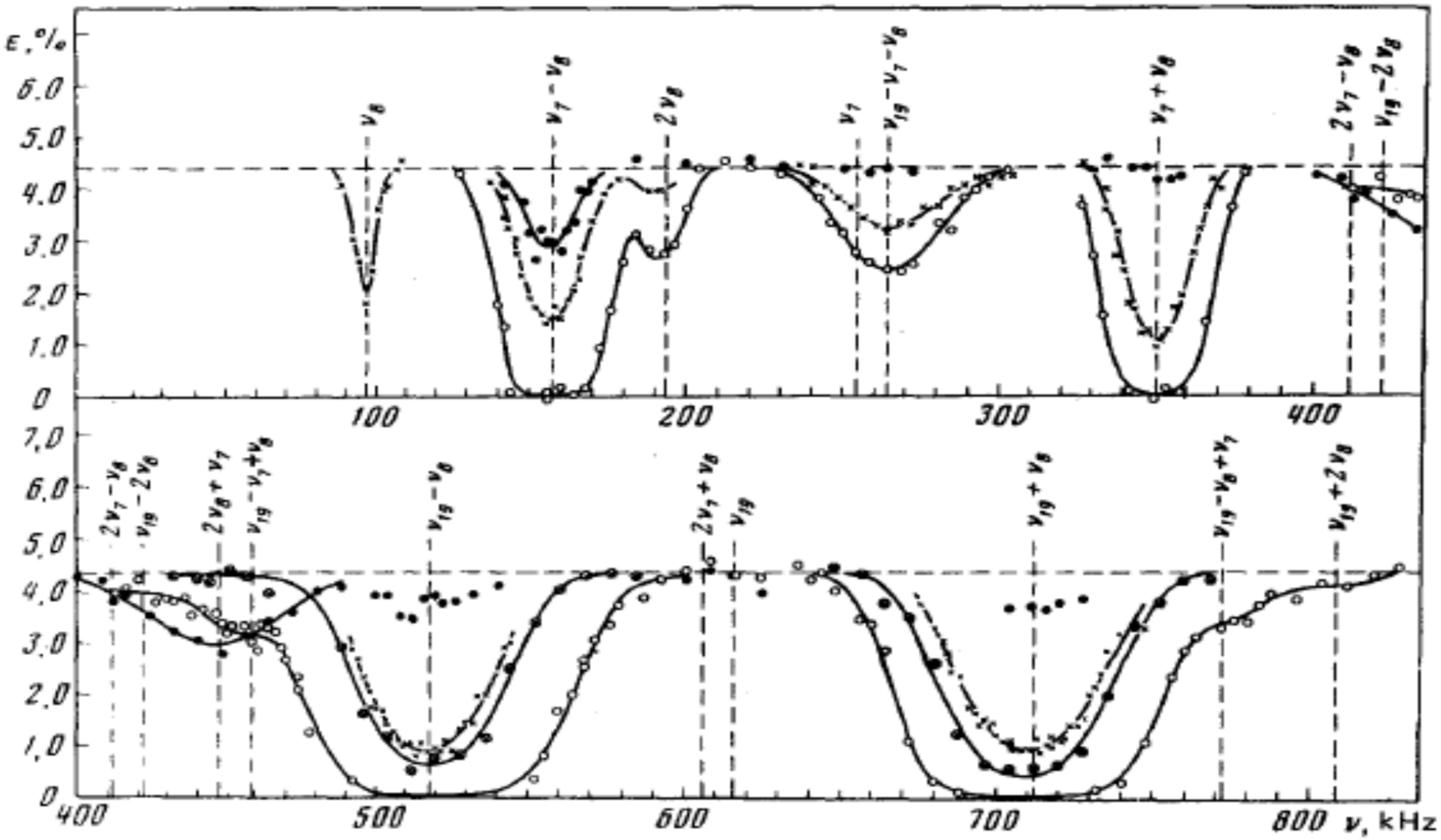
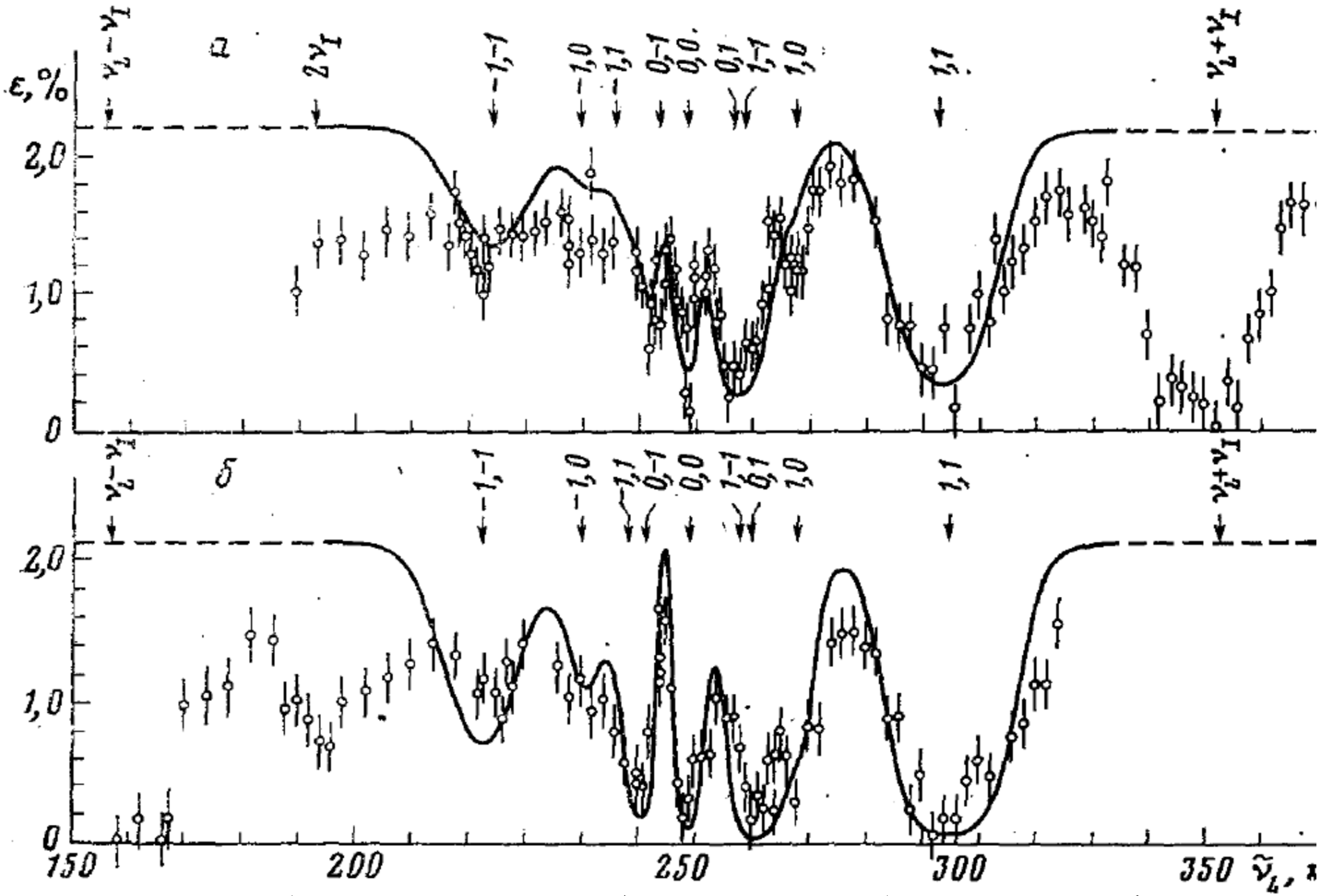


