Fresh Look at Tensor Polarized Deuterons at Nuclotron/NICA and HIAF

N.N. Nikolaev

L.D.Landau Institute of Theoretical Physis, Chernogolovka
N.N.Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna
Moscow Institute of Physics and Technology, Dolgoprudny

in collaboration with

D.Gou, V. Ladygin, F. Rathmann, A. Silenko, Yu. Uzikov

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XXth Workshop in High Energy Spin Physics

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Dedicated to the memory of

Igor M. Sitnik

(24.06.1941 – 29.07.2026)

an avid proponent of polarized deuterons

and

oscillating polarizations

Stay tuned to complementary talks:

- Yu.N. Filatov on Spin Transparency mode at the NICA accelerator complex. Plenary talk, 13:20, 11 Sept.

- Boxing Gou on Efforts towards polarized beams and spin physics at HIAF. Plenary talk, 09:30, 09 Sept.

Spin-1 deuterons are uniquely endowed with tensor polarization
Pioneering studies at LHEP, SATURNE, COSY (see V. Ladygin's talk)

Open issues for Nuclotron/NICA and HIAF:

- LHEP tensor asymmetries → is the deuteron more than a pn bound state?
- First look at the gluon tensor structure function of the deuteron
- Two-spin asymmetries in the unexplored energy domain
- Unique facility to search for the millistrong CP-violation beyond the Standard Model with potential implications for the baryon asymmetry of the Universe via vector-tensor spin asymmetry in pd scattering
- Tensor polarizability driven spin dichroism and birefringence
- Search for the new quantum number of the deuteron: tensor polarizability
- Polarized deuterons as axion and EDM antennas

One needs multiple switches of vector and tensor polarizations

- A new paradigm of continuous rf driven flips of bunch polarizations and time-stamped horizontal (radial & longitudinal) polarization

  Forerunners: I. Sitnik et al. (2002), JEDI Collab. (2012 and so forth)

  Challenges:

- Long polarization lifetime
- Stabilization of rapid precessions of the horizontal polarization
- Frequent switching of the relative polarization of colliding bunches
- Extraction of horizontally (radially & longitudinally) polarized beams onto external targets

Doable at the expense of very modest new instrumentation at Nuclotron/NICA and HIAF

Paves the road to the first experimental program of full scale tensor polarization physics

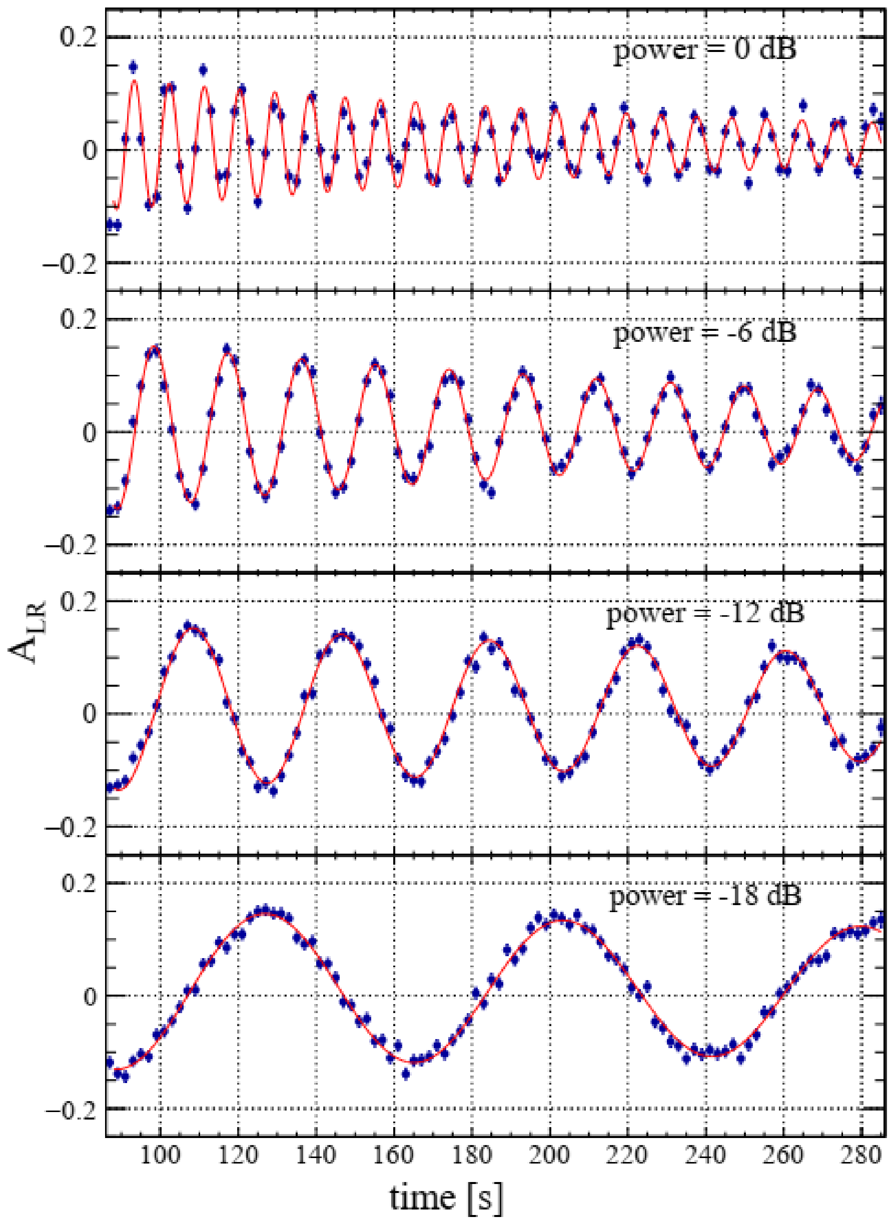
Proton spin lifetime in COSY: JEDI window to depolarization mechanism

C. Weidemann et al., Phys. Rev. ST Accelerators and Beams, 18, 020101 (2015)

- 49.3 MeV protons in COSY
- Without spin-flips the vertical polarization lifetime (2.7 +/- 0.5) 10^5 s
- 99 spin flips during 300 s (0.15 Hz)
- RF flipping polarization lifetime 240 s.
- Polarization loss by spin decoherence in the horizontal plane? Or is the spin-flip per se a culprit?
- JEDI: depolarization of the idle precession of the horizontal polarization. Tune sextupole families to zero chromaticity → spin coherence time up to 1500 s.

