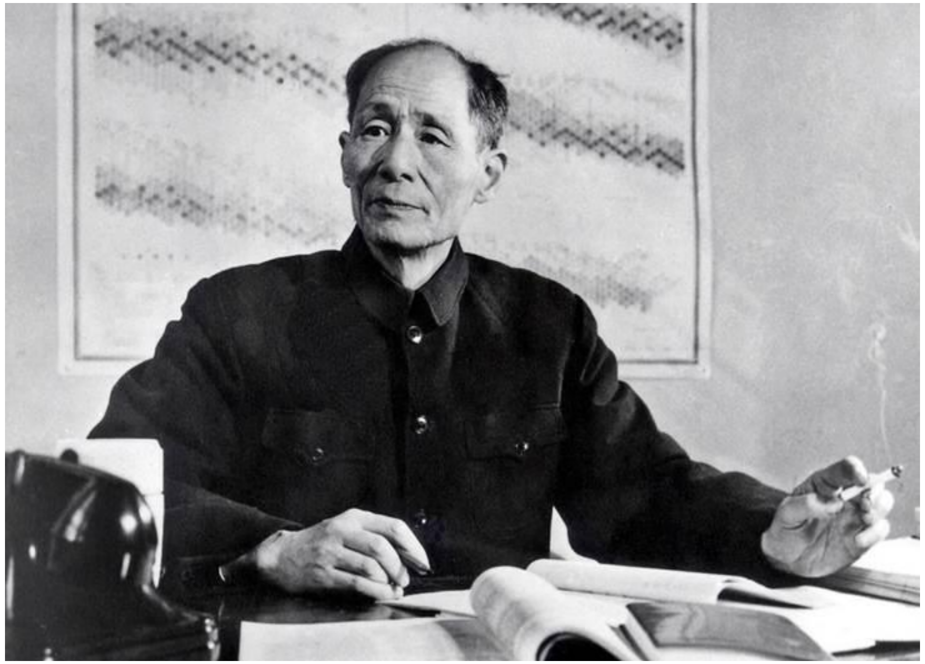
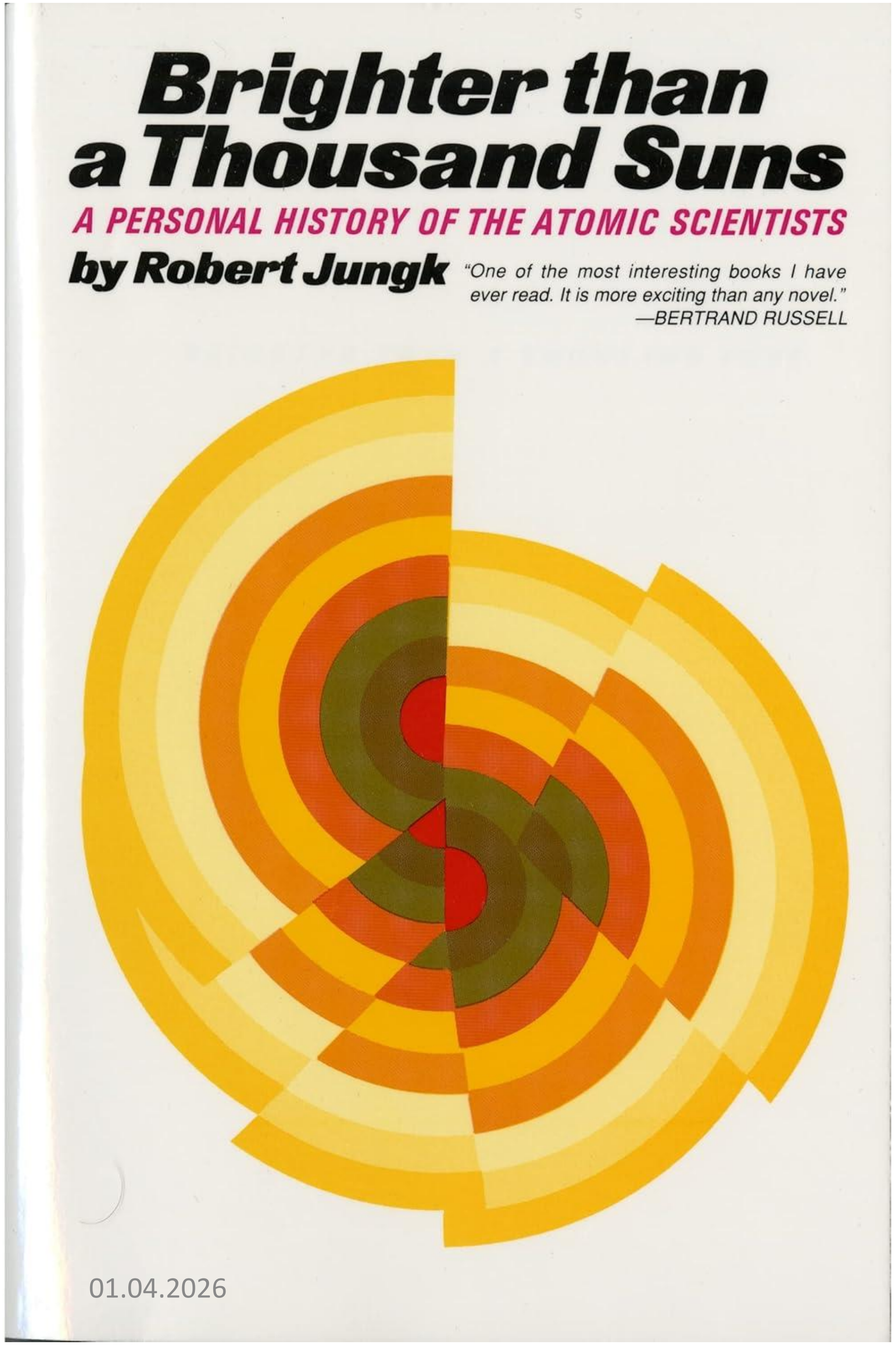