FIG. 1. The angular asymmetry of β emission of ^{8}Li nuclei as a function of frequency ν of the rf field. The frequencies ν_8, ν_7, and ν_{19} are the Larmor frequencies of the ^{8}Li, ^{7}Li, and ^{19}F nuclei. The points ○ were measured with an rf field rotating in the direction of precession of the ^{8}Li, ^{7}Li, and ^{19}F nuclei (their g factors are positive); the amplitude of the field H_1 was 6-8 G in the frequency range 130-400 kHz and 3-4 G in the range 400-800 kHz. The points ● were measured with the same rf field amplitudes H_1, but with field rotating in the opposite direction. The points × and ⊗ were measured with the direction of rotation of H_1 the same as that of precession of the nuclei, but with smaller amplitudes H_1: $H_1 = 0.02$ G for the ν_8 resonance; $H_1 = 1.7$ G for the $\nu_7 \pm \nu_8$ resonances; $H_1 = 5$ G for the $\nu_{19} - \nu_7 - \nu_8$ resonance; $H_1 = 0.6$ G and $H_1 = 0.9$ G for the $\nu_{19} \pm \nu_8$ resonances. The resonance near 450 kHz with the opposite direction of rotation of H_1 is related to resonance depolarization of the neutron beam by the rf field (the g factor of the neutron is negative). The absolute statistical accuracy of a single measurement is $\pm 0.14\%$.

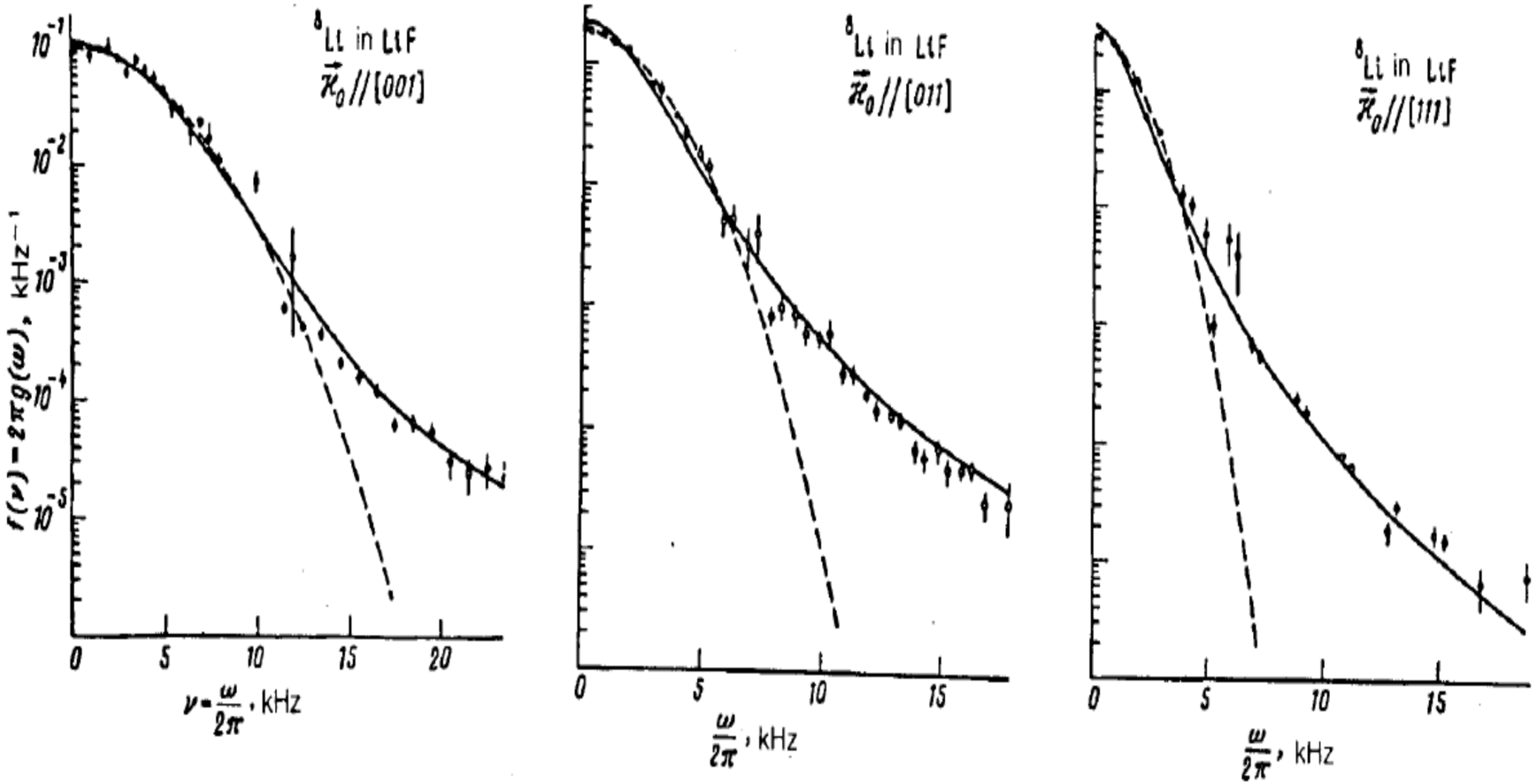
Rearragement of three-spin resonance $\nu = \nu_F - \nu_L - \nu_I$ under the influence of two strong rf-fields with frequencies ν_F and $\tilde{\nu}_L \sim \nu_L$.



kHz

H_{1F}=10 G, (a - H_{1L}=6.1 G, б - H_{1L}=9.7 G), ν_F=614.6 kHz, ν_L=253.9 kHz, ν_I=96.7 kHz.

Yu.G.Abov et al. Izv. Akad. Nauk SSSR, Ser. Fiz. 47, 2299, 1983.



NMR line shape function: theory vs experiment, 8Li in LiF,
no fitting parameters .
Gulko et al. JETP Lett. 1993, Abov et al. Phys. Part. Nucl. 1996

Dipole transport of nuclear polarization in model disordered spin system ^{8}Li-^{6}Li in LiF single crystal.
RWDM – random walks in disordered media

Spin dynamics.