G. Guidoboni al. Phys. Rev. Lett. 117, 054801 (2016)

- **Presume the technique will be applicable at NICA and HIAF**



Spin decoherence: Spin-off from the JEDI axion search

S.Karanth et a., Phys. Rev. X 13, 031004 (2023)

- Polarization damping stronger for higher spin-flip frequency & larger spin-flip phase $x=2\pi f_{sf}\, t$
- First evidence for a **prominent** synchrotron oscillation driven depolarization: theory in

N. Nikolaev et al. *PRAB 27* (2024) 111002.

- Avergge over ensemble → Non-exponential attenuation and nonlinear spin-flip phase walk

$$D(x) = \frac{1}{\sqrt{1 + Q_{\rm sy}^2 x^2}} \qquad Q_{\rm sy} = \frac{1}{2}(K + G\gamma)^2 \sigma_{\rm sy}^2$$

$$\phi(x) = \arctan(Q_{\rm sy} x)\,.$$

$\sigma_{\rm sy} \ll 1$ is the rms angular length of a bunch

- JEDI data analysis is in progress

Spin envelopes in spin flip (y=vertical, x=radial, z= tangential, fipper axis)

- Idle precession: $\vec{S}(n) = \mathbf{R}_s(n\theta_s)\vec{p}(n)$

$$\theta_s = 2\pi\nu_s \qquad \nu_s = 2\pi G\gamma,$$

$$\mathbf{R}_s(\theta_s) = \begin{pmatrix} \cos\theta_s & 0 & \sin\theta_s \\ 0 & 1 & 0 \\ -\sin\theta_s & 0 & \cos\theta_s \end{pmatrix}$$

- Envelope with solenoid spin flipper

$$\vec{p}(n) = \mathbf{E}(x)\vec{p}(0) \qquad \mathbf{E}(x) = \begin{pmatrix} \cos x & \sin x & 0 \\ -\sin x & \cos x & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$S_y(n) = S_y(0)\cos x\,,$$
$$S_x(n) = S_y(0)\cos\theta\sin x\,,$$
$$S_z(n) = -S_y(0)\sin\theta\sin x\,,$$

- Oscillating helicity → SM P-violation

I.Koop et al. PEPAN 52, 549(2021)

- Doublle helicity pp, dd at NICA → gluon helicity SF
- Different imperfection fields in two rings may detune spin precessions → synchronize spin
- precessions by static Wien filters to fine tune spin ptrecession frequencies
- Periodical switch of one of the helicities by +/- π bumps of the spin precession phase by a static Wien filter

Tensor polarization of deuterons

- $\mathbf{T}_{\mathrm{mn}} = \frac{1}{2}(S_{\mathrm{m}}S_{\mathrm{n}} + S_{\mathrm{n}}S_{\mathrm{m}} - \frac{2}{3}\delta_{\mathrm{mn}}\vec{S}^2)$ 5 independent elements --- 5 dimensions ?

- Spin-1 dumbbell deuteron: S and D waves → electric quadrupole moment, entirely negligible effect in the magnetic storage rings
- Weak tensor polarizability. Never measured experimentally. Baryshevsky (2008)

- Tensor envelope evolution is entirely driven by that of the vector polarization

Silenko 2015, Nikolaev, Rathmann, Silenko, Uzikov (2020)

$$\mathbf{t}(n) = \mathbf{R}_{\mathrm{s}}^{-1}(n\theta_{\mathrm{s}})\mathbf{T}(n)\mathbf{R}_{\mathrm{s}}(n\theta_{\mathrm{s}})$$

$$\mathbf{t}(n) = \mathbf{E}(x)\mathbf{t}(0)\mathbf{E}^{\mathrm{T}}(x)$$

- only 3x3 matrices, no need to solve secular equaation in 5D

Evolution of tensor polarization: a reference particle

$$\left.\begin{array}{l}
\frac{1}{2}(t_{xx}(n) - t_{yy}\ (n)) = \\
= \frac{1}{2}(t_{xx}(0) - t_{yy}(0))\cos 2x + t_{xy}(0)\sin 2x\,, \\
t_{xy}\ (n) = -\frac{1}{2}(t_{xx}(0) - t_{yy}(0))\sin 2x + t_{xy}(0)\cos 2x
\end{array}\right\}$$

Vector in vertical XY plane, rotates with double spin-flip frequency

$$\left.\begin{array}{l}
t_{xz}(n) = t_{xz}(0)\cos x + t_{yz}(0)\sin x\,, \\
t_{yz}(n) = -t_{xz}(0)\sin x + t_{yz}(0)\cos x\,,
\end{array}\right\}$$

Vector in vertical XY plane, rotates with the spin-flip frequency

$$t_{zz}(n) = t_{zz}(0)\,,$$

Unique Fourier signatures!

We found eigenfunctions without ever troubling with a secular equation for 5x5 matrix

Where is millistrong parity-even T-violation?

$$\begin{aligned}\sigma_{tot} = \sigma_0 & \\ & + \sigma_{\rm tt}((\vec{P}^d \cdot \vec{P}^p) - (\vec{P}^d \cdot \vec{k})(\vec{P}^p \cdot \vec{k})) \\ & + \sigma_{\rm zz}(\vec{P}^{\rm d} \cdot \vec{k})(\vec{P}^{\rm p} \cdot \vec{k}) \\ & + \sigma^{\rm T} T_{\rm ab} k_{\rm a} k_{\rm b} \\ & + \sigma^{\rm p}_{\rm PV}(\vec{P}^p \cdot \vec{k}) \\ & + \sigma^{\rm d}_{\rm PV}(\vec{P}^{\rm d} \cdot \vec{k}) \\ & + \sigma^{\rm T}_{\rm PV}(\vec{P}^{\rm p} \cdot \vec{k}) T_{\rm ab} k_{\rm a} k_{\rm b} \\ & + \sigma_{\rm TVPV}(\vec{k} \cdot [\vec{P}^{\rm p} \times \vec{P}^{\times} d]) \\ & + \sigma_{\rm TVPC} k_{\rm a} T_{\rm ab} \epsilon_{\rm bcd} P^{\rm p}_{\rm c} k_{\rm d} \,,\end{aligned}$$

TVPC

$$k_{\rm a} T_{\rm ab} \epsilon_{\rm bcd} P^{\rm p}_{\rm c} k_{\rm d} = T_{\rm xz} P^{\rm p}_{\rm y} - T_{\rm yz} P^{\rm p}_{\rm x} \,.$$

Flavor conserving T- and C-violating millistrong interaction is a source of CP violation beyond the SM.