杨澄中
Forum

Lanzhou IMP CAS
Huizhou, 03.04.2026

Tests of Fundamental symmetries at storage rings and HIAF-EicC as a Silk Road to T-violation and Axions

Nikolai Nikolaevich Nikolaev
L.D. Landau Institute of Theoretical Physics
Russian Academy of Sciences



One of the most interesting books I have ever read.
It is more exciting than any novel.

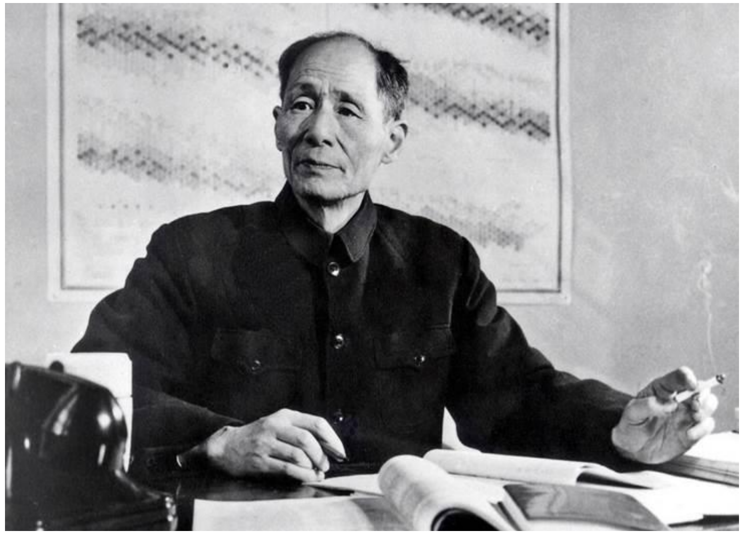
--- BERTRAND RUSSELL

This truly fascinating book was one of major reasons I got interested in nuclear and particle physics, and applied in 1964 to Moscow Institute of Physics and Technology and, thanks to Prof. Yang Jiancheng and Dr. Boxing Gou, eventually made it to this forum

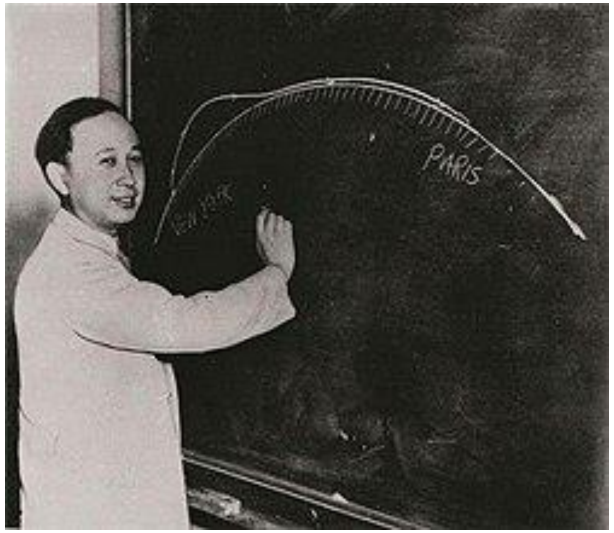
Nuclear Heros of XX Centrury

杨承宗

杨澄中



钱学森

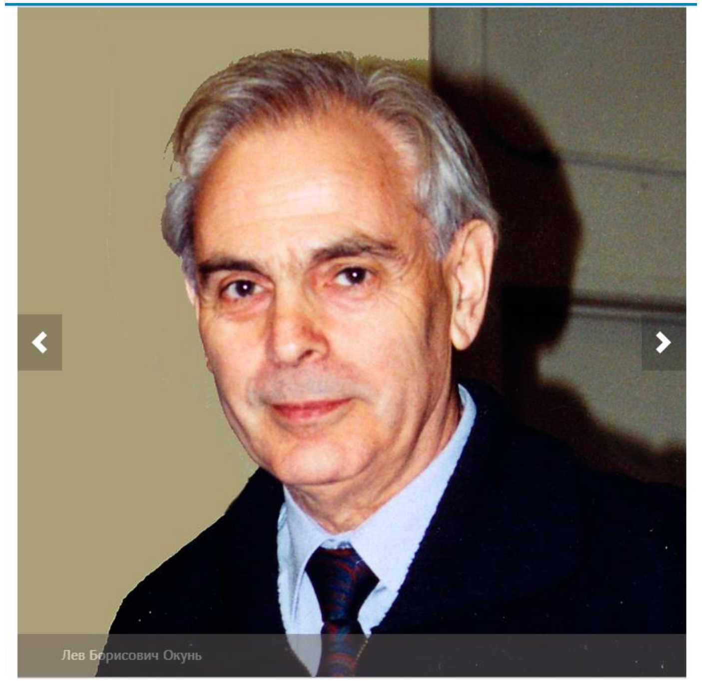


周光召

周光召 worked in Joint Institute of Nuclear Physics in Dubna, USSR (1957-1960), published about 20 papers, closely collaborated with prof. L. Lapidus. Foreign member of the Russian Academy of Sciences (1988)