Single crystal LiF, $\frac{g(^8Li)-g(^6Li)}{g(^8Li)} = 0.0057.$

$H_0 = 200\text{G} \leftrightarrow$ flip-flop ^{8}Li-^{6}Li has the same speed as flip-flop ^{6}Li-^{6}Li, other cross-relaxation transitions are forbidden.

$$\frac{\partial p_{i0}}{\partial t} = -\sum_j (\nu_{ji} p_{i0} - \nu_{ij} p_{j0}), \qquad p_{i0}(t=0) = \delta_{i0},$$

$p_{i0}(t) = \langle I_i^z(t) \rangle$ – quantum statistical average value of the z-component (polarization) of the i-th nucleus, placed at $\mathbf{r}_i$ ($i = 0 \leftrightarrow {}^8$Li, and $i \neq 0 \leftrightarrow {}^6$Li). The rates of polarization transfer:

$$\nu_{ji} = \xi_j \nu_{ji}^0 \left(\frac{1-3\cos^2\theta_{ji}}{(r_{ij}/d)^3} \right)^2, \quad \nu_{ji}^0 = \frac{\pi S(S+1)}{6} \left(\frac{g_i g_j \beta_n^2}{\hbar d^3} \right)^2 g_{ij}(\omega_{ij}),$$

$$\xi_j = I_j(I_j+1)/[S(S+1)],$$

g_i — g-factor, β_n is nuclear magneton, θ_{ji} is the angle between $\mathbf{H}_0$ and $\mathbf{r}_{ji} = \mathbf{r}_j - \mathbf{r}_i$, $d = 2.01 \cdot \sqrt{2}$ Å is minimal Li-Li distance, ω_{ij} is difference of the Larmor frequencies.

To obtain the first impression about influence of the disorder we should take into account, that

$$\left\langle \exp\left(-\sum_j v_{j0} t\right)\right\rangle = \exp\left(-(\beta t)^{1/2}\right), \qquad \beta \sim v(r_a = r_0/c^{1/3}).$$

Here $c \to 0$, but βt is finite (continuum media approximation),

½=d/s, *d=3* – space dimention,

s=6 – dependence of transition rate on distance.

Forster constant

$$\beta = \frac{512}{243}\pi^3 c^2 v_0$$

indicates natural scale of time in the problem.

The path integrals:

$$\mathcal{P}_{\mathbf{xy}}(t) = \left(e^{-At}\right)_{\mathbf{xy}} = \int_{\mathbf{q}(0)=\mathbf{x}}^{\mathbf{q}(1)=\mathbf{y}} D\mathbf{p}(\tau) D\mathbf{q}(\tau) \exp(I[p,q]),$$

$$I[p,q] = i \int_{\mathbf{x}}^{\mathbf{y}} \mathbf{p} d\mathbf{q} + n \int d^3 z \left(e^{-t \int_0^1 d\tau A^z(\mathbf{q}(\tau),\mathbf{p}(\tau))} - 1 \right),$$

$$A^z(\mathbf{q},\mathbf{p}) = \nu_{\mathbf{zq}} \left(1 - e^{-i\mathbf{p}(\mathbf{z}-\mathbf{q})} \right).$$

The representation is similar to, but more complex than path integrals in famous polaron problems. Superfield path integral representations for $P_{\mathbf{xy}}(t) = \langle \tilde{P}_{\mathbf{xy}} \rangle_c$ exist as well.

Example of superfield representation.

$$\mathcal{P}_{\mathbf{xy}}(\lambda) = \int_0^\infty dt \exp(-\lambda t)\mathcal{P}_{\mathbf{xy}}(t) = \left(\frac{1}{\lambda + A}\right)_{\mathbf{xy}} .$$

Bose-fields $a_{\mathbf{x}}$ and $a^\dagger_{\mathbf{x}}$.
Fermi-fields $\alpha_{\mathbf{x}}$ and $\alpha^\dagger_{\mathbf{x}}$.
$\phi = \{a, \alpha\}$, $\phi^\dagger = \{a^\dagger, \alpha^\dagger\}$.

$$\phi^\dagger O \phi = \sum_{\mathbf{xy}} \left(a^\dagger_{\mathbf{x}} O_{\mathbf{xy}} a_{\mathbf{y}} + \alpha^\dagger_{\mathbf{x}} O_{\mathbf{xy}} \alpha_{\mathbf{y}}\right) ,$$

$$\mathcal{P}_{\mathbf{xy}}(\lambda) = \int \delta a \delta a^\dagger \delta\alpha \delta\alpha^\dagger \alpha^\dagger_{\mathbf{x}} \alpha_{\mathbf{y}} \exp(-I(\phi^\dagger, \phi))$$

$$I(\phi^\dagger, \phi) = \lambda \phi^\dagger \phi + c \sum_{\mathbf{z}} \left(1 - \exp\left(-\phi^\dagger A^{\mathbf{z}} \phi\right)\right) .$$

$$A^{\mathbf{z}}_{\mathbf{xy}} = \nu_{\mathbf{zy}} \left(\delta_{\mathbf{xy}} - \delta_{\mathbf{xz}}\right) , \quad \nu_{\mathbf{zy}} \propto |\mathbf{z} - \mathbf{q}|^{-6},$$

Divergencies are seen clearly, but the theory exists as expansion in powers of c^m at least.

Main problem of numerical simulation -

infinite disordered sample in finite computer program.

We use infinite **crystal** with large **disordered unite cell,** containing $100<N_d<4000$ spins of ^6Li. As a result we can apply Bloch's theorem and receive Bloch's eigenvalues and eigenfunctions for matrix of dimension $N_d \bullet N_d$ and than we can calculate observable values, applying integration over Brillouin's zone.

Results are stable within 2% for N_d>400 spins.

Main problem in experiment.

