Entanglement: A possible source of information on nuclear structure

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CHSH violation & Test of Bell's Inequality

- In 1976, M. Lamehi-Rachti and W. Mittig performed one of the first Bell-inequality tests with massive particles, using low-energy proton–proton scattering.
- They measured the spin–spin correlation of the two outgoing protons for different analyzer settings and compared it to Bell's limit and to quantum mechanics.
- Their results were consistent with quantum mechanics and violated Bell's inequality, showing non-classical correlations in a hadronic system (with some experimental assumptions about the analyzers).

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Quantum mechanics and hidden variables: A test of Bell's inequality by the measurement of the spin correlation in low-energy proton-proton scattering

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(Received 11 August 1975; revised manuscript received 26 July 1976)

The inequality of Bell has been tested by the measurement of the spin correlation in proton-proton scattering. Measurements were made at $E_p = 13.2$ and 13.7 MeV using carbon analyzers of 18.6 and 29 mg/cm^2, respectively, accumulating a total of 10^4 coincidences. The experimental analyzing power, geometric correlation coefficients, and energy spectra are compared to the result of a Monte Carlo simulation of the apparatus. The results are in good agreement with quantum mechanics and in disagreement with the inequality of Bell if the same additional assumptions are made. The conditions for comparing the results of the experiments to the inequality of Bell are discussed.