May it help to resolve a mistery of baryon asymmetry in the Universe? It remains an entirely unexplored option.

Depolarization from averaging over ensemble

- Spin tune $\nu_{\rm sf}(\xi) = \nu_{\rm sf} J_0(2\xi\sqrt{Q_{\rm sy}})$
- Spin-flip phase $x \to x(Q_{\rm sy}\xi) = J_0(2\xi\sqrt{Q_{\rm sy}x}) \approx (1 - Q_{\rm sy}\xi^2)x$
- Synchrotron amplitude distribution $F(\xi) = 2\xi\exp(-\xi^2)$

$$\frac{1}{2}(t_{\rm xx}(n) - t_{\rm yy}(n)) = D(2x)[(\frac{1}{2}(t_{\rm xx}(0) - t_{\rm yy}(0))\cos(2x - \phi(2x)) + t_{\rm xy}(0)\sin(2x - \phi(2x))],,$$

$$t_{\rm xy} = D(2x)[\frac{1}{2}(t_{\rm xx}(0) - t_{\rm yy}(0))\sin(2x - \phi(2x)) + t_{\rm xy}(0)\cos(2x - \phi(2)x))],,$$

$$t_{\rm xz}(n) = D(x)[t_{\rm xz}(0)\cos(x - \phi(x)) + t_{\rm yz}(0)\sin(x - \phi(x))],$$

$$t_{\rm yz}(n) = D(x)[-t_{\rm xz}(0)\sin(x - \phi(x)) + t_{\rm yz}(0)\cos(x - \phi(x))],$$

$$t_{\rm zz}(n) = t_{\rm zz}(0),$$

Boundary condition for stored polarization

$$\langle \vec{S} \rangle = S_{\mathrm{y}} \vec{e}_{\mathrm{y}}, \quad \langle S_{x,z}(0) \rangle = 0,$$

$$\langle T_{yx}(0) \rangle = \langle T_{yz}(0) \rangle = \langle T_{xz}(0) \rangle = 0\,, \qquad \langle T_{xx}(0) \rangle = T_{zz}(0) \rangle = -\frac{1}{2} \langle T_{yy}(0) \rangle\,.$$

Flipping & depolarizing and spectator components of **T**

$$\frac{1}{2}[T_{\mathrm{xx}}(n) - T_{\mathrm{zz}}(n)] = \frac{3}{8}\langle T_{\mathrm{yy}}(0)\rangle \cos(2\theta_{\mathrm{s}} n) - \frac{3}{8}\langle T_{\mathrm{yy}}(0)\rangle \underline{Q(2x)\cos(2x - \phi(2x))} \cos(2\theta_{\mathrm{s}} n)$$

$$T_{\mathrm{xz}}(n) = -\frac{3}{8}\langle T_{\mathrm{yy}}(0)\rangle \sin(2\theta_{\mathrm{s}} n) + \frac{3}{8}\langle T_{\mathrm{yy}}(0)\rangle \underline{Q(2x)\cos(2x - \phi(2x))} \sin(2\theta_{\mathrm{s}} n)\,,$$

$$T_{\mathrm{xy}}(n) = \frac{3}{4}\langle T_{\mathrm{yy}}(0)\rangle \underline{Q(2x)\sin(2x - \phi(2x))} \cos(\theta_{\mathrm{s}} n)\,,$$

$$T_{\mathrm{zy}}(n) = -\frac{3}{4}\langle T_{\mathrm{yy}}(0)\rangle \underline{Q(2x)\sin(2x - \phi(2x))} \sin(\theta_{\mathrm{s}} n)\,,$$

$$\frac{1}{2}T_{\mathrm{yy}}(n) = -\frac{1}{2}[T_{\mathrm{xx}}(n) + T_{\mathrm{zz}}(n)] = \frac{1}{8}\langle T_{\mathrm{yy}}(0)\rangle + \frac{3}{8}\langle T_{\mathrm{yy}}(0)\rangle \underline{Q(2x)\cos(2x - \phi(2x))}],\,,$$

Fresh look at the tensor polarimetry

- CNI polarimetry is indispensable (consumes a tiny fraction of the beam interactions)
- Take advantage of the Glauber eclipse effect driven dichroism complement the CNI polarimeter by large FOM forward counters to detect inelastic interaction

$$\sigma_{\rm tot} = \sigma_0(1 + A_{\rm zz}T_{\rm zz})$$

- Analyzing power A_{zz} ~0.3%
- Fourier extraction of the tensor asymmetry

$$T_{\rm zz}(n) = \frac{1}{2}\langle T_{\rm yy}(0)\rangle\{-1 + \frac{3}{2}\sin^2(\theta)[1 + Q(2x)\cos(2x - \phi(2x))]\}$$

- **Tensor comagnetrometry:**
- Fourier analysis of the tensor polarimeter → spin precession frequency
- Basis of synchronization of spin precessions in two rings by static Wien filters

Prospects of the Fourier analyzed flipping and oscillating deuteron polarization at Nuclotron/NICA

- Spin flip frequency 0.02 Hz → 144 flips for 1 h fill
- NICA bunch length ~60 cm → σ_{sy}=0.0012, ~ 100 times smaller than at COSY!

  O. Kozlov et al. PEPAN 53, 1021 (2022)
- RF solenoid run at side band K=0: Q_{sy} = 7e-7
- 1 h fill: Q_{sy} x ~ 0.001 → synchrotron oscillation effects were sunstantial at COSY but are expected to be entirely negligible at NICA away of spin resonances
- Still shorter bunches are anticipoated at HIAF

Conclusions

New instrumentation per Nuclotron and NICA rings:

- RF solenoid spin-flippers
- Resonably large FOM detectors to count inelastic events for the comagnetometry purposes
- Static Wien filters for synchronization of polarizations of colliding bunches: CW ring as a comagnetometer for ACW ring
- The same static Wien filters for switching the relative polarization of colliding bunches
- A feedback from vertical polarization to synchronize the spin-flip phases of colliding bunches

The oscillating polarization regime is feasible at NICA

Thank you for your patience!

