Discrete Symmetry Tests and Rare Processes at HIAF

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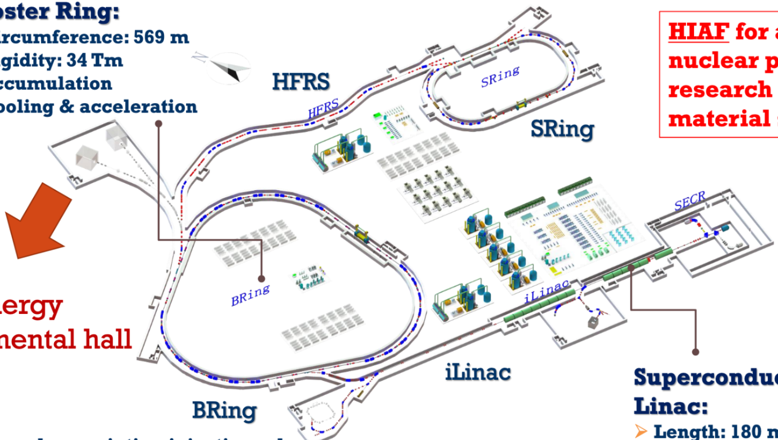
HIAF platform and H-NS detector

HIAF accelerator chain and high-energy experimental hall

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- Accumulation
- Cooling & acceleration

HIAF for atomic physics, nuclear physics, applied research in biology and material science etc.



High energy experimental hall

- Two-plane painting injection scheme
- Fast ramping rate operation

Superconducting Ion Linac:
- Length: 180 m
- Energy: 17 MeV/u (U^{34+})
- CW and pulse modes

HIAF beam parameters

Ion	Intensity (ppp)	Kine_Energy (GeV/u)
$^{238}U^{35+}$	2.0×10^{11}	0.84
$^{238}U^{76+}$	5.0×10^{10}	2.5
$^{129}Xe^{27+}$	3.6×10^{11}	1.4
$^{78}Kr^{19+}$	5.0×10^{11}	1.7
$^{40}Ar^{12+}$	7.0×10^{11}	2.3
$^{18}O^{6+}$	8.0×10^{11}	2.6
p	5.0×10^{12}	9.3

Detector concept most relevant here: H-NS

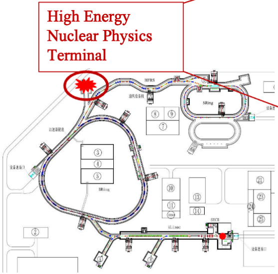
Mag. Field: 1.5 Tesla

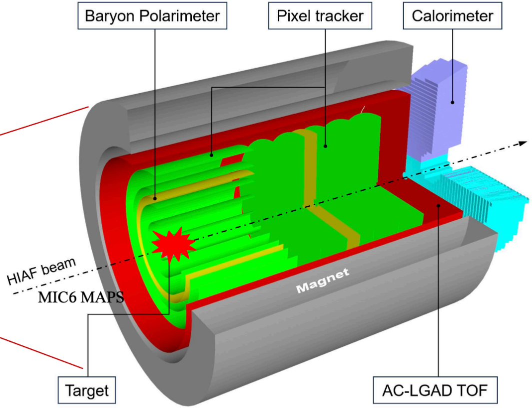
Tracker: MIC6, 30X30 μm^2, 0.8%X/X_0

LGAD: $\sigma_t \sim 30$ ps , 300X300 μm^2

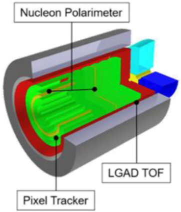
Calorimeter: $\sigma_E \sim 3\%$ @ 1GeV

Polarimeter: nucleon and photon polarization





Projection of Λ and proton polarization (beam energy: 9.3 GeV)