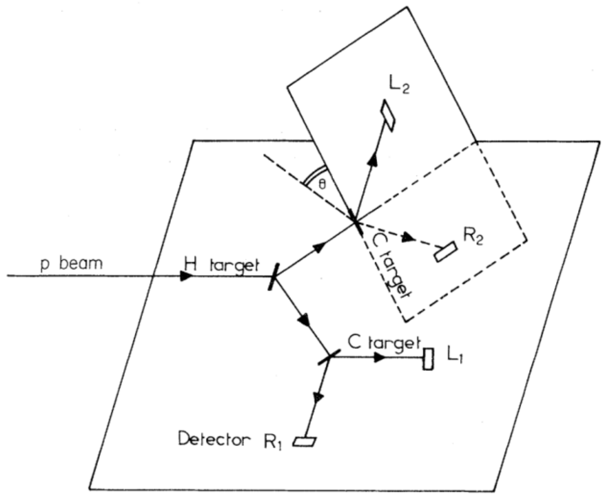
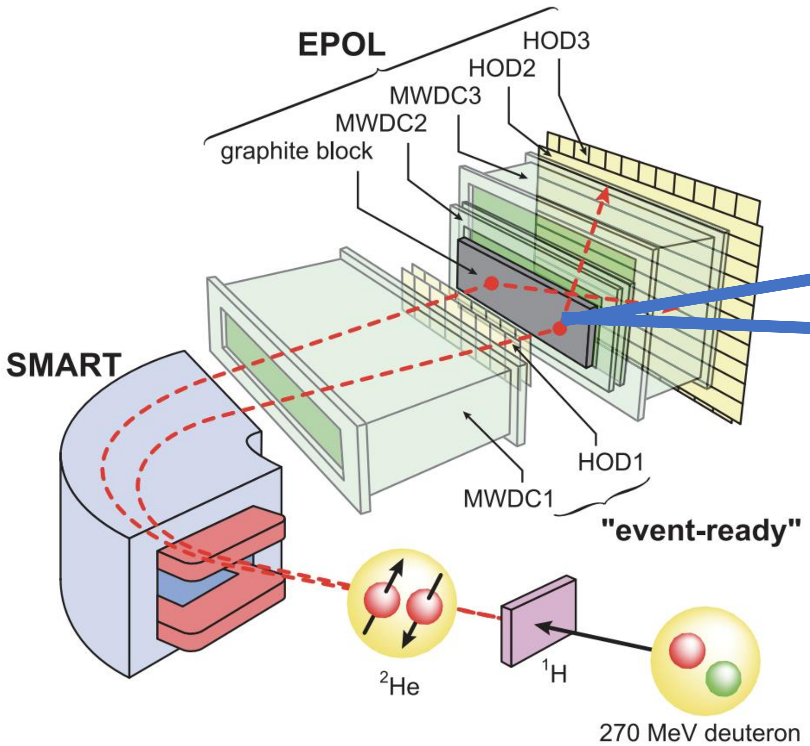
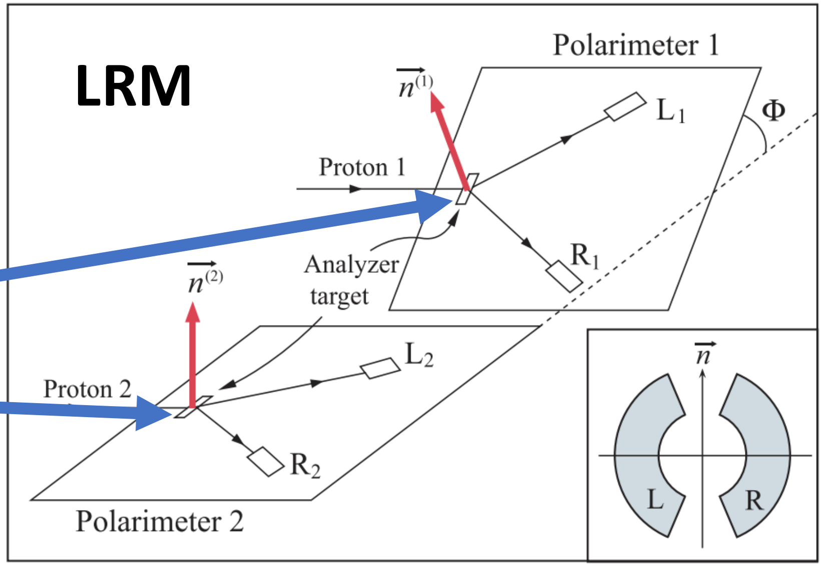
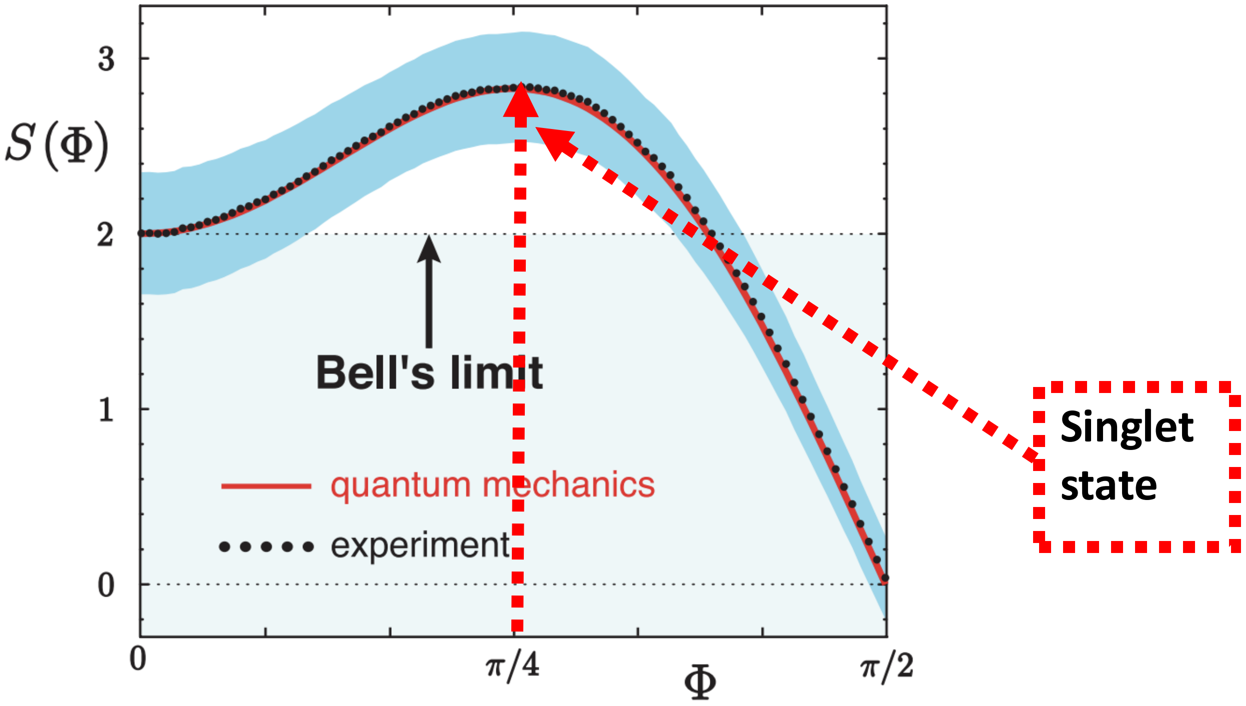


FIG. 2. Schematic experimental setup for the measurement of the spin correlation in proton-proton scattering.