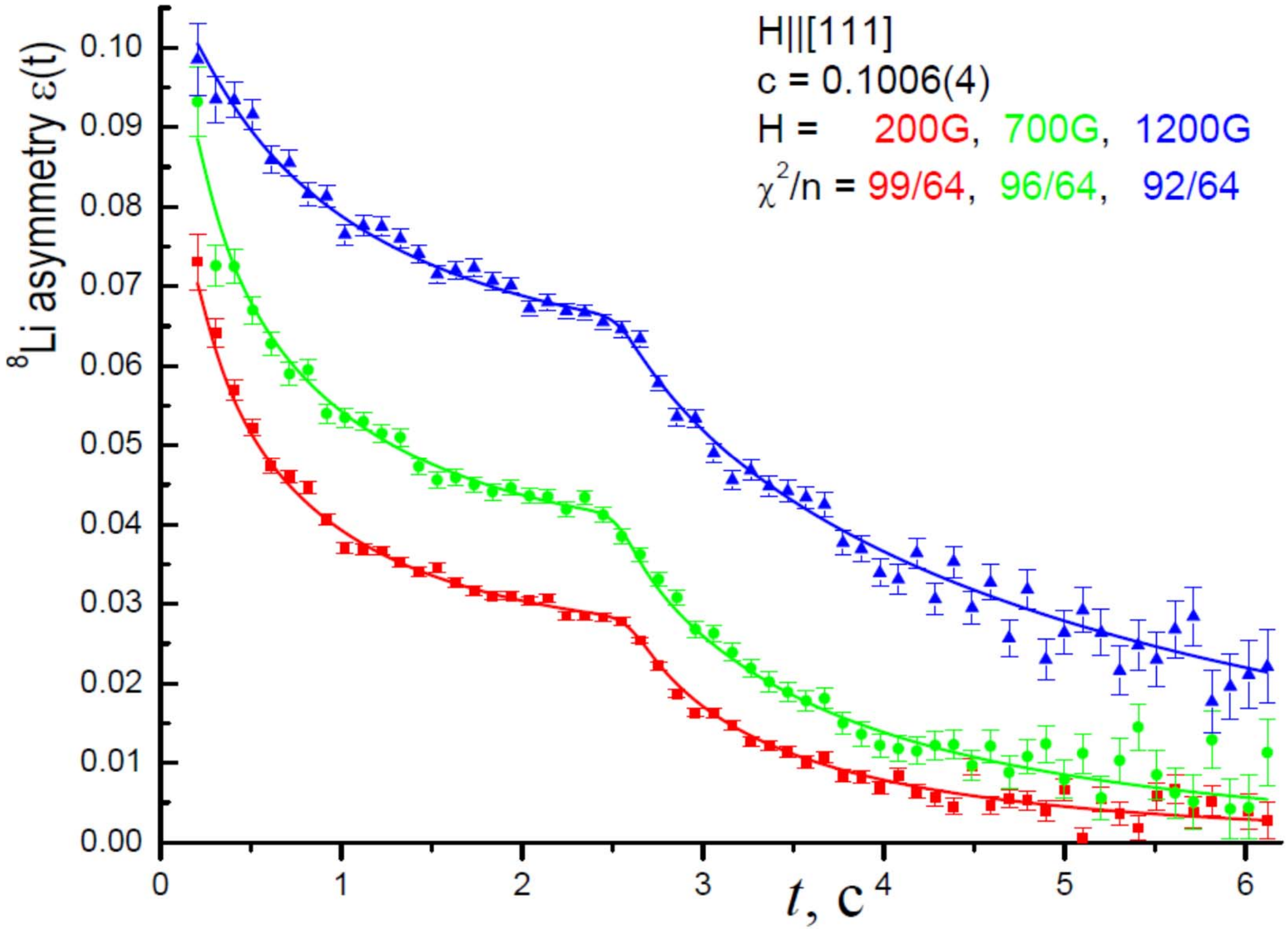
$\boldsymbol{\beta} \leq 10\ s^{-1}$, and measurements at $t \geq 3$ s are required, while $T_{1/2}=0.84$ s.
⇔ small statistics – long measurements.

Related problem: Concentration c=10% (corresponding to $\boldsymbol{\beta} \approx 10\ s^{-1}$) is not small enough to neglect the correlations of local fields – dependence of ν_{ij}^{0} on $\mathbf{r}_{ij}$ is important =

= **correlation of local fields on impurity spins.**

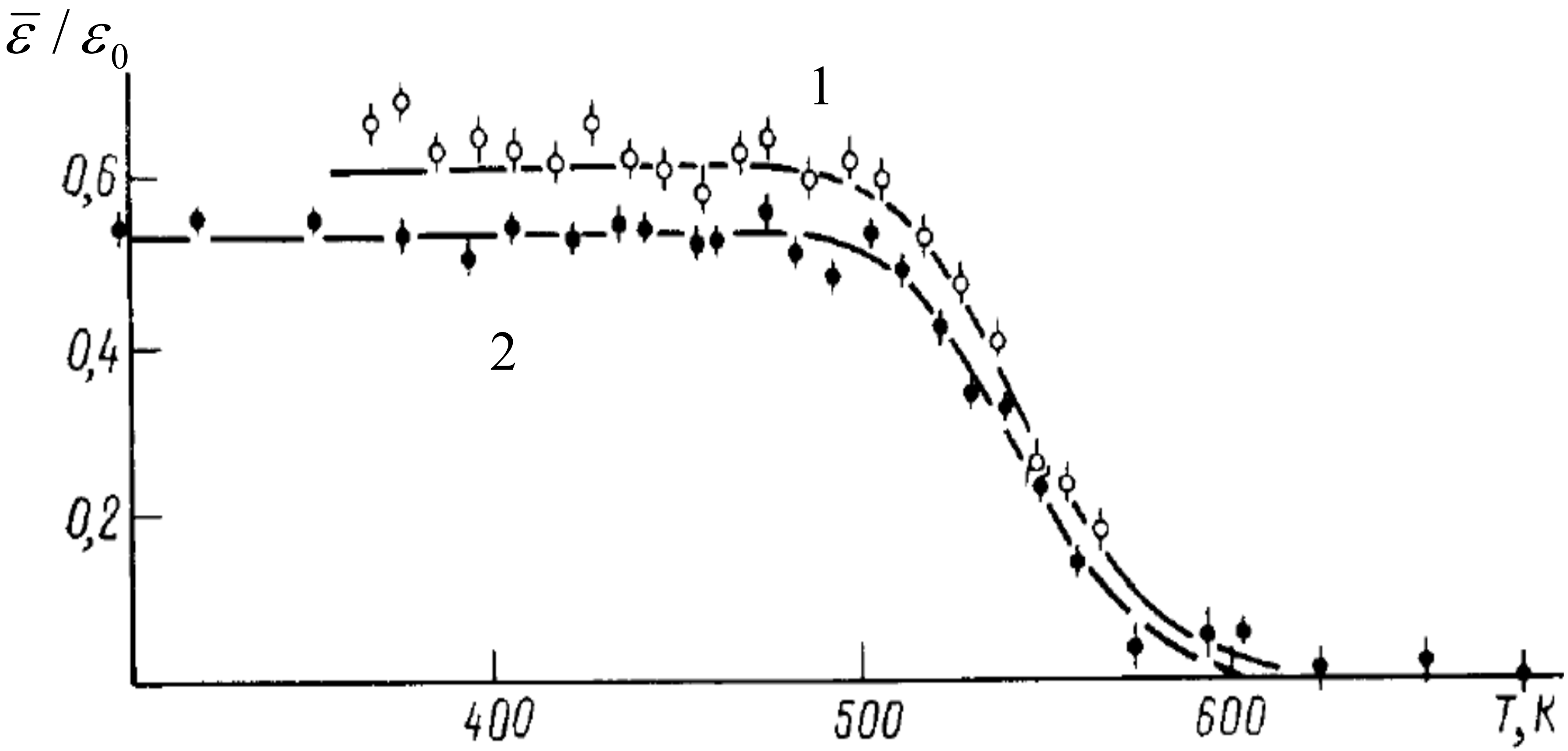
$$\nu_{ji} = \xi_j \nu_{ji}^0 \left(\frac{1-3\cos^2\theta_{ji}}{(r_{ij}/d)^3} \right)^2, \quad \nu_{ji}^0 = \frac{\pi S(S+1)}{6} \left(\frac{g_i g_j \beta_n^2}{\hbar d^3} \right)^2 g_{ij}(\omega_{ij})$$

Dependence of kinetics of depolarization of ^{8}Li on external field Ho. Solid line – theory. Natural time scale: $\beta \approx 10$/s.
No fitting parameters.
Step on the lines corresponds to end of neutron pulse.