Lev Borisovich Okun

One of Designers of the 1st Chinese Research Reactor

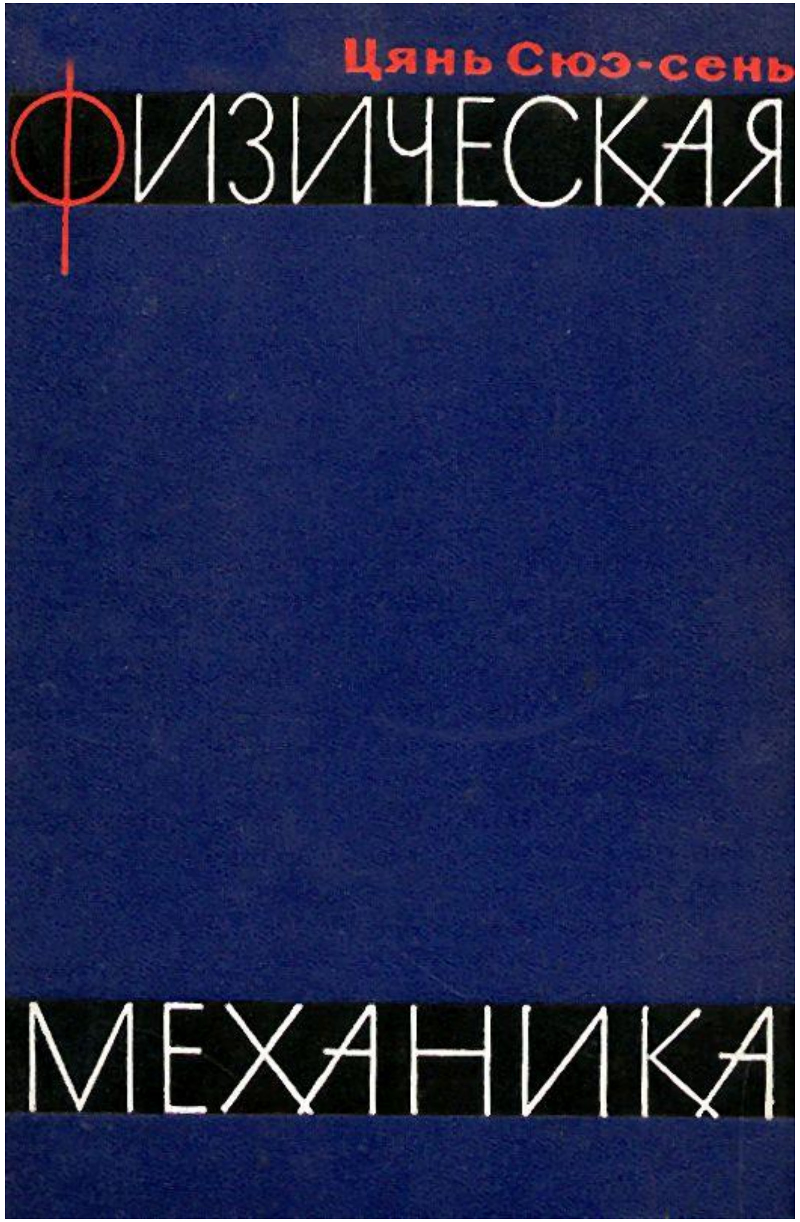


ITEP: Institute of Theoretical and Experimental Physics, Moscow (Lab-3 of Soviet Atomic Project, Heavy Water Reactors, Thorium Cycle. Theory Department: Landau, Pomeranchuk et al.)

Host of the Chair of Elementary Particle Physics of the Moscow Institute of Physics & Technology (MIPT, Fiztekh)

Alma mater: 1964-1970 MS (graduate classes from 7th semester on at ITEP), 1970-1973 PhD (ITEP).

3 semesters in the neutron physics lab at the ITEP Heavy Water Reactor, after passing the Landau theoretical minimum exam in 1966 became a theory student of Okun.



Qián Xuésēn, Physical Mechanics, Russian edition, 1965

Reaction of a 3rd semester student in 1965: 650 pages of a strange collection of quite diverse subjects, didn't look like a textbook in any one of them.

Hence I put it aside and refrained from purchasing.

The same former student, as a fresh member of the Landau Institute of Theoretical Physics in 1973: spotted the book in the Institute library.