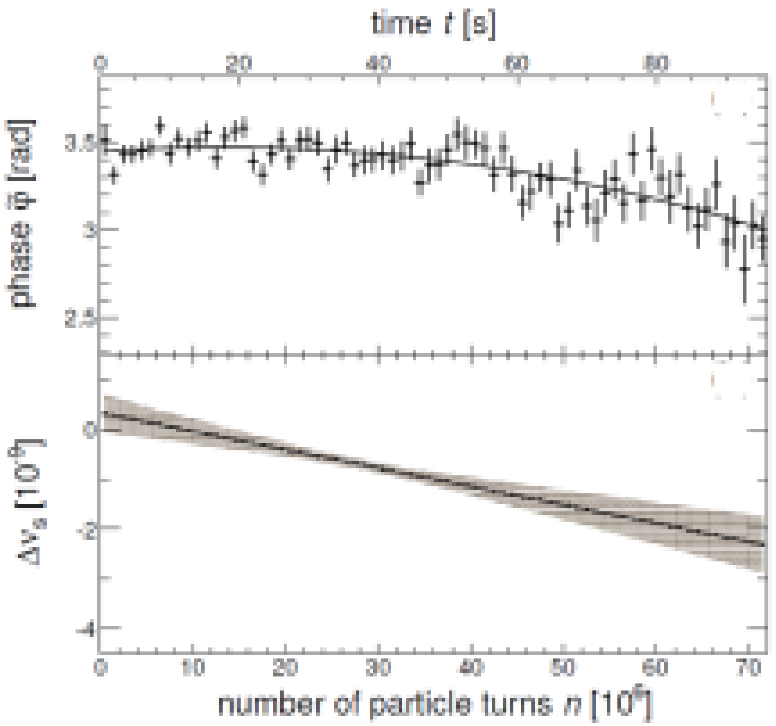
Precision determination of the spin tune [13] II

JEDI Collab. @ COSY

Precise time-stamping of events,

- allows us to monitor phase of measured asymmetry with (assumed) fixed spin tune ν_s in a 100 s cycle:

$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{d\tilde{\phi}}{dn} \qquad (9)$$
$$= \nu_s^{\text{fix}} + \Delta\nu_s(n)$$



Origin of frequency walk:
hystereis in magnets?
unstable temperature?

COSY was not designed as even 10^{-6} ring

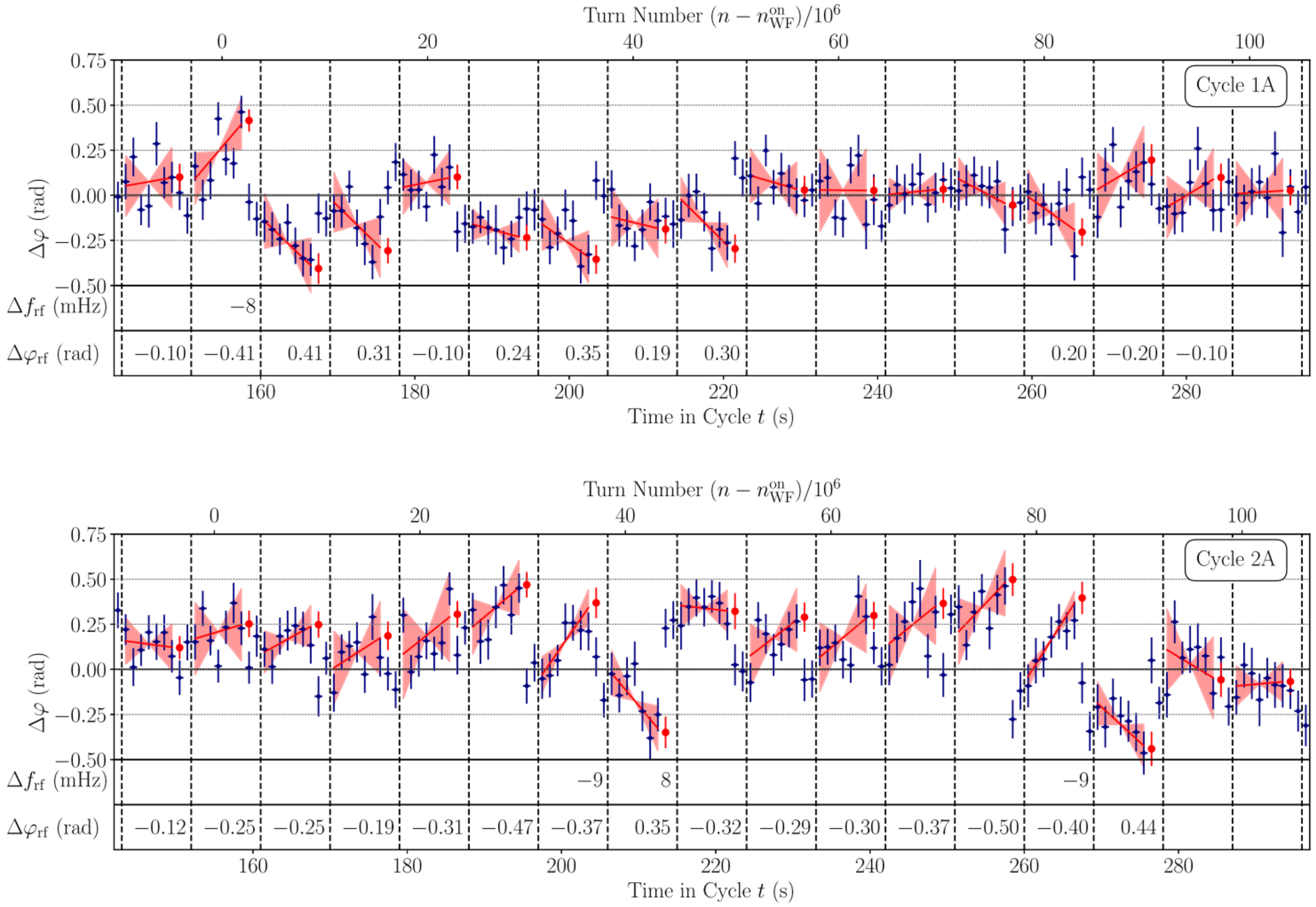
Experimental technique allows for:

- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval.
- In a 100 s cycle at $t \approx 38$ s, interpolated spin tune amounts to $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$, *i.e.*, $\Delta\nu_s/\nu_s \approx 10^{-10}$.
- $\Rightarrow$ **new precision tool to study systematic effects in a storage ring.**

Excellent example of Ramsay's theorem in action

JEDI @ COSY: example of corrections for the spin precession phase walk

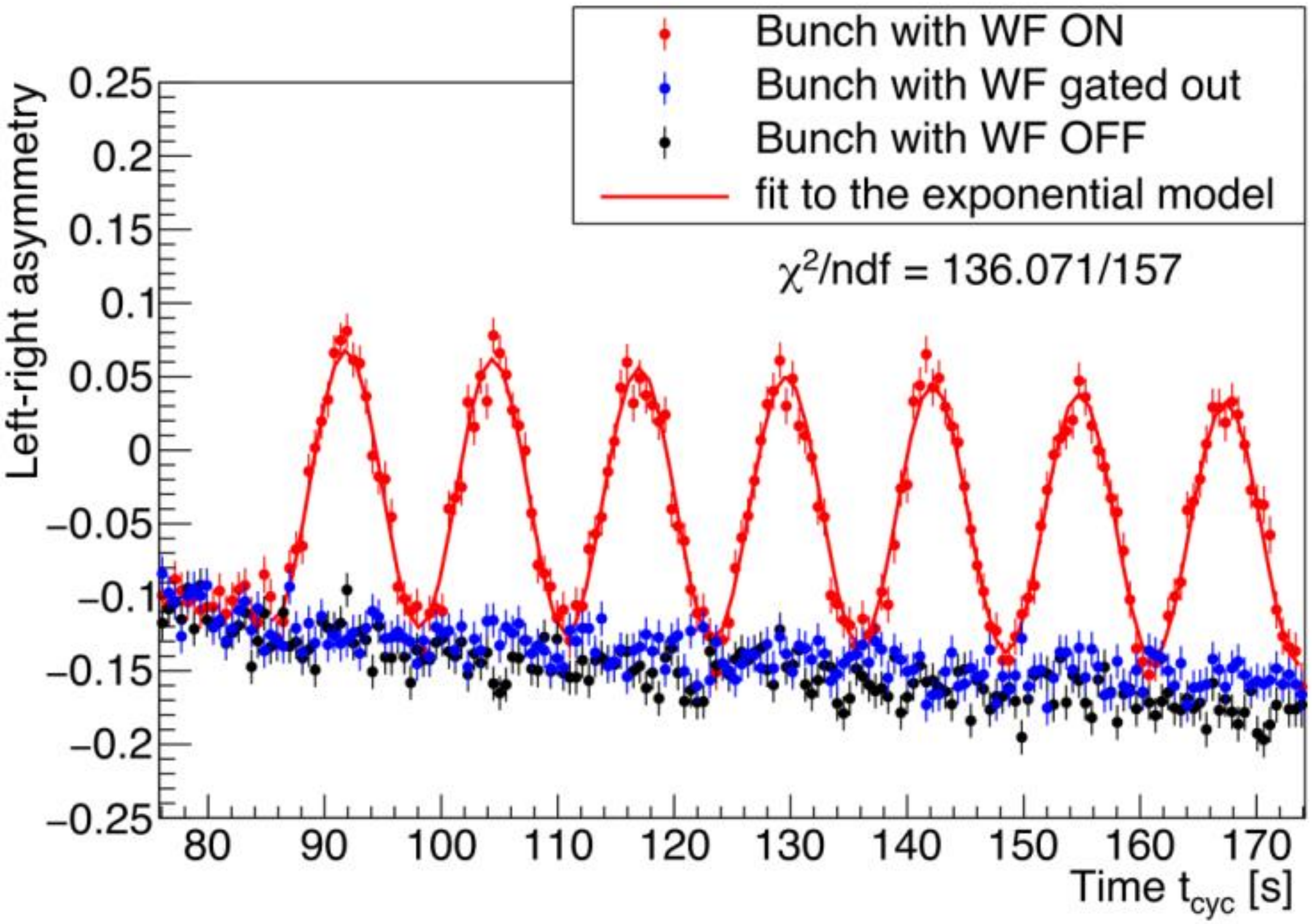
V. HEJNY *et al.* PHYS. REV. ACCEL. BEAMS **28**, 062801 (2025)



$\sigma_\phi = 0.2$ rad

Comagnetometry for continuous spin flips to maintain the spin resonance: monitor the in-plane precession of gated out pilot bunch