Yu.G.Abov, A.D.Gulko, F.S.Dzheparov, et al. Phys. At. Nucl. 77, 682, 2014.

Application of the RWDM to study of slow atomic hopping with hopping rates up to ~ 1/sec.



Dependence of ^8Li β-decay asymmetry on temperature in LiF single crystal. H_0=200 G, 1 ⇔ $\mathbf{H_0}$**||<100>**, **2 ⇔** $\mathbf{H_0}$**||<110>.** Yu.G.Abov et. al. Sov. Phys. JETP **72**, 534, 1991.

Nonanalytic dependence of intensity of forbidden resonance $\omega=\omega_I+\omega_S$ on applied RF power in disordered ^8Li-^6Li system

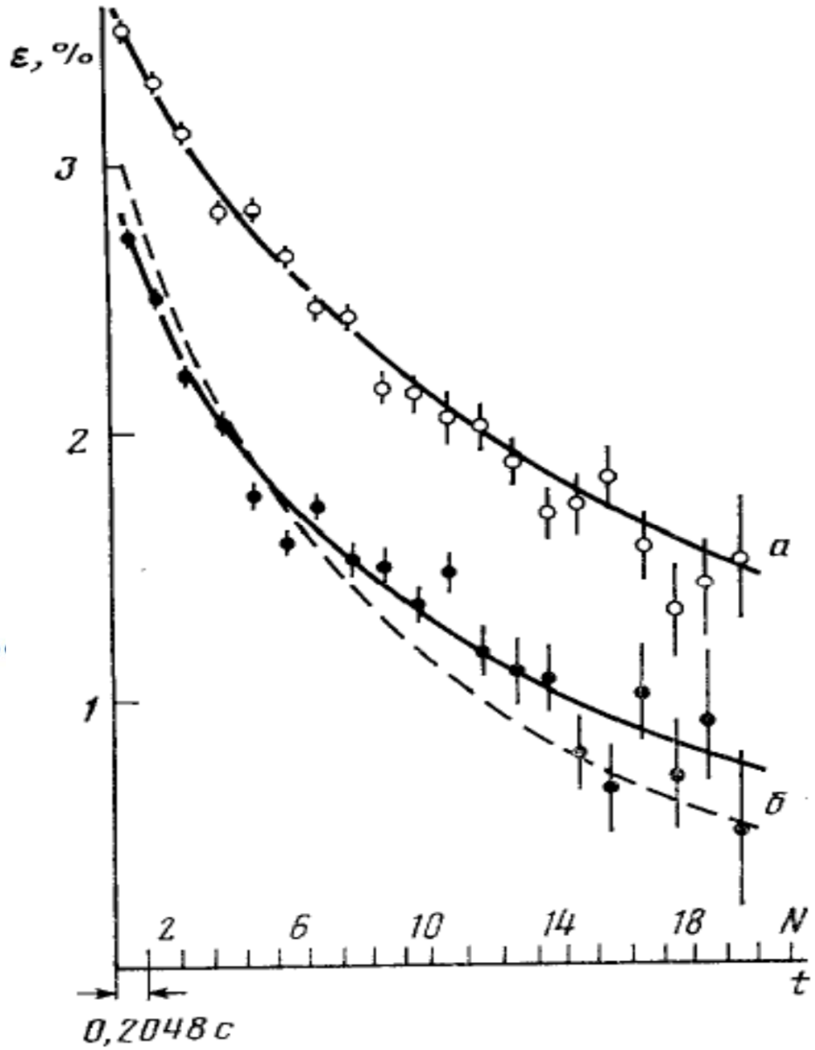
$$\frac{d}{dt}p_{i0} = -\sum_j (v_{ji}p_{i0} - v_{ij}p_{j0}) - \sum_j (\mu_{ji}p_{i0} + \mu_{ij}p_{j0}),$$

$$p_{i0}(t=0) = \delta_{i0}.$$

$$\frac{\mu_{ij}}{v_{ij}} \sim \left(\frac{H_1}{H_0}\right)^2 = \gamma \ll 1.$$

$$\langle p_{i0}(t)\rangle \approx \exp\left(-(\beta_e t)^{1/2}/2\right).$$

$$\beta_e = \beta\left(1 + \frac{27}{4}\sqrt{\gamma}\right).$$



Conclusions for studies of model ^8Li-^6Li system

1. Kinetics of delocalization of nuclear polarization in disordered spin subsystem is studied in experiment and theory.
2. Existence of the spin diffusion in disordered spin subsystem is established.
3. Full numerical-analytical description of the kinetics is constructed.
4. Pronounced preasymptotical effects are revealed.
5. Field dependence of the kinetics is measured.
6. Field dependence of the kinetics is described taking into account both static and dynamic correlations of local fields.
7. Temperature dependence of the kinetics produces a possibility to measure slow displacements of Li nuclei with hopping rate in order of 1/s.
8. Nonanalytic dependence of intensity of forbidden resonance on applied RF power is revealed.
9. Extensive consequences for spin dynamics in random media are obtained (new theory of line shape functions, of spectral transport and so on are developed).