CHSH violation & Test of Bell’s Inequality







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Spin Correlations of Strongly Interacting Massive Fermion Pairs as a Test of Bell’s Inequality

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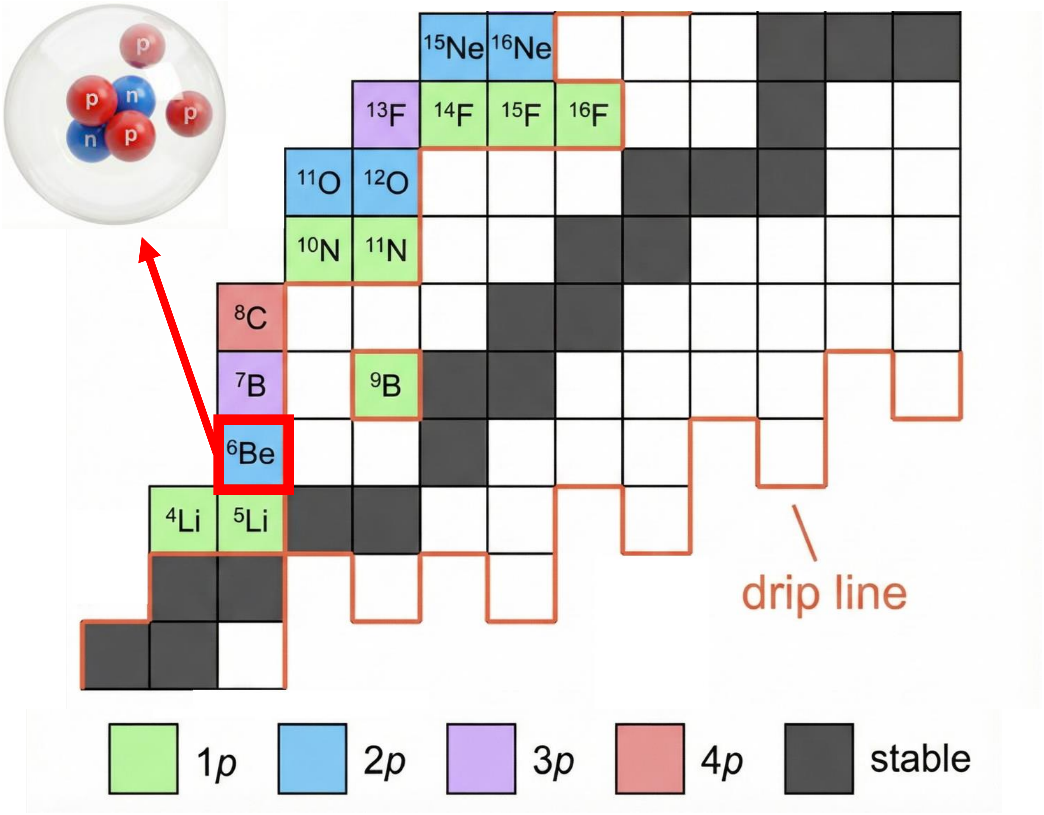
Two-proton decay from ^{6}Be

Two-proton emission: a rare decay mode where nuclei beyond the proton drip line eject a pair of protons.