JEDI, J. Slim et al. *Phys.Rev.Res.* 7 (2025) 2, 023257



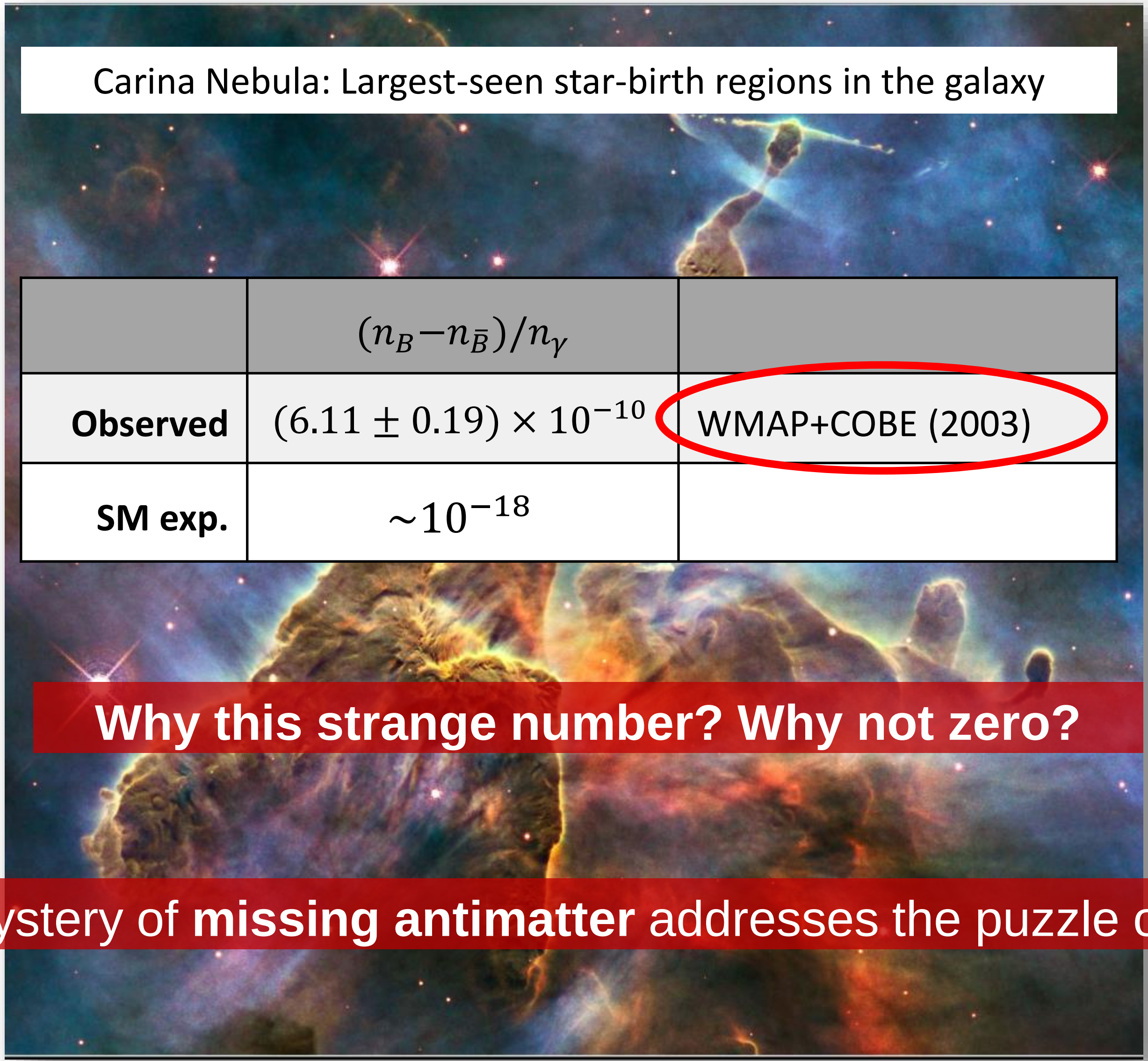
Fast switches with switch time of < 10 ns

f_{SF} =0.07944+/-0/.00010 Hz

1 h SF phase walk ~ 2 rad

Synchronize SF phases of colliding bunches by the flipper field strength

CP and the observed Baryon Asymmetry in Universe



Carina Nebula: Largest-seen star-birth regions in the galaxy

	$(n_B - n_{\bar{B}})/n_\gamma$	
Observed	$(6.11 \pm 0.19) \times 10^{-10}$	WMAP+COBE (2003)
SM exp.	$\sim 10^{-18}$	

Why this strange number? Why not zero?

Mystery of **missing antimatter** addresses the puzzle of our existence

Sakharov's fundamental criterions

- Baryon number noncoservation
- CP violation
- Nonequilibrium expansion at baryon number generation

All present in the SM, bot it is short of strength

Electric dipole moments (EDMs)

For particles with EDM $\vec{d}$ and MDM $\vec{\mu}$ ($\propto \vec{s}$),

- non-relativistic Hamiltonian:

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

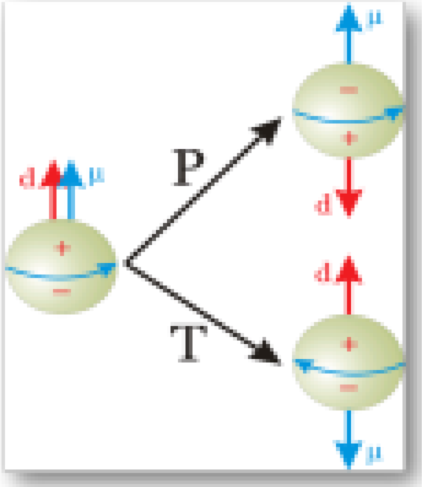
- **Energy of magnetic dipole** invariant under P and T:

$$-\vec{\mu} \cdot \vec{B} \overset{P \text{ or } T}{\Longrightarrow} -\vec{\mu} \cdot \vec{B}$$

No other direction than spin $\Rightarrow$ $\vec{d}$ parallel to $\vec{\mu}$ ($\vec{s}$).

- **Energy of electric dipole** $H = -\vec{d} \cdot \vec{E}$, includes term

$$\vec{s} \cdot \vec{E} \overset{P \text{ or } T}{\Longrightarrow} -\vec{s} \cdot \vec{E}, \qquad (1)$$



EDMs violate both P and T symmetry

- EDMs possibly constitute the missing cornerstone to explain surplus of matter over antimatter in the Universe.
  - Non-vanishing EDMs would add 4th quantum number to fundamental particles (besides m, q, and s).

Naive estimate of scale of nucleon EDM

(Okun, 1965)

From Khriplovich & Lamoreux [4] and Nikolaev [5]:

- CP and P conserving magnetic moment $\approx$ nuclear magneton μ_N.