The βNMR facility at TRIUMF: new tools for Materials Science at the nanoscale

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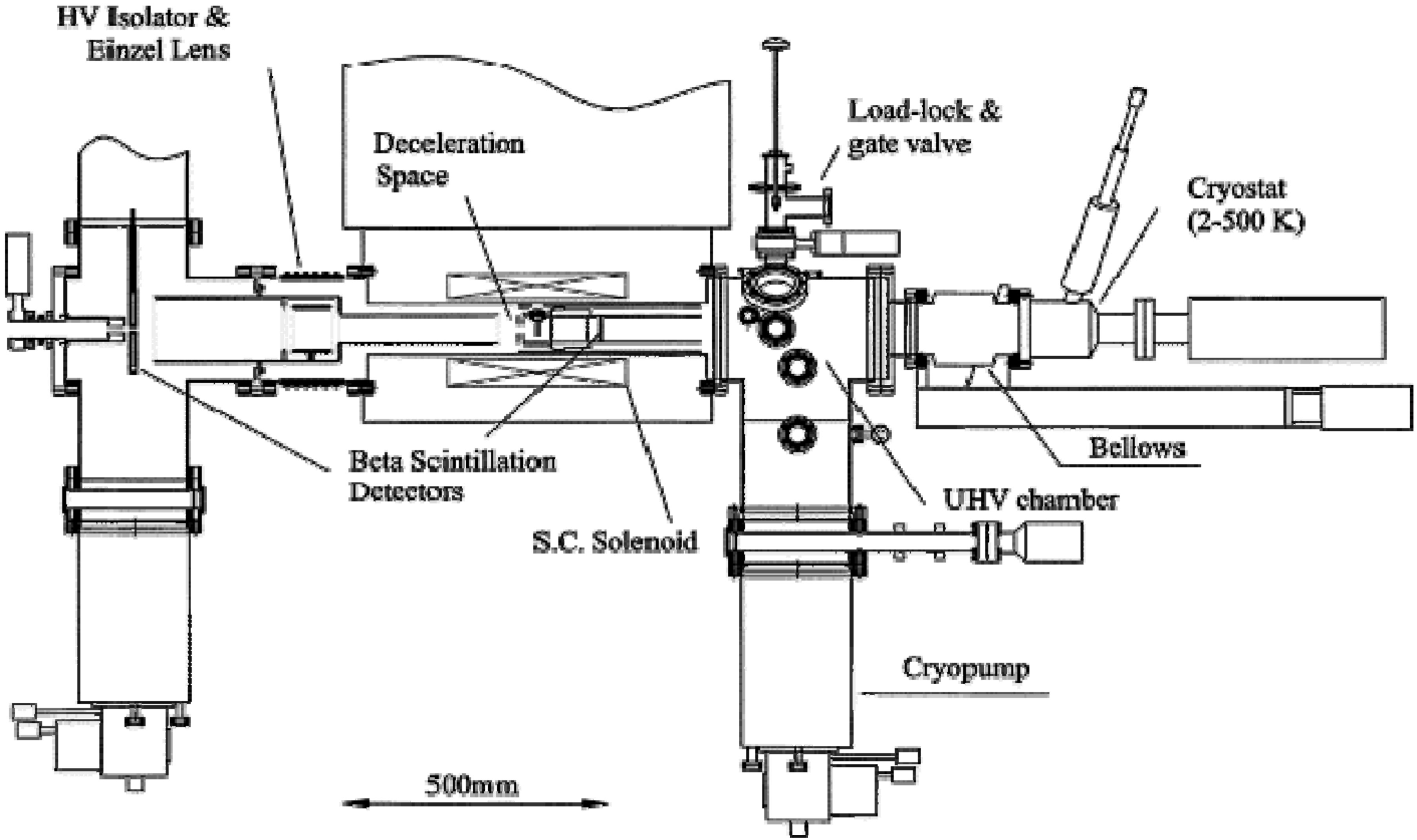
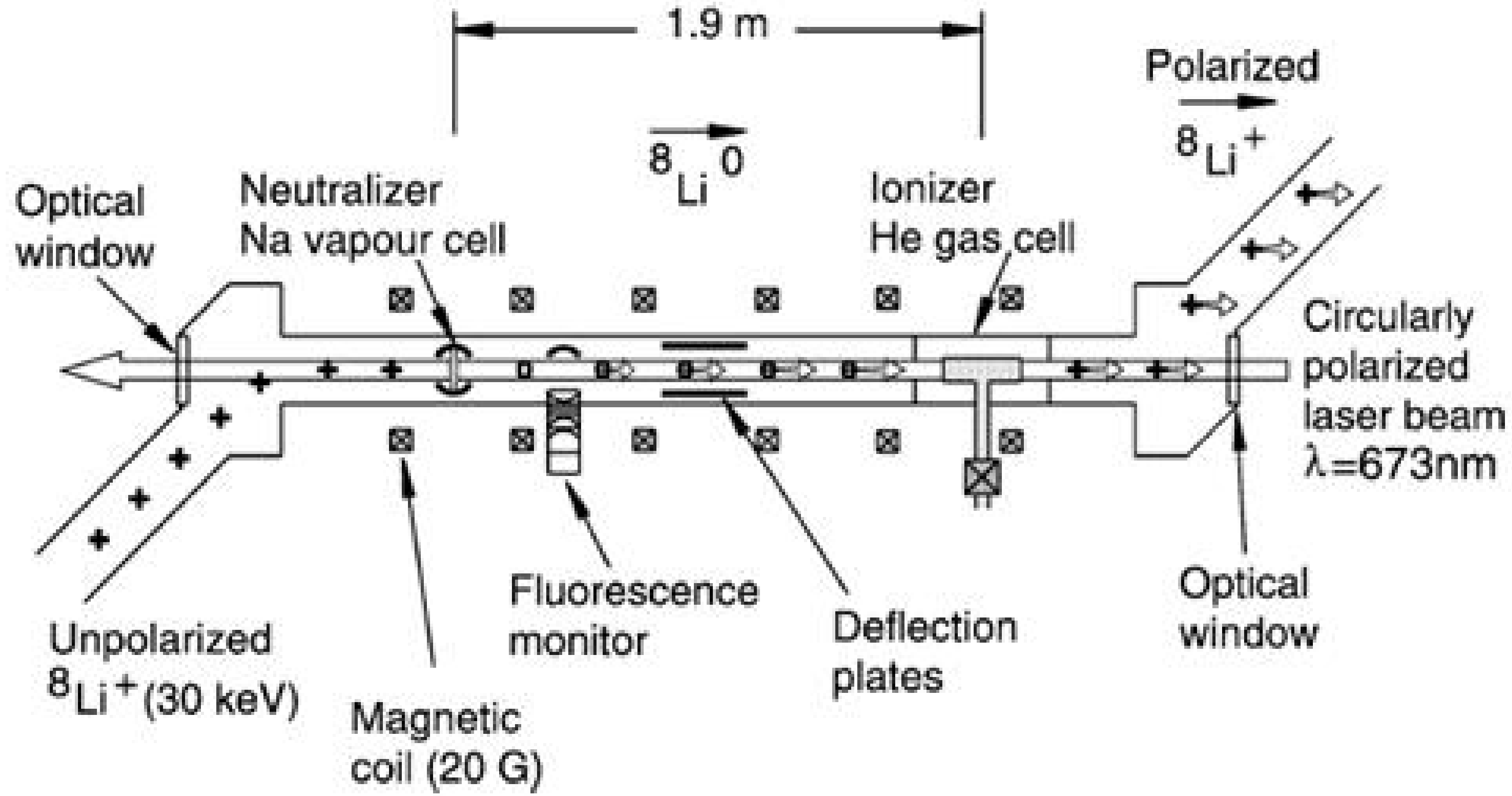
[2]TRIUMF, Vancouver

β-NMR spectrometer at ISAC.



The beam enters from the left, passes through an aperture in the backward scintillation detector and is focussed onto the sample in the center of the 9 T superconducting magnet. Betas are detected with two scintillation counters