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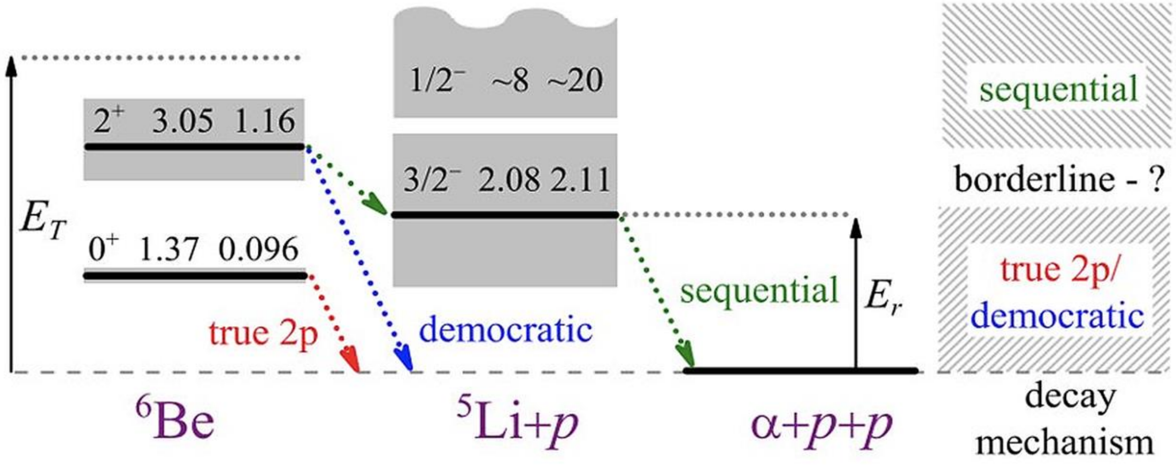
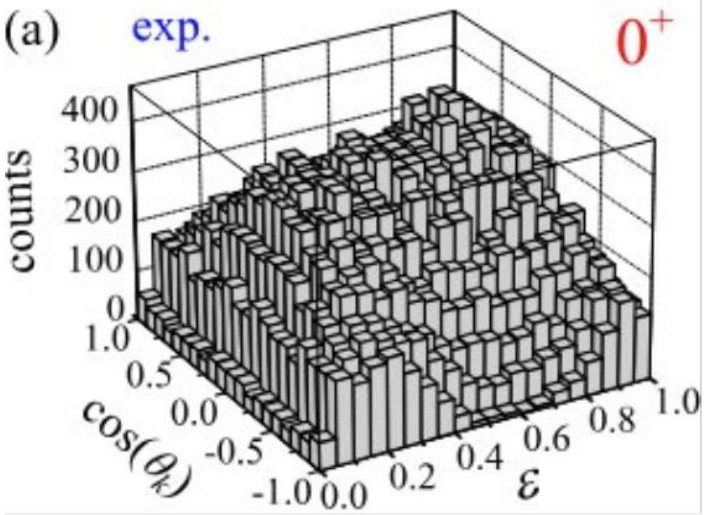
^{6}Be: the lightest 2p emitter, α+p+p.

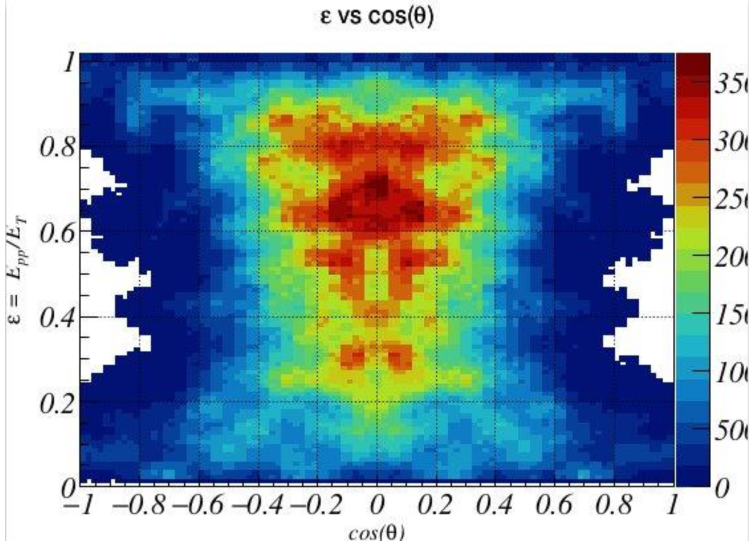
Its ground state and the first 2^+ excited state show a rich mix of **true**, **democratic**, and **sequential** 2p decays.



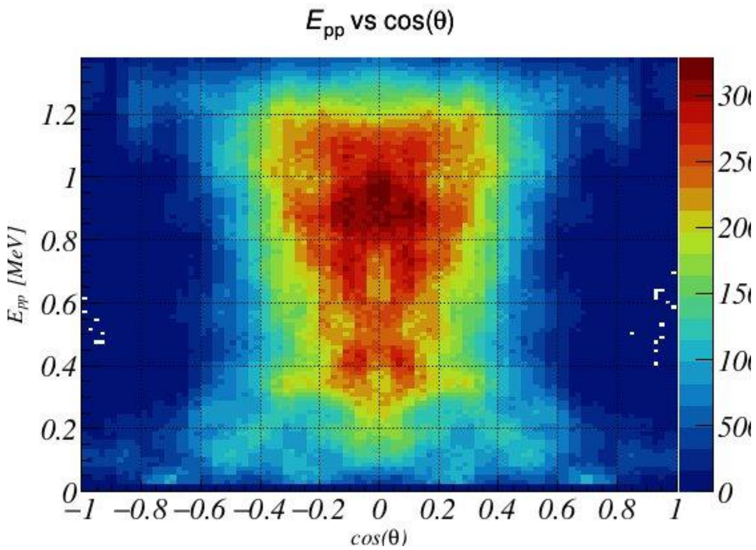
PRL 109, 202502 (2012)