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\,\mathrm{e\,cm}.$$

- A non-zero EDM requires:
  - P violation: price to pay is $\approx 10^{-7}$, and
  - CP violation (from K decays): price to pay is $\sim 10^{-3}$.
- In summary:

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\,\mathrm{e\,cm}}$$

- In Standard model (without θ_{QCD} term):

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-24}\,\mathrm{e\,cm} \sim 10^{-31}\,\mathrm{e\,cm}}$$

Region to search for Beyond Standard Model (BSM) physics

- from nucleon EDMs with $\theta_{QCD} = 0$:

$$\boxed{10^{-24}\,\mathrm{e\,cm} > |d_N| > 10^{-31}\,\mathrm{e\,cm}}.$$

PSI(2020): ultracold neutrons

$d_n < 1.8\mathrm{x}10^{-26}$ e cm --- about ultimate limit with neutrons, possible improvements by at most factor 10

Don't ask too much from dimensional estimates:

SM: Shabalin, 1978
Extra suppression by QCD coupling at electroweak scale

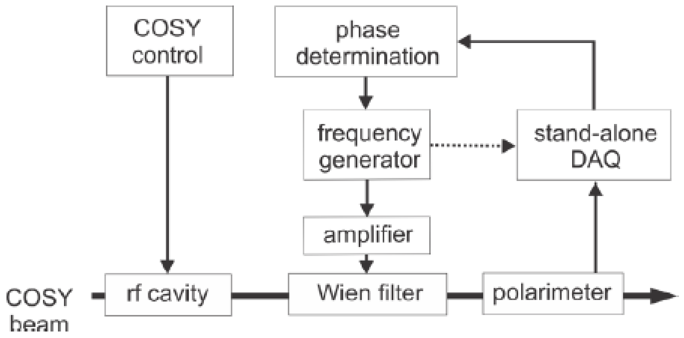
$d_n \sim 10^{-34}$ e cm

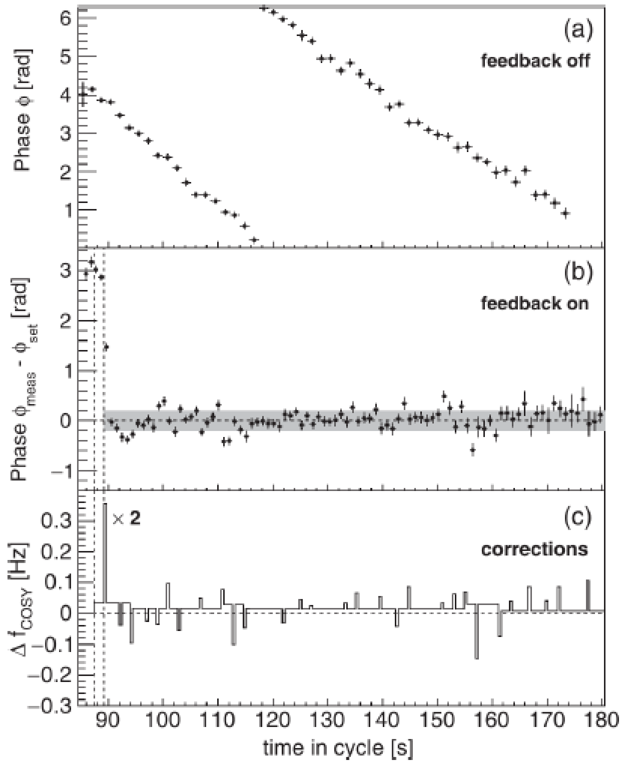
Confirmed by later studies

Phase locking spin precession in machine to device RF

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)

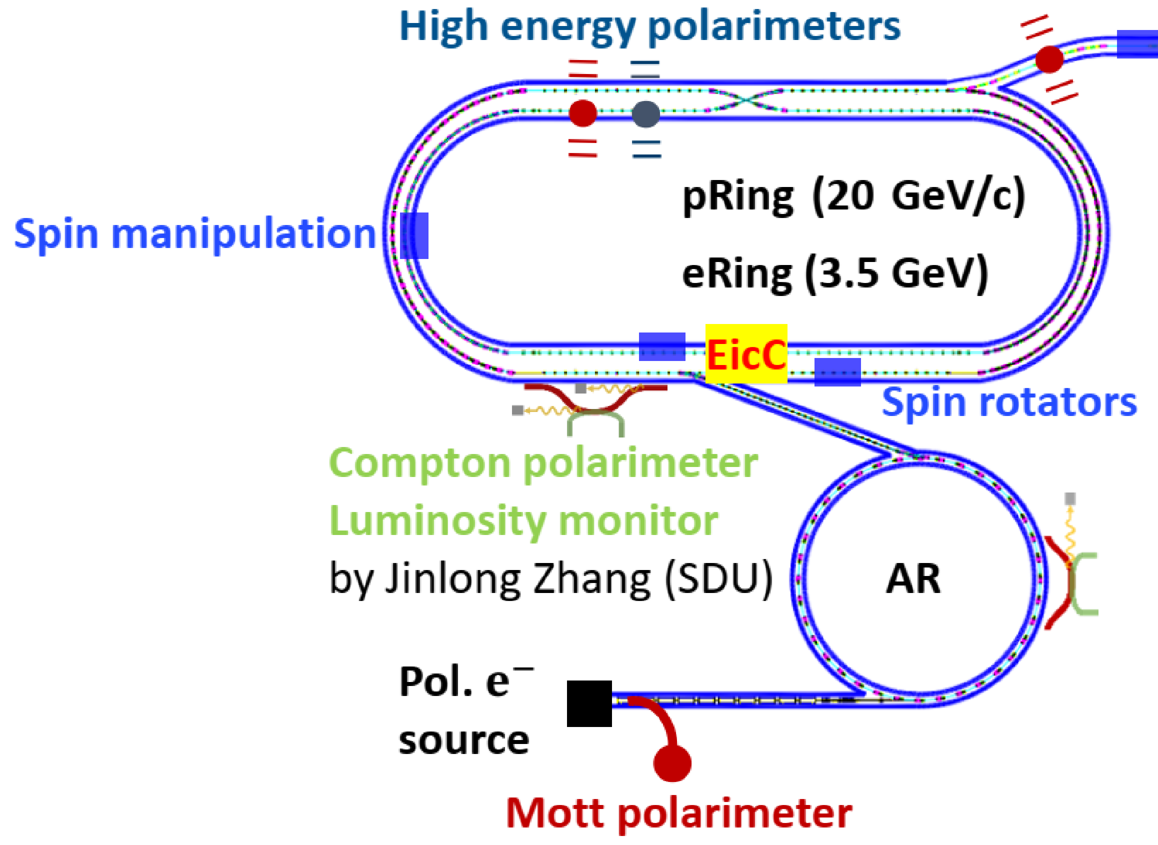




Major achievement : Error of phase-lock $\sigma_\phi = 0.21$ rad [18].