And heard a comment by a senior colleague who had started his scientific carrier in the Soviet Atomic Project:

"A remarkable book! All you always wanted to know about how to manufacture nuclear bomb, but were afraid to ask about. You don't need a nuclear spy to learn that by early 1960's Chinese had a full knowledge of how to accomplish that."

The proof came at Lop Nur in 1964.3

Two proven pillars of modern physics: QCD and electroweak SM

- Unification of QED and the Fermi-Lee-Yang-Feynman-Gell-Mann-Marshak-Sudarshan theory of weak interactions

- The Yang-Mills nonabelian gauge theory → Fritzsch-Gell-Mann → QCD

- Khriplovich-t'Hooft-Politzer-Gross-Wilczek QCD → asymptotic freedom
  → quantitative theory of short range strong interactions
  but as yet with a limited success in the low energy physics

- **A triumph of the SM**: the discovery at LHC of the Higgs boson
  with a mass close to some expectations from the SM + some experimental input

- **A major frustration for LHC: an unforgiving Nature** decided to reject
  a supersymmetric unification of QCD and EW SM

- A legacy of supersymmetry: new mathematics
  46200 published papers
  3940 PhD theses
  410 books

More Flies in the Ointment (in Russian: a spoon of tar in a jar of honey) → strong need for the Physics Beyond the Standard Model (BSM)

- Unresolved mass hierarchy in the SM: from 0.1 eV for ν to 0.2 TeV for the top-quark
- Neutrino mixing: who set the mixing angles? Mixing of quarks? Scale for CP violation?
- Inflation in early Universe
- CP in QCD: CP-odd $L_{\bar{\theta}} = -\frac{1}{32\pi^2}\bar{\theta} g_S^2 G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$ is allowed, leads to the neutron EDM
- PSI (2020): $d_n < 1.8\times10^{-26}$ e·cm → $\bar{\theta} \sim 10^{-10}$. Who ordered such a fantastic suppression?
- Origin of dark matter: Peccei-Quinn axions?
- Our very existence → baryon asymmetric Universe from the zero baryon number Big Bang
  → Sakharov's fundamental criterions: Baryon number noncoservation
  CP violation
  Nonequilibrium expansion at baryon number generation
- SM asymmetry ~ 10^{-18} instead of observed 6×10^{-10} . Wrong timing of baryon generation, wrong phase transition, and much too feeble CP violation. 60 years after Sakharov's work as yet an open issue!

Legacy of baryon asymmetry: 4200 publications, 450 PhD theses, 15 books

As yet poorly explored millistrong CP violation BSM

- Suggested by L. Okun ; T.D. Lee & L. Wolfenstein ; J. Prentki & M. Veltman (1965) to explain CP(T)-violating $K_L \rightarrow 2\pi$ decay discovered by J. Cronin et al. in 1964.

- Millistrong (semistrong) as CP-violation is an ~ 10^{-3} effect

- CPT theorem: T(CP)-violating, P-conserving (TVPC) → C-violating ! Matter-antimatter asymmetry
- Searched for in the direct and inverse nuclear reactions, nuclear γ-transitions, spin observables in polarized **pp** scattering, hyperon decays . . . all in vain

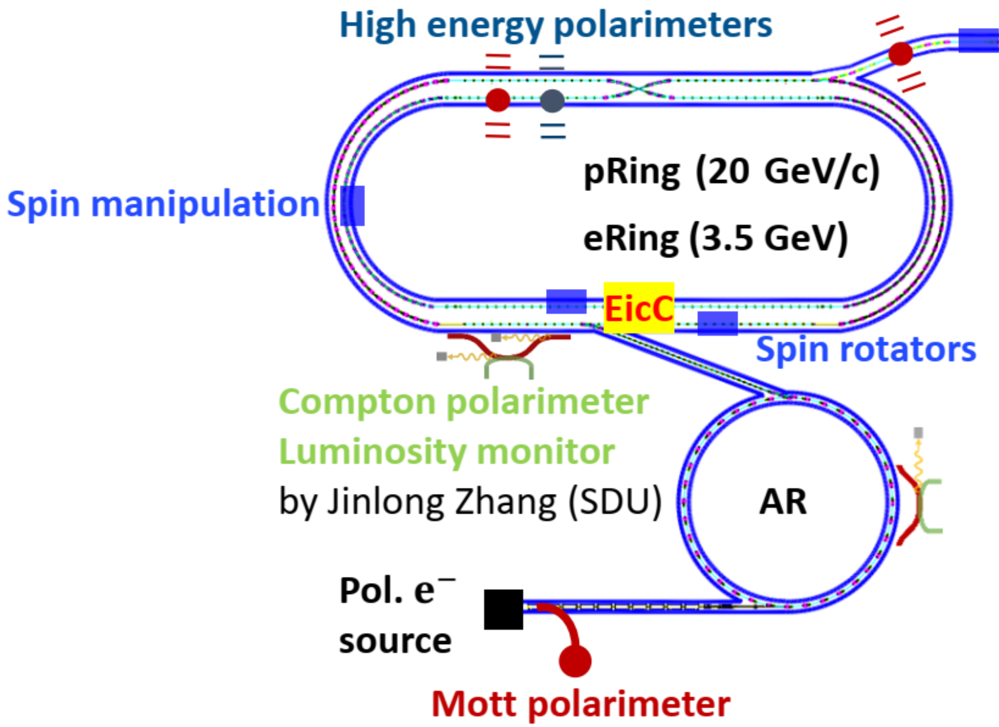
- Plausible reasons: no room for fundamental TVPC interaction in the SM
- In the meson-baryon world TVPC ρ-exchange is possible but numerically T-violation effects are strongly suppressed