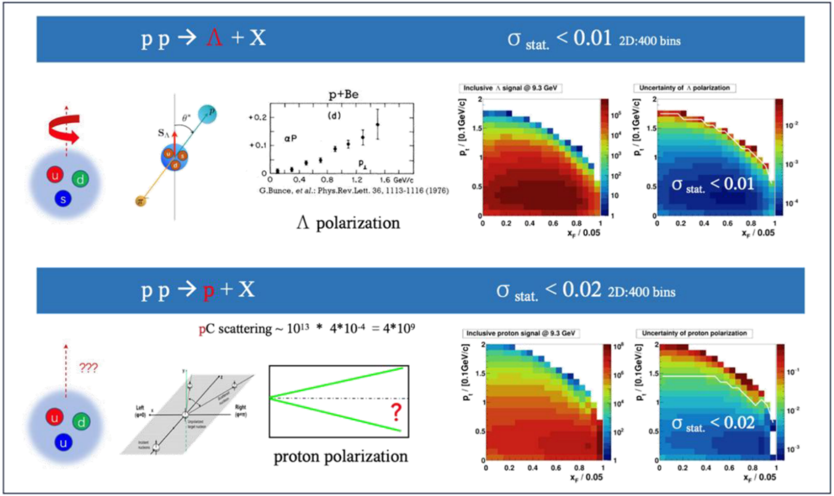
H-NS

Reaction: p+p

Event rate:1MHz

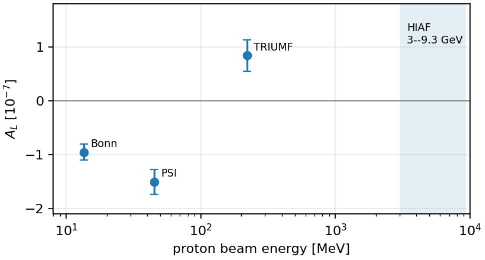
Time: 3 months

- pp → Λ+X N ~ 10^{11}
- pp → p+X N ~ 10^{13}
- pp → pKΛ N ~ 10^{10}



Hadronic parity violation with hyperon spin

Elastic *pp* parity violation: what has been measured?



Most precise direct elastic $\vec{p}p$ PV points

T_p	Experiment	$A_z\ [10^{-7}]$
13.6 MeV	Bonn	-0.93 ± 0.21
45 MeV	PSI	-1.50 ± 0.23
221 MeV	TRIUMF	$+0.84 \pm 0.34$

Historical observable: final spins summed

$$d\sigma^{pp}(h) = d\sigma_0^{pp}\ [1 + hP_b A_L^{pp}]$$

With final proton polarimetry in principle

$$d\sigma^{pp}(h, \lambda_p) = d\sigma_0^{pp}\ [1 + hP_b A_L^{pp} + \lambda_p P_L^p + hP_b \lambda_p D_{LL}^{pp}]$$

- PV: A_L^{pp} is the measured beam-helicity rate asymmetry.
- PV: P_L^p is a final-helicity observable, but needs a proton polarimeter.
- PC: $d\sigma_0^{pp}$ and D_{LL}^{pp} give the elastic strong-spin baseline.
- Elastic *pp* is the natural HIAF control benchmark; no established direct 3–9.3 GeV result.

Refs: Review: Haxton–Holstein, PPNP 71 (2013). Elastic data: Bonn 13.6 MeV, PSI 45 MeV, TRIUMF 221 MeV. Non-low-energy attempts: 800 MeV *pp*; 6 GeV/*c* p-H_2O transmission.

Longitudinal $\vec{p}p \to pK^+\Lambda$: what is gained?

Longitudinal-beam cross section with Λ self-analysis

$$\frac{dN_h}{d\cos\theta_L^*} \propto d\sigma_0(\Phi_3)\Big[1 + hP_bA_L^{pK\Lambda}(\Phi_3) + \alpha_\Lambda\big(P_L^\Lambda(\Phi_3) + hP_bD_{LL}^{p\to\Lambda}(\Phi_3)\big)\cos\theta_L^*\Big]$$

Observables from the same event sample

- yield difference gives the beam-helicity asymmetry;
- average decay slope gives the final-Λ helicity;
- slope difference gives the longitudinal spin transfer.