A uniqe case of self-comagnetometry in idle precession vs. standard two-species comagnetometry

HIAF-EicC



High Intensity Heavy-ion Accelerator Facility (HIAF)

✓ to be commissioned in 2025

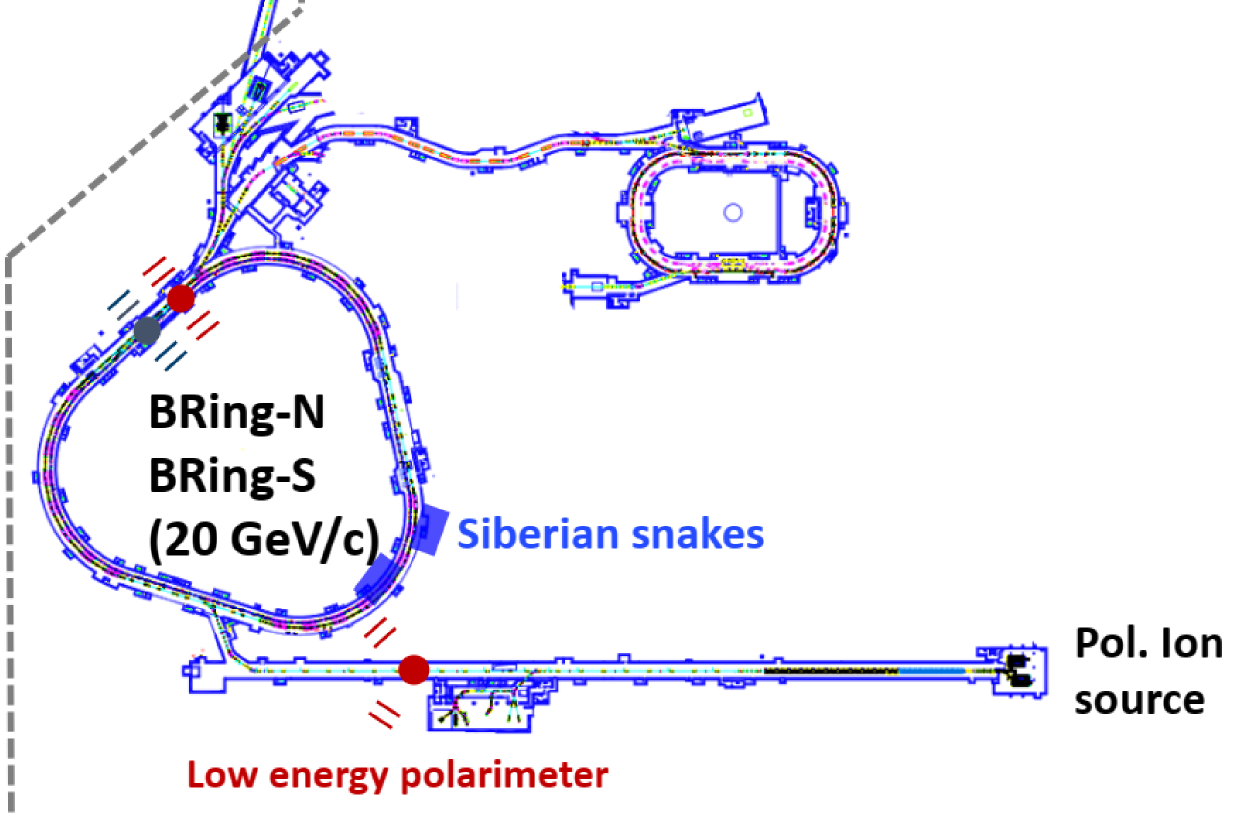
Zhou *et al. AAPPS Bulletin* (2022) 32:35
https://doi.org/10.1007/s43673-022-00064-1

AAPPS Bulletin

REVIEW ARTICLE Open Access

Status of the high-intensity heavy-ion accelerator facility in China

Xiaohong Zhou*, Jiancheng Yang and the HIAF project team

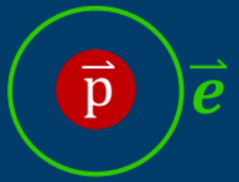


Electron ion collider in China (EicC)

- currently being proposed
- initial driving force of polarized beam development at IMP

Spin physics at HIAF

- Nice spin physics at HIAF with polarized target and (un)polarized beams
- Polarized gas target will be used as both proton target and electron target



- Ideas and collaborations are more than welcome!

① pol. e target **unpol. beams (A, p)**

$Z^{Q+} + \vec{e} \rightarrow Z^{(Q-1)+} + \hbar\omega$ pol. electron capture (atomic physics)

$p\vec{e} \rightarrow pe$ proton EM radii, new boson search

② pol. p target **unpol. heavy ion beams (C, Ca, Au, …)**

$A\vec{p} \rightarrow Ap$ → many body structure
nuclear physics

③ heavy target **pol. d beams**

$\vec{d}A \rightarrow Anp$ EOS nuclear physics

④ pol. p target **pol. p beams**

$p\vec{p} \rightarrow pp$
$\vec{p}\vec{p} \rightarrow pp$

$\left.\begin{array}{l} A_{\mathrm{N}} \\ A_{\mathrm{NN}} \end{array}\right\} \rightarrow$ NN spin dynamics
glueball in t channel
hadron physics

⑤ pol. d target **pol. p beams**

$\vec{p}\vec{d} \rightarrow pd$ test of time reversal symmetry

Testing SM by Parity Violation (PV)

- The observable: PV beam helicity dependence of the total X-section and elastic scattering
- New approach: single turn extraction of horizontal polarized beam onto extrenal target--- time-tag control of the extracted horizontal beam helicity
- A challenge to experimentalists: the expected asymmetries are few 10^{-8} to 10^{-7} --- counting events is entirely hopeless, measure beam current upstream and downstream thick nuclear target instead
- I.A. Koop, A.I. Milstein, N.N. Nikolaev, A.S. Popov, S.G. Salnikov, P.Yu. Shatunov, Yu.M. Shatunov, *Tests of Fundamental Discrete Symmetries at the NICA Facility: Addendum to the Spin Physics Programme*, Physics of Particles and Nuclei, 52(4), 549-554 (2021); Physics of Particles and Nuclei, 52(6), 1044-1119 (2021)
- Polarimetry requirements: < 1 GeV/c deuterons are favored
- High energy: B.G. Zakharov, Sov. J. Nucl. Phys. Sov. J. Nucl. Phys., 42 (3), 479-482 (1985)]