- TVPC can be realized as a nonrenormalizable 4-fermion interaction → strong at short distances and high temperatures in the early Universe

- Need smart students to expore whether the mullistrong interaction might boost a baryogenesis

Silk Road to Millistrong T-Violation

HIAF-EicC



High Intensity Heavy-ion Accelerator Facility (HIAF)

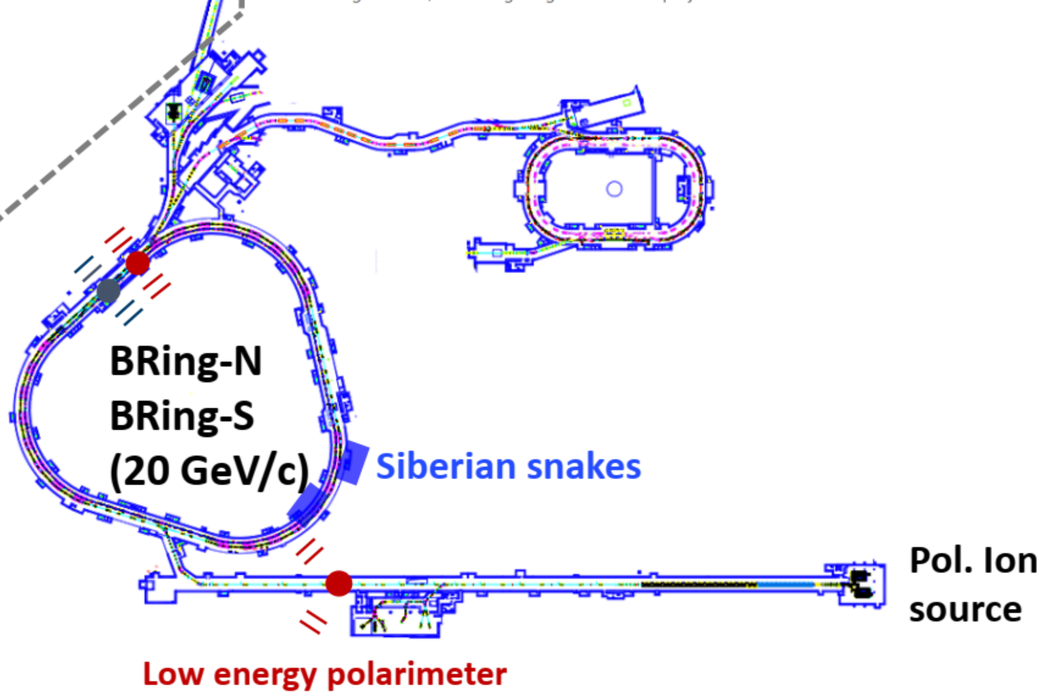
✓ **to be commissioned in 2025**

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

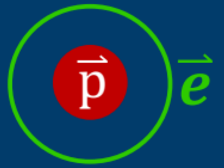


Electron ion collider in China (EicC)

- **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**

$p\vec{p} \rightarrow pp$

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

A_{N}, A_{NN} → 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

25

Courtesy of Boxing Gou

Null experiment TVPC observable in pd total X-section at ~10^{-6} sensitivity

Inspired by the JEDI collaboration expts at COSY ring in Juelich

$$\sigma_{\mathrm{tot}} = \sigma_0 + \sigma_{\mathrm{TT}}\left[\left(\mathbf{P}^{\mathrm{d}}\cdot\mathbf{P}^{\mathrm{p}}\right) - \left(\mathbf{P}^{\mathrm{d}}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\mathrm{p}}\cdot\mathbf{k}\right)\right]$$
$$+ \sigma_{\mathrm{LL}}\left(\mathbf{P}^{\mathrm{d}}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\mathrm{p}}\cdot\mathbf{k}\right) + \sigma_{\mathrm{T}} T_{mn}k_m k_n$$
$$+ \sigma^{\mathrm{p}}_{\mathrm{PV}}\left(\mathbf{P}^{\mathrm{p}}\cdot\mathbf{k}\right) + \sigma^{\mathrm{d}}_{\mathrm{PV}}\left(\mathbf{P}^{\mathrm{d}}\cdot\mathbf{k}\right)$$
$$+ \sigma^{\mathrm{T}}_{\mathrm{PV}}\left(\mathbf{P}^{\mathrm{p}}\cdot\mathbf{k}\right) T_{mn}k_m k_n$$
$$+ \sigma_{\mathrm{TVPV}}\left(\mathbf{k}\cdot\left[\mathbf{P}^{\mathrm{d}}\times\mathbf{P}^{\mathrm{p}}\right]\right)$$
$$+ \sigma_{\mathrm{TVPC}} k_m T_{mn}\epsilon_{nlr}P^{\mathrm{p}}_{l}k_r .$$