Поляризующая секция пучка бета-ядер ^{8}Li в ISAC-TRIUMF



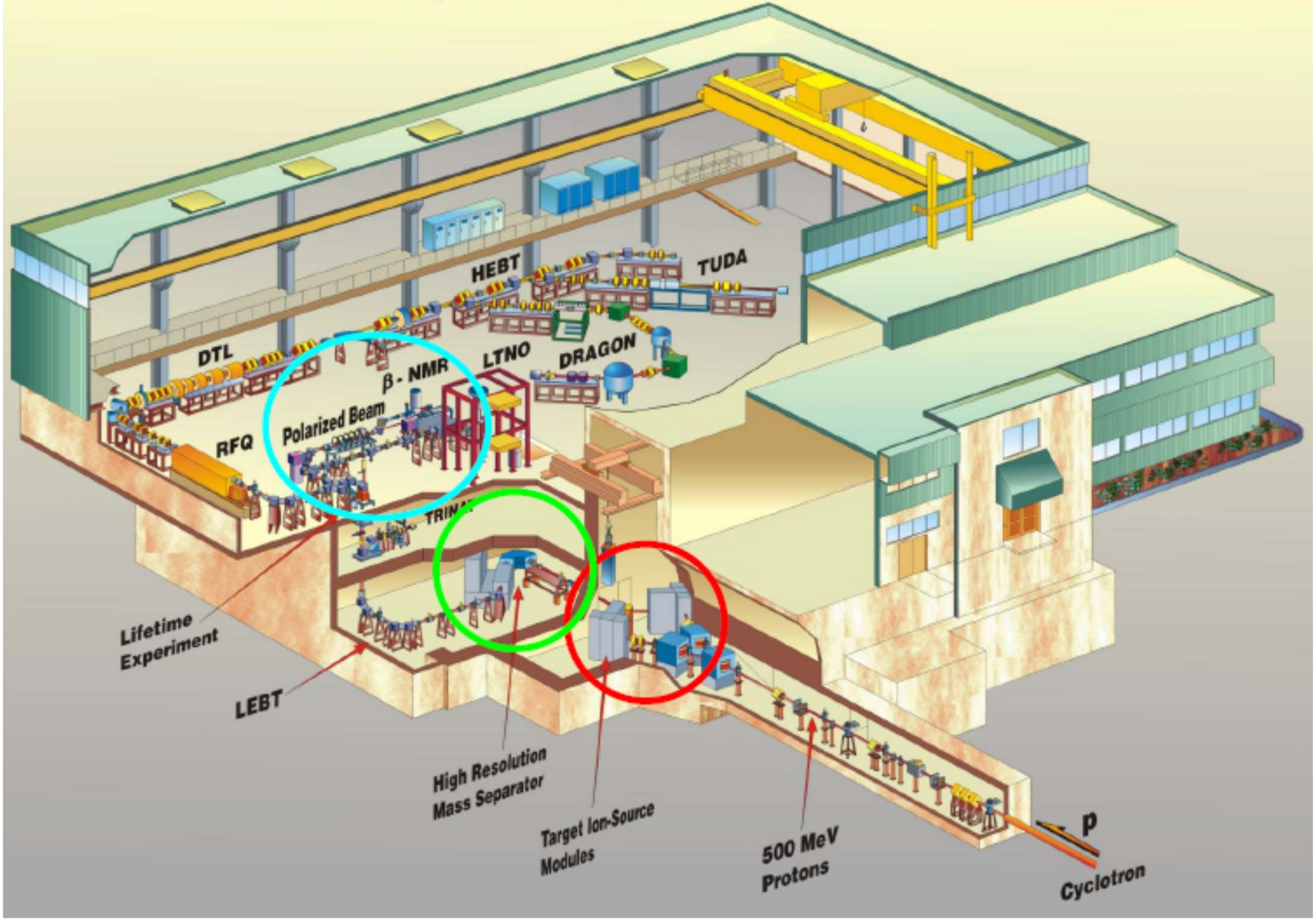
Для поляризации бета ядер использован циркулярно поляризованный лазерный свет - атомы поляризуются лазерным излучением, атомная поляризация посредством сверхтонкого взаимодействия передается ядрам ^{8}Li

Isotopes for βNMR at ISAC

Isotope	Spin	$\tau_{1/2}$	γ (MHz/T)	β-Decay Asymmetry	Estimated Rate (s^{-1})
^{8}Li	2	0.8	6.3	0.33	10^8
^{11}Be	1/2	13.8	22	~0.3	10^7
^{15}O	1/2	122	10.8	0.66	10^8
^{19}O	5/2	26.9	4.6	0.71	10^8
^{17}Ne	1/2	0.1		0.33	10^6

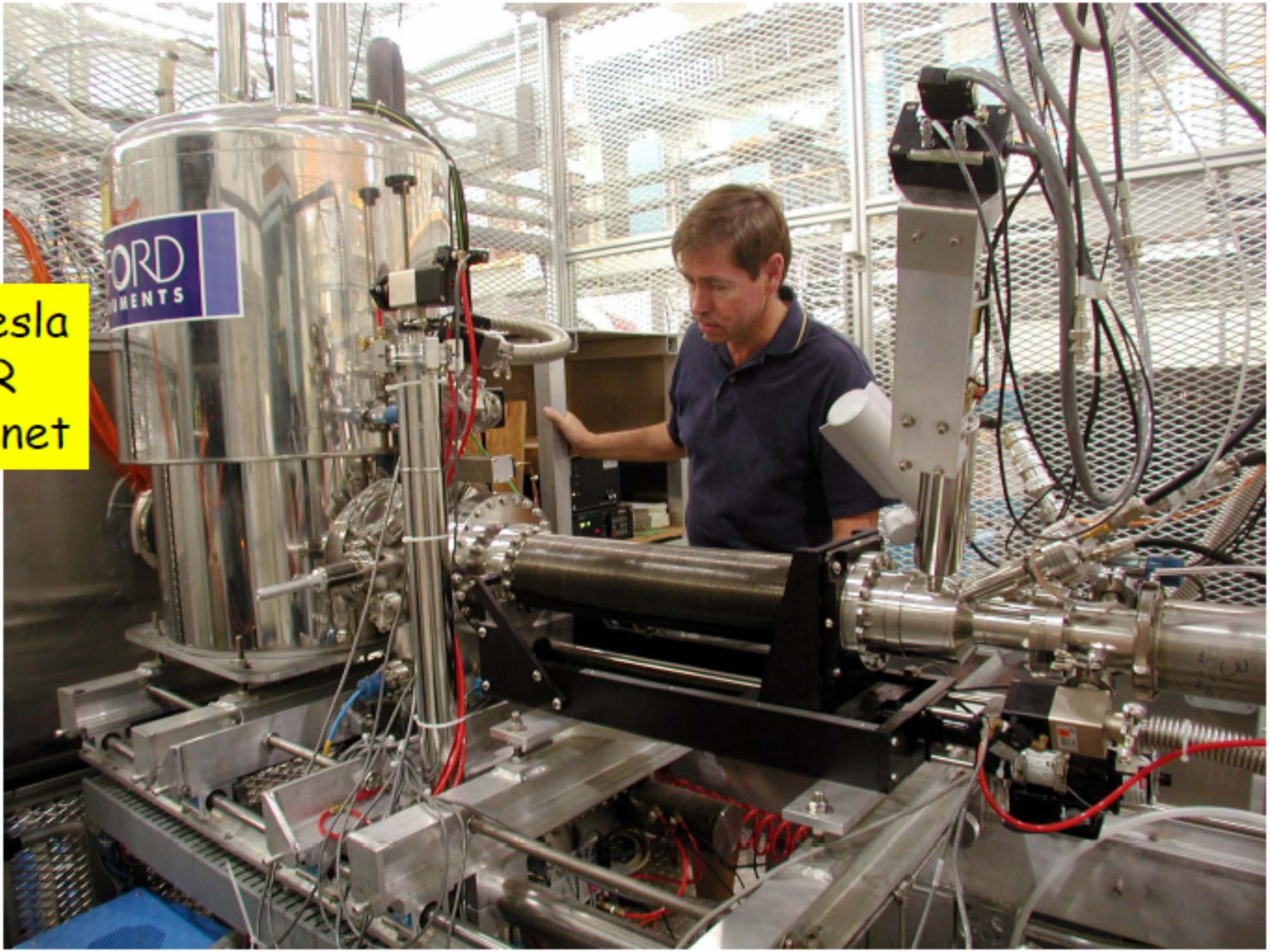
require: light, short-lived,
high asymmetry