Complete energy-angular correlations for the 0^+





0^+



- ^{6}Be decays into a three-body final state α +p+p, so we study energy–angular correlations between the fragments.
- The energy sharing and the relative emission angle act as a fingerprint of the decay dynamics and p-p nuclear correlation.
- Different patterns correspond to different mechanisms: diproton-like (correlated) vs democratic / sequential decay.

PRL 109, 202502 (2012)

Spin entanglement of two-proton decay

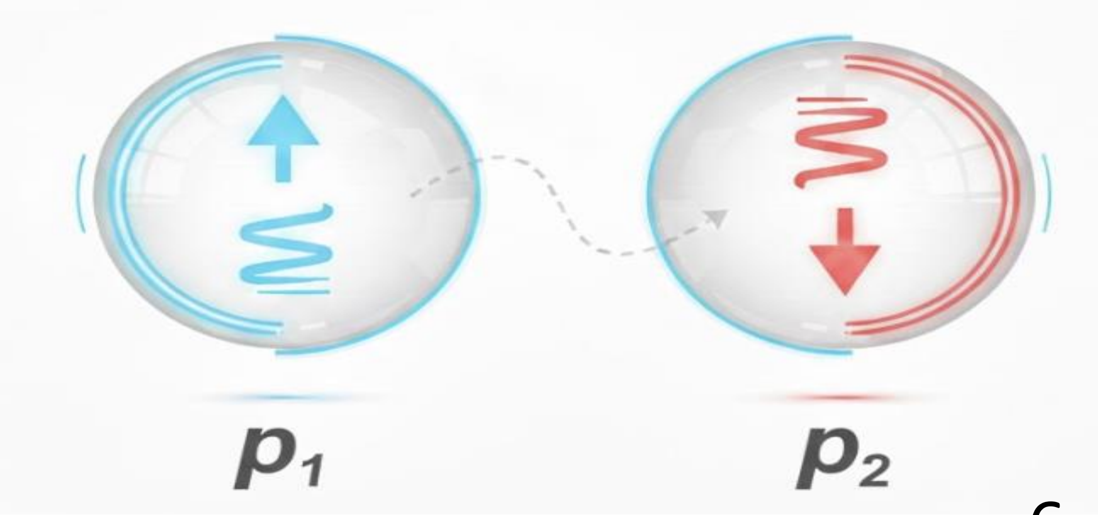
Definition (non-separability): $|\psi^- > \neq |\psi_A > \otimes |\psi_B >$

Physical meaning:
Non-classical correlations between local measurement outcomes.

Example: spin singlet $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

⇒ perfect anti-correlation along any common axis.

Two spin-1/2 particles in a singlet state

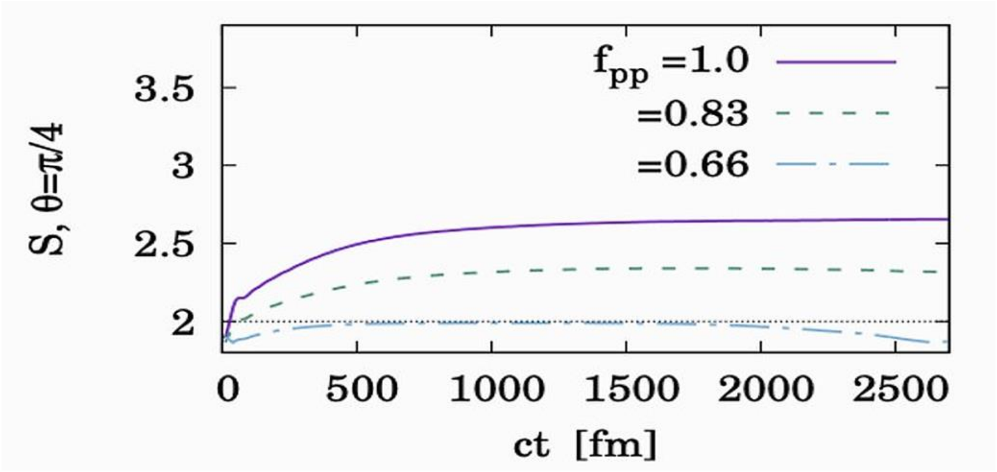


Oishi (2024/25): CHSH violation in $^{6}Be \rightarrow \alpha+p+p$.