Y-axis is normal to the ring plane

Z-axis $\mathbf{k}$ is a collision axis along the beam momentum,

$$k_m T_{mn}\epsilon_{nlr}P^{\mathrm{p}}_{l}k_r = T_{xz}P^{\mathrm{p}}_{y} - T_{yz}P^{\mathrm{p}}_{x} .$$

Off-diagonal tensor polarization is a a must for the T-violation signal

Polarized deuteron beam, rf NMR spin flipper, internal nuclear polarized atomic hydrogen target:
N.N. Nikolaev, F. Rathmann, A.J. Silenko, Yu.N. Uzikov, Physics Letters B 811, 135983 (2020);

Alternative option: polarized proton beam, nuclear polarized atomic deuterium target with rotating polarization: Boxing Gou et al., Lanzhou IMP

Both options are feasible at HIAF-EicC !

Systematics-free NMR TVPC signal in storage ring pd expt with rf spin flipper (solenoid)

$$T_{yy}(n) = \frac{1}{2}T_{yy}(0)\cdot\left[-1+3\cos^2\epsilon n\right],$$
$$T_{xx}(n) = \frac{1}{2}T_{yy}(0)\cdot\left[-1+3\sin^2\epsilon n\cdot\cos^2\theta_s n\right],$$
$$T_{zz}(n) = \frac{1}{2}T_{yy}(0)\cdot\left[-1+3\sin^2\epsilon n\cdot\sin^2\theta_s n\right],$$
$$T_{yx}(n) = \frac{3}{2}T_{yy}(0)\cdot\sin\epsilon n\cdot\cos\epsilon n\cdot\cos\theta_s n,$$
$$T_{yz}(n) = -\frac{3}{2}T_{yy}(0)\cdot\sin\epsilon n\cdot\cos\epsilon n\cdot\sin\theta_s n,$$
$$T_{xz}(n) = -\frac{3}{4}T_{yy}(0)\cdot\sin^2\epsilon n\cdot\sin 2\theta_s n.$$

Polarized d's in a ring, nuclear polarized atomic hydrogen cell target
θ_s **phase of spin** precession per turn in a guding filed of a ring
ε spin flip phase per pass through the spin flipper in a ring

Polarized beams stored in a ring

$$T_{xx}(0) = T_{zz}(0) = -\tfrac{1}{2}T_{yy}(0).$$
$$T_{yx}(0) = T_{yz}(0) = T_{xz}(0) = 0$$

→ **Unique systematics free Fourier signature of T-violation.**
Enhance uniqueness by target spin flips

N.N. Nikolaev, F. Rathmann, A.J. Silenko, Yu. Uzikov, Physics Letters B 811, 135983 (2020);
Boxing Gou at al., Lanzhou IMP, closely related idea with proton beam and deuterium target

Both options are feasible at HIAF-EicC !

Message for HIAF-EicC: don't miss a unique potential of high sensitivity with oscillating polarization

CP Puzzle in QCD: P & T violating

$$L_{\bar{\theta}} = -\frac{1}{32\pi^2}\bar{\theta} g_S^2 G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{a\rho\sigma}$$

preserves renormalizibilty

$$G^{a\mu\nu}\tilde{G}^a_{\mu\nu} = \partial_\mu K^\mu \,, \qquad K^\mu = \epsilon^{\mu\nu\rho\sigma}\left(A^a_\nu G_{\rho\sigma} - \frac{1}{3} g_s f^{abc} A^a_\nu A^b_\rho A^c_\sigma\right)$$

Unobservable in perturbation theory, but Adler-Bell-Jackiw anomaly and instanton vacuum give observable CP violation

$$L_{CPV} = 3m^*\bar{\theta}(\bar{\Psi} i\gamma_5 \Psi)\,. \qquad m^* = \frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s} \approx \frac{m_u m_d}{m_u + m_d}$$

Exact Peccei-Quinn chiral symmetry $U(1)_{PQ}$ if there is a massless quark

EDM of nucleons $\qquad d_N \sim \bar{\theta}\frac{m^*}{\Lambda_{QCD}}\mu_N \approx \bar{\theta}\times 10^{-16}\ \mathrm{e\cdot cm}$

PSI (2020): $\quad d_n < 1.8\times 10^{-26}\,\mathrm{e{\cdot}cm} \quad \rightarrow \quad \bar{\theta} \sim 10^{-10}.$

Peccei-Quinn: swap the QCD angle for the dynamic pseudoscalaar field: $\quad \bar{\theta} \rightarrow \frac{1}{f_{(a)}} a(x)$

Spontaneous breaking of $U(1)_{PQ}$ → light pseudoscalar axion as a likely source of dark matter

Weinberg (1978) from πNN to aNN → $-\frac{\hbar}{2f_{(a)}} g_f \partial_\mu a(x)\overline{\Psi}\gamma^\mu\gamma_5\Psi \qquad m_{(a)} \approx m_\pi \frac{f_\pi}{f_{(a)}}\frac{\sqrt{m_u m_d}}{m_u + m_d}\,,$