ISAC at TRIUMF



βNMR Spectrometer

9 Tesla
NMR
Magnet



Currently (2013) the list of approved β -NMR experiments is:

β-NMR Investigation of Spin Polarized ^{8}Li in Semiconductors;

β -NMR Study of Single Molecule Magnets Films;

Light-Induced Magnetism in Manganite Thin Films Studied with β -NMR ;

β -NMR Search for Spontaneous Magnetism Near the Surface of Unconventional Superconductors;

β -NMR Investigation of Finite Size Effects in Metallic Thin Films and Nanoparticle Arrays;

Hyperfine Magnetic Fields in Fe/Ag Magnetic Multilayers Probed with Low Energy Spin Polarized ^{8}Li;

Depth Resolved β -NQR Study of the Cubic to Tetragonal Phase Transition in $SrTiO_3$ and Related Perovskite Compounds;

Magnetic Multilayers and Giant Magnetoresistance;

Semiconductor Quantum Wells Investigated by β -NMR;

β -NMR Investigation of Type-II Superconductors;

Absolute Magnetic Penetration Depth in the Meissner State of Superconductors Measured with Low Frequency β -NMR;

Photoinduced Dynamics and Reactivity of β -NMR Investigation of the Meissner State of Superconductors with Low-Energy Polarized 8Li;

Nature of the Quantum Critical Transition in the Electron-Doped Superconducting Films of $Pr_{2-x}Ce_xCuO_4$;

Unambiguous Site Identification of ^{8}Li in Cu Using Cross-relaxation;

Microscopic Investigations by β -NMR of Proximity Effects in Metal Superconductor Bilayers;

Investigation of Magnetic proximity effect by ^{8}Li β -NMR;

^{8}Li Investigation of Spin Transport through Ferromagnet-Semiconductor Junction;

Microscopic Investigations by β -NMR of Proximity Effects in Metal Superconductor Bilayers;

Investigation of Magnetic proximity effect by ^{8}Li β -NMR;

^{8}Li Investigation of Spin Transport through Ferromagnet-Semiconductor Junction;

β -NMR Investigation of the magnetism at the interface between insulating $SrTiO_3$ and $LaAlO_3$;

β -NMR experiment on $LiCoO_2$ film; low-T magnetism and high-T diffusive behavior;

β -NMR studies of the surface states of topological insulators;

Study of Vacancy Defects in Topological Insulators;

Studies of Interface Phenomena Involving Topological Insulators;

Depth-Resolved Measurements of Dynamics in Polymer Thin Films using Spin-Polarized Radioactive Probes;

Search for Electric Field Induced Magnetism Near the surface of Pd films;

β -NMR studies of topological crystalline insulator states;

Lithium diffusion in polymers;

Site identification of ^{8}Li in GaAs;

Surface and bulk spin reorientation transitions in Fe-oxide based systems studied using β -NMR;

β -NMR study of spin injection in Fe/GaAs heterostructures;

β -NMR study of interface effects in Li^{+} ion diffusion in solids;

^{8}Li β -NMR studies of the metallic state of strongly correlated transition metal oxides

Electric field induced transition in $SrTiO_3$;

β -NMR investigations of the topological magneto-electric effect.

•**Future studies**

•The same processes in new and complex substances.

•Quantum chemistry of fluorine or/and silver containing compounds (quadrupole interactions).

•Main new directions:

1) Study of reaction of damaged media on new damages, created during production of β-nuclei in the substance.

2) Study of reaction of substances with strong electron correlations on creation of β-nuclei in the sample.

3) Relaxation processes for quantum computing.

Reviews:

Yu.G.Abov, A.D.Gulko, F.S.Dzheparov. Physics of Atomic Nuclei **69**, 1701, 2006.

F.S.Dzheparov. J. Physics, Conf. Ser. **324**, 012004, 2011.

Yu.G.Abov, F.S.Dzheparov, A.D.Gulko, D.V.Lvov. Applied Magnetic Resonance **45**, 1205, 2014.

Last article on spin transport in model disordered system ^{8}Li-^{6}Li:

Yu.G.Abov, A.D.Gulko, F.S.Dzheparov et al. Physics of Atomic Nuclei **77**, 682, 2014.

Home page of Canada beta-NMR group:

http://bnmr.triumf.ca/

Чем заменить TRIUMF?

- Можно использовать реакцию срыва $^{7}Li(d,p)^{8}Li$ и обойтись скромными энергиями дейтонов в дипазоне 0.2-5 МэВ. Например, реакция $^{7}Li(d,p)^{8}Li$ имеет сечение около 175 mb в диапазоне энергий от 0.6 МэВ до 5 МэВ. Оценка длины пробега дейтрона в жидком литии с начальной энергией 5 МэВ дает значение $L \approx 0.06$ см и коэффициент преобразования дейтонов в ядра $\approx 5\times10^{-4}$. Поэтому для производства 10^{10} ядер ^{8}Li в секунду достаточно иметь ток дейтронов J=3мкА, что, по литературным данным, вполне реалистично. Выбранные параметры обеспечивают два порядка величины для компенсации потерь интенсивности пучка радиоактивных ядер на пути до мишени и при поляризации ядер.

Возможно создание пучков на основе любых из известных радиоактивных ядер. В настоящее время находят применение бета-активные ядра с временами жизни в интервале 0.01-100с и мессбауэровские состояния. Естественно ожидать, что в ближайшее будущем наибольшее применение найдут мессбауэровские ядра ^{57}Fe и следующие бета-активные ядра $^{8}Li(T_{1/2}=0.842с, I=2)$, $^{11}Be(13.8с, I=3/2)$, $^{12}B(0.0204с, I=1)$, $^{11}C(0.0204с, I=3/2)$, $^{15}C(2.45с, I=3/2)$, $^{12}N(0.0110с, I=1)$, $^{16}N(7.13с, I=2)$, $^{17}N(4.17с, I=1/2)$, $^{19}N(0.270с, I=1/2)$, $^{15}O(122с, I=1/2)$, $^{20}F(11с, I=2)$, $^{20}Na(0.446с, I=2)$, $^{25}Al(7.18с, I=5/2)$, $^{31}Al(0.644с, I=5/2)$, $^{27}Si(4.1с, I=5/2)$, $^{29}P(4.1с, I=1/2)$, $^{31}S(2.6с, I=1/2)$, $^{32}Cl(0.298с, I=1)$, $^{33}Cl(2.52с, I=3/2)$.

The ITEP works were fulfilled in collaboration with

S.S.Trostin, O.N.Ermakov, I.G.Ivanter, V.E.Shestopal, S.V.Stepanov, M.I.Bulgakov, S.P.Borovlev, V.M.Garochkin, A.A.Lyubarev

Thank you for attention!