Common with elastic pp rate measurement

- $d\sigma_0$: PC unpolarized yield.
- A_L: PV beam-helicity rate asymmetry.

Added directly by Λ self-analysis

- P_L^Λ (PV): final Λ helicity from average decay slope.
- $D_{LL}^{p\to\Lambda}$ (PC): longitudinal helicity transfer from slope difference.

Three-body map: $A_L, P_L^\Lambda, D_{LL} = f(M_{K\Lambda}, M_{p\Lambda}, \cos\theta_\Lambda, \ldots)$.
Purpose: locate PC–PV interference before phase-space cancellation.

Refs: Self-analysis and H-NS concept: H-NS WP, arXiv:2606.06553. Strange-production spin data: DISTO, arXiv:nucl-ex/9906011; COSY-TOF, arXiv:1607.06305.

Elastic pp vs. exclusive $pK^+\Lambda$: roles in a HIAF PV program

Elastic $\vec{p}p \to pp$

Strengths

- Largest rate and simplest event definition.
- Directly connected to the historical pp PV database.
- Best channel to validate helicity flips, relative luminosity and false-asymmetry control.

Limitations at HIAF energies

- No established direct elastic-pp PV measurement in 3–9.3 GeV.
- GeV elastic amplitudes contain many partial waves and strong inelastic-channel effects.
- Final proton spin needs a secondary polarimeter.

Exclusive $\vec{p}p \to pK^+\Lambda$

Strengths

- Clean strange-baryon tag: K^+, displaced $\Lambda \to p\pi^-$, missing-mass constraints.
- Λ decay gives direct final-state polarimetry.
- Access to $A_L^{pK\Lambda}$, P_L^{Λ}, $D_{LL}^{p\to\Lambda}$ over Dalitz variables and resonance regions.

Limitations

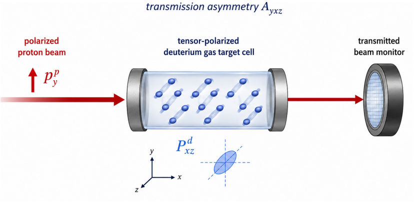
- Lower effective yield than elastic pp.
- More complex amplitude interpretation: N^*, exchange mechanisms, FSI, $N\Sigma$ cusp.
- Published data exist for P-even spin dynamics, not PV A_L/P_L^{Λ}.

Strategy: elastic pp = control benchmark; $pK^+\Lambda$ = new strange-baryon spin-PV channel.

Refs: Elastic PV context: Haxton–Holstein, PPNP 71 (2013); van Oers, arXiv:nucl-ex/9708003. $pK^+\Lambda$ spin baseline: DISTO and COSY-TOF.

TVPC null tests

TVPC null test: what is actually measured?



Mode: forward transmission. A stored polarized beam crosses a tensor-polarized deuterium target; beam loss / lifetime probes a total-cross-section asymmetry.

Caution: ordinary exclusive "naive-*T*-odd" correlations can be mimicked by strong phases or FSI.

$$\sigma_{\text{tot}} = \sigma_0 + \cdots + \widetilde{\sigma}\, p_y^p P_{xz}^d$$

$\widetilde{\sigma}$: **P-even, T-odd**. The signal is isolated through the double-spin correlation $p_y^p P_{xz}^d$.

Define $(s,t) = (\text{sign}\, p_y^p,\ \text{sign}\, P_{xz}^d)$. Then

$$A_{y,xz} \simeq \frac{\sigma(+,+) - \sigma(+,-) - \sigma(-,+) + \sigma(-,-)}{\sigma(+,+) + \sigma(+,-) + \sigma(-,+) + \sigma(-,-)}, \qquad \frac{\widetilde{\sigma}}{\sigma_0} \simeq \frac{A_{y,xz}}{p_y^p P_{xz}^d}.$$

- The four-state combination cancels first-order single-spin terms and suppresses common-mode drifts.
- Via the optical theorem, the loss-rate asymmetry probes the forward scattering amplitude.