Relic axion dark matter

Coherent axion galactic halo $a(x) = a_0 \cos\left(\omega_{(a)} t - \boldsymbol{k}_{(a)} \cdot \boldsymbol{x}\right)$

$$\omega_{(a)} = \frac{m_{(a)} c^2}{\hbar} \qquad a_0 = \frac{1}{m_{(a)}} \sqrt{\frac{2\rho_{\mathrm{DM}} \hbar}{c^3}}$$

Preskill, Wise, Wilczek (1983)
Abbott, Sikivie (1983)
Dine, Fischler (1983)
Review: Sikivie (2021)

Oscillating EDM $d_{\mathrm{N}}^{(a)}(x) = \frac{a(x)}{f_{(a)}} \kappa_{(a)} \frac{\mu_{\mathrm{N}}}{c}$

Axion halo acts on spin as a psedomagnetic field (P. Vorobiev, I.Kolokolov, I. Fogel (1989), R. Barbieri (1989))

Spins in storage rings move ~1000 times faster than Earth w.r.t. galatic halo axions → enhanced pseudomagnetic field, Foldy-Wouthuysen treatment is mandatrory Silenko (2021)

Instantaneous spin rotation

$$\boldsymbol{\Omega}^{(a)} = \frac{a_0}{f_{(a)}} \left[g_{\mathrm{f}} \omega_{(a)} \sin\left(\omega_{(a)} t\right) \frac{\boldsymbol{v}}{c} - \kappa_{(a)} \gamma \cos\left(\omega_{(a)} t\right) \frac{\boldsymbol{v}}{c} \times \boldsymbol{\Omega}_{\mathrm{c}} \right]$$

pseudomagnetic field (= rf solenoid) oscillating EDM (= rf Wien filter)

$\pi/2$ phase shift of two spin rotators with orthogonal spin rotation axes --- spin rotations are in sync

Axion induced resonance spin-flip angular velocity Silenko (2022), NNN (2022)

$$\Omega_{\mathrm{res}} = \frac{a_0}{2 f_{(a)}} \frac{v}{c} \gamma \left| g_{\mathrm{f}} G - \kappa_{(a)} \right| \Omega_{\mathrm{c}}$$

is independent of the spin-axion phase difference

Dynamics of the Froissart-Stora scan: axion phase ambiguity

Duration of the spin-jump must be shorter than the axion coherence time $\tau_a = \frac{h}{m_a v^2}$, Q ~ 10^6
JEDI sensitive to m_a = 0.5 neV, lab velocity wrt axions halo v ~10^{-3} →

τ ~ 10 s, tune ramp rate properly

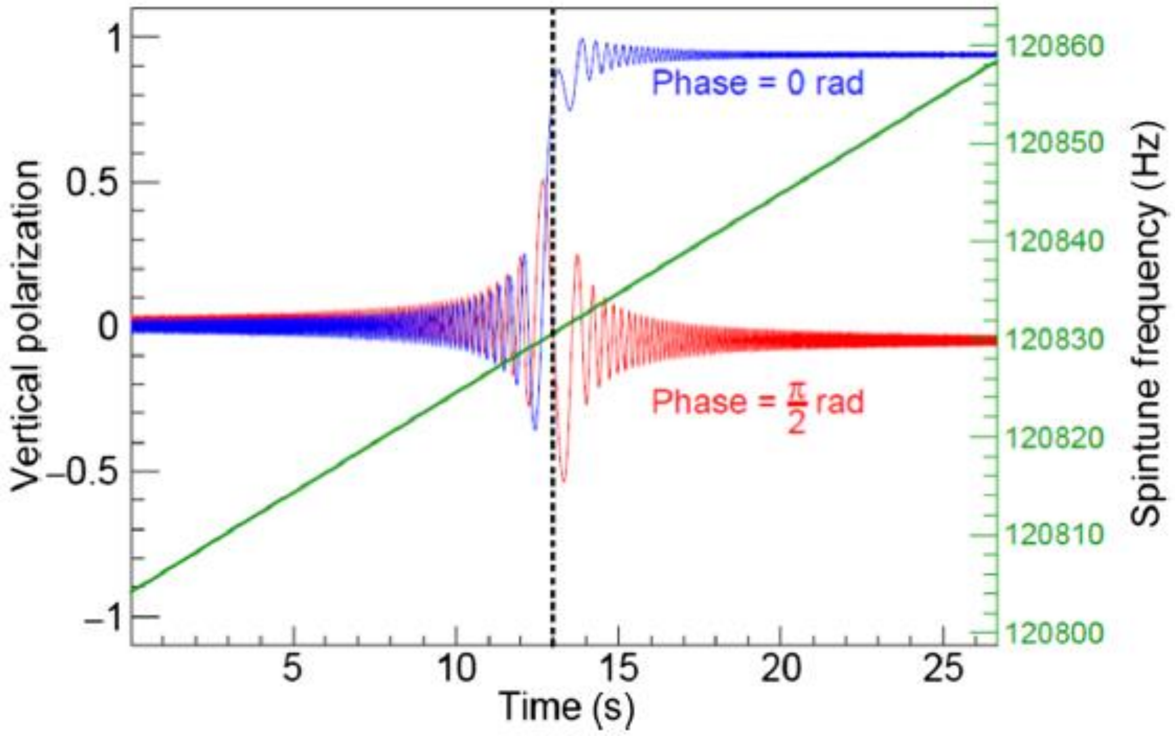
At least 1 s for single determination of the spin phase