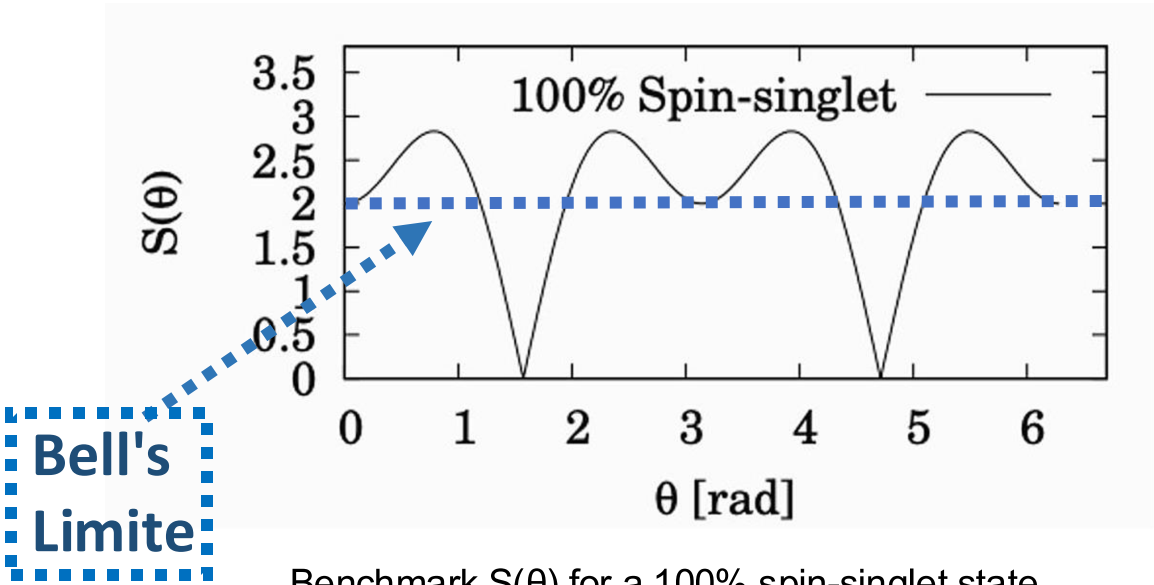
Setup : time-dependent three-body model **(α+p+p)**, with **p−p** interaction tuned to reproduce the energy release by $\mathbf{f_{pp}}$

Observable : CHSH parameter **S** computed from proton spin correlations.

Main result : for realistic **fpp ≈ 1**, **S** reaches ~ **2.6 (>2)** -> **CHSH** violation (entanglement signature).