Genuine null test: for any *T*-invariant strong/EM interaction, $\widetilde{\sigma} = 0$. A nonzero signal indicates TVPC; false asymmetries are instrumental.

Refs: TRIC proposal, arXiv:nucl-ex/9810003; Uzikov–Haidenbauer, PRC 94 (2016).

TVPC world status and polarized total-cross-section expansion

Direct experimental status

Measured
earlier direct tests:
typical sensitivity 10^{-3}–10^{-4}

Measured
polarized neutron + aligned ^{165}Ho
$A_5 = (1.1 \pm 2.3) \times 10^{-5}$

Proposed
COSY/TRIC *pd* transmission
phase-I 10^{-4}, goal 10^{-6}

No published *pd* null-test result has reached the TRIC design goal; no nonzero TVPC signal is established.

Complete polarized total cross section

$$\sigma_{\text{tot}} = \underbrace{\sigma_0 + \sigma_1\, \mathbf{p}^{p} \cdot \mathbf{p}^{d} + \sigma_2 (\mathbf{p}^{p} \cdot \hat{\mathbf{k}})(\mathbf{p}^{d} \cdot \hat{\mathbf{k}}) + \sigma_3 P^{d}_{zz}}_{\text{T-even / PC}} + \underbrace{\widetilde{\sigma}\, p^{p}_{y} P^{d}_{xz}}_{\text{TVPC}} .$$

Ordinary spin terms
$\sigma_1, \sigma_2, \sigma_3$ are allowed by *P* and *T*; they validate transmission and spin control.

TVPC target term
$\widetilde{\sigma}\, p^{p}_{y} P^{d}_{xz}$ is the unique *P*-even, *T*-odd forward null-test term.

Key message: the observable is a specific total-cross-section coefficient, not a generic exclusive *T*-odd correlation.

Refs: Ho transmission: arXiv:nucl-ex/9605005; TRIC proposal, arXiv:nucl-ex/9810003; Simonius, arXiv:nucl-th/9702013.

HIAF/SRing opportunity: a dedicated TVPC program

Dedicated SRing experiment — not part of the baseline H-NS detector program.

Why HIAF/SRing is attractive

- SRing covers the sub-GeV to few-GeV region where TVPC sensitivity is often discussed.
- Repeated beam–target crossings convert total-cross-section changes into a beam-lifetime signal.
- Multi-energy scans help avoid accidental zeros and test the energy dependence.
- Deuterium is theoretically cleaner than complex aligned nuclei such as ^{165}Ho.
- Polarized H^+/D^+, spin manipulation and polarimetry are active HIAF R&D topics.

Main advantage: storage-ring operation plus multi-energy capability.

Suggested staged roadmap

Stage 1: validate ordinary spin terms; demonstrate false-asymmetry control at $\sim 10^{-4}$.

↓

Stage 2: scan candidate energies; search at the $\sim 10^{-5}$ scale.

↓

Stage 3: rotating-spin / harmonic route toward the 10^{-6} regime.

Refs: SRing/HIAF materials; TRIC proposal, arXiv:nucl-ex/9810003; rotating-spin idea, arXiv:2004.09943; H-NS WP, arXiv:2606.06553.

Rare and forbidden strange-hadron processes

Rare strange-hadron program: three classes

Class	Candidate processes	What HIAF measures
Nonleptonic $\lvert\Delta S\rvert = 1$ weak reactions	$pp \to \Sigma^+ p$, $pp \to \Lambda p \pi^+$	channel-specific final-state reconstruction; cross sections and energy dependence
Rare hyperon decays / light mediator	$\Sigma^+ \to p e^+ e^-$; $\Sigma^+ \to pX$, $X \to e^+ e^-$	branching fraction, m_{ee} spectrum and narrow-peak search
Forbidden B/L-violating processes	forbidden Λ, Ξ decays; $\Lambda - \bar{\Lambda}$ and same-sign-kaon benchmarks	direct limits in exclusive electron / strange final states

H-NS baseline favors electron final states; dimuon modes require dedicated muon identification.