Spin-flip frequency is independent of the entirely unknown relative spin-axion phase Δ

But the resonant spin jump is ~ cos Δ

Multiple bunch solution for the phase problem

N.B. Rotation of spin from the initial vertical to the horizontal one is entirely free of the phase ambiguity → axion signal is an emergence of the precessing in-plane polarization → JEDI Fourier technique



JEDI @ COSY

Tune antenna rampimg beam energy

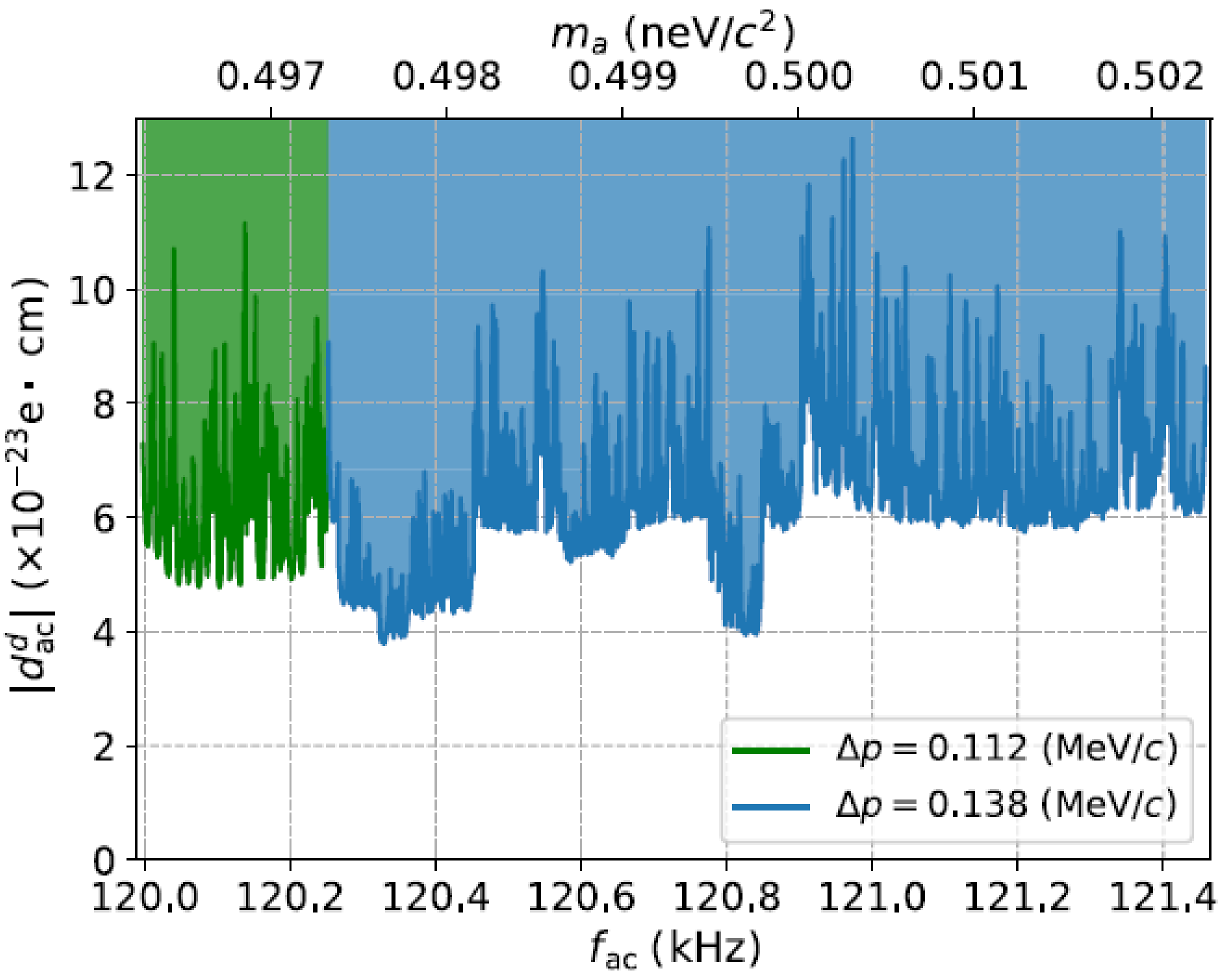
Altogether 103 ramps

Frequency range 120-121.4 kHz

Axion mass range 4.95-5.02 neV/c^2

Strong bound on the deuteron oscillating EDM from ALP

Basically no direct bound on the permanent EDM in PDP tables



The spin as axion antenna probes a pseudomagnetic aspect of the axion field which is different from the Marcel Ayme' "Le pass-muraille" (1941) approach exposed by Yannis Semertzidis

Montartres, Paris, France, a monument to the axion (Dutilleul) by a celebrated French actor Jean Marais, a friend of Marcel Ayme'

Some day some place an axion shall pull itself through the wall in a full glory.

Don't miss your chance to be the first to greet it.

Thanks to IMP for hospitality

Thank you for your attention!