S(t) and dependence on f_{pp}



Benchmark S(θ) for a 100% spin-singlet state

T. Oishi, arXiv:2407.11136

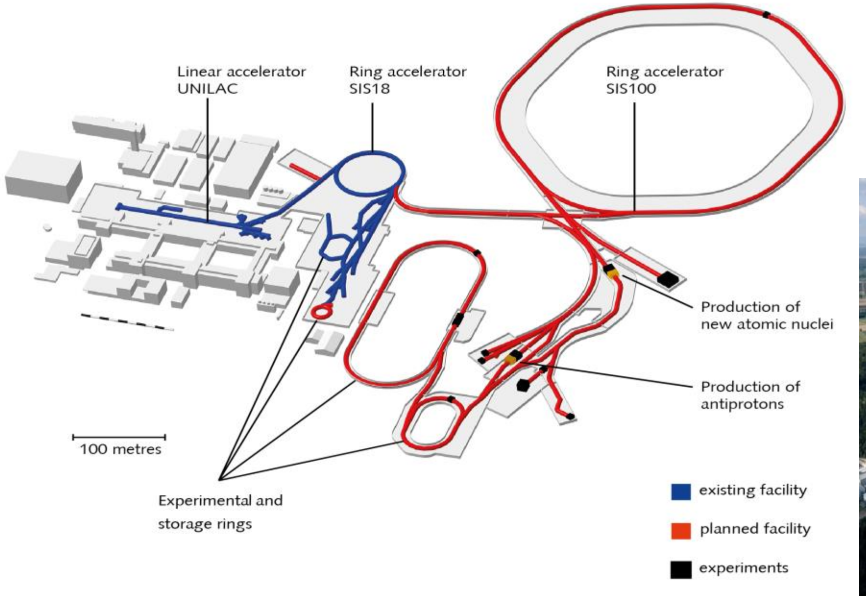
Experimental concept at R3B/GLAD

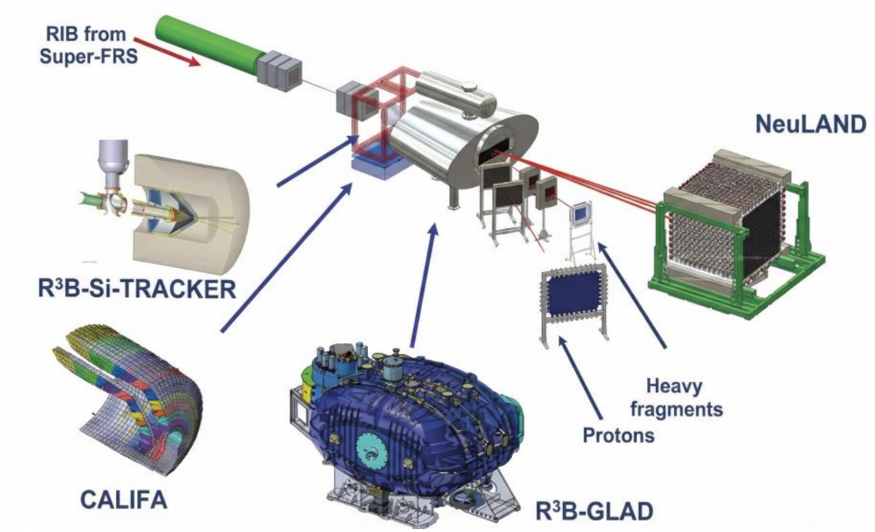
GSI/FAIR (Darmstadt, Germany): accelerator facility delivering relativistic radioactive-ion beams (RIBs) for nuclear structure and reactions.

How beams are made: stable primary beam → fragmentation/fission on a production target → in-flight separation → secondary exotic beam.

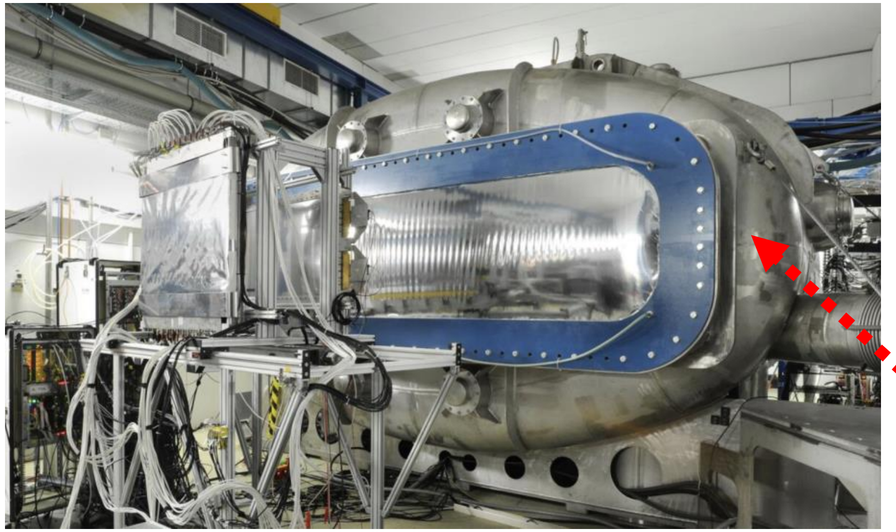
R3B (Reactions with Relativistic Radioactive Beams): a kinematically complete setup: detect all reaction products (charged fragments + neutrons/γ) in coincidence.

Why it matters: complete detection ⇒ full event reconstruction (4-momenta, invariant mass) ⇒ access to correlations and decay mechanisms.