Refs: H-NS WP, arXiv:2606.06553; HyperCP, PRL 94 (2005); LHCb, PRL 135, 051801 (2025); CLAS, PRD 92 (2015).

Weak and rare hyperon processes: theory and experiment

Process	Theory size	Experimental status
$\lvert\Delta S\rvert = 1$: $pp \to \Sigma^+ p$, $pp \to \Lambda p \pi^+$	natural weak amplitude scale $G_F m_\pi^2 \simeq 2.3 \times 10^{-7}$; no reliable channel-specific cross-section prediction	free-hadron data sparse; hypernuclear benchmark: $\Gamma_{\text{NM}}/\Gamma_\Lambda = 0.424 \pm 0.024$, $\Gamma_n/\Gamma_p = 0.45 \pm 0.11$
$\Sigma^+ \to p e^+ e^-$	SM: $(7.4\text{–}8.3) \times 10^{-6}$	old result: $(7.7 \pm 4.6) \times 10^{-6}$; only measurement has about 60% relative uncertainty
World reference: $\Sigma^+ \to p\mu^+\mu^-$; mediator search $\Sigma^+ \to pX$, $X \to e^+e^-$	SM dimuon: $(1.2\text{–}7.8) \times 10^{-8}$; light-mediator rate model dependent	LHCb: $(1.08 \pm 0.17) \times 10^{-8}$; no compelling narrow state

Flagship rare-decay benchmark at HIAF: $\Sigma^+ \to p e^+ e^-$, measuring the branching fraction and m_{ee} spectrum; the dimuon mode is a world-status reference.

Refs: Sasaki et al., PTEP 2018, 113D01; Parreño–Bennhold–Holstein, arXiv:nucl-th/0312047; LHCb, arXiv:2504.06096; Roy–Tandean–Valencia, arXiv:2404.15268.

Forbidden B/L-violating channels: current limits

Process	**Theory size**	**Current limit**
Forbidden Λ decays	SM-forbidden at observable rates	CLAS: $\mathcal{B} < (4\text{–}200) \times 10^{-7}$
$\Xi^0 \to K^- e^+$, $\Xi^0 \to K^+ e^-$	SM-forbidden at observable rates	BESIII: $\mathcal{B} < 3.6 \times 10^{-6}$, $< 1.9 \times 10^{-6}$
$\Lambda - \bar{\Lambda}$ oscillation	$\lvert\Delta B\rvert = 2$, dimension-9 six-quark operators	BESIII: $P < 1.4{\times}10^{-6}$, $\delta m < 2.1{\times}10^{-18}$ GeV
Dinucleon $pp \to K^+ K^+$	SM-forbidden; BSM scale is model dependent	Super-K: $\tau > 1.7 \times 10^{32}$ yr

Summary

Summary: HIAF symmetry and rare-process program

Program	Main channels / observables	HIAF implementation and next step
Hyperon spin	$pp \to pK^+\Lambda$, $pA/AA \to \Lambda X$; production polarization and spin transfer	H-NS baseline; establish high-statistics hyperon samples and validate spin reconstruction
Hadronic PV	elastic pp: A_L^{pp}; $pK^+\Lambda$: A_L, P_L^{Λ}, D_{LL}	longitudinally polarized proton beam; use elastic pp as control and strange final states as the new channel
TVPC null test	polarized pd forward transmission; $\widetilde{\sigma}/\sigma_0$	dedicated SRing internal-target experiment; staged validation from 10^{-4} toward long-term 10^{-6}
Rare / weak processes	$\Sigma^+ \to pe^+e^-$, $\Sigma^+ \to pX$; selected $\lvert\Delta S\rvert = 1$ and forbidden Λ/Ξ channels	select a few benchmark channels; quantify parent-hyperon yields, reconstruction efficiency and dominant backgrounds

Program logic: start from hyperon production and spin, add polarized-beam / target upgrades, then validate a small number of rare-process benchmarks.

Refs: Summary based on H-NS WP and the world-status slides above; quantitative reach requires dedicated detector and sensitivity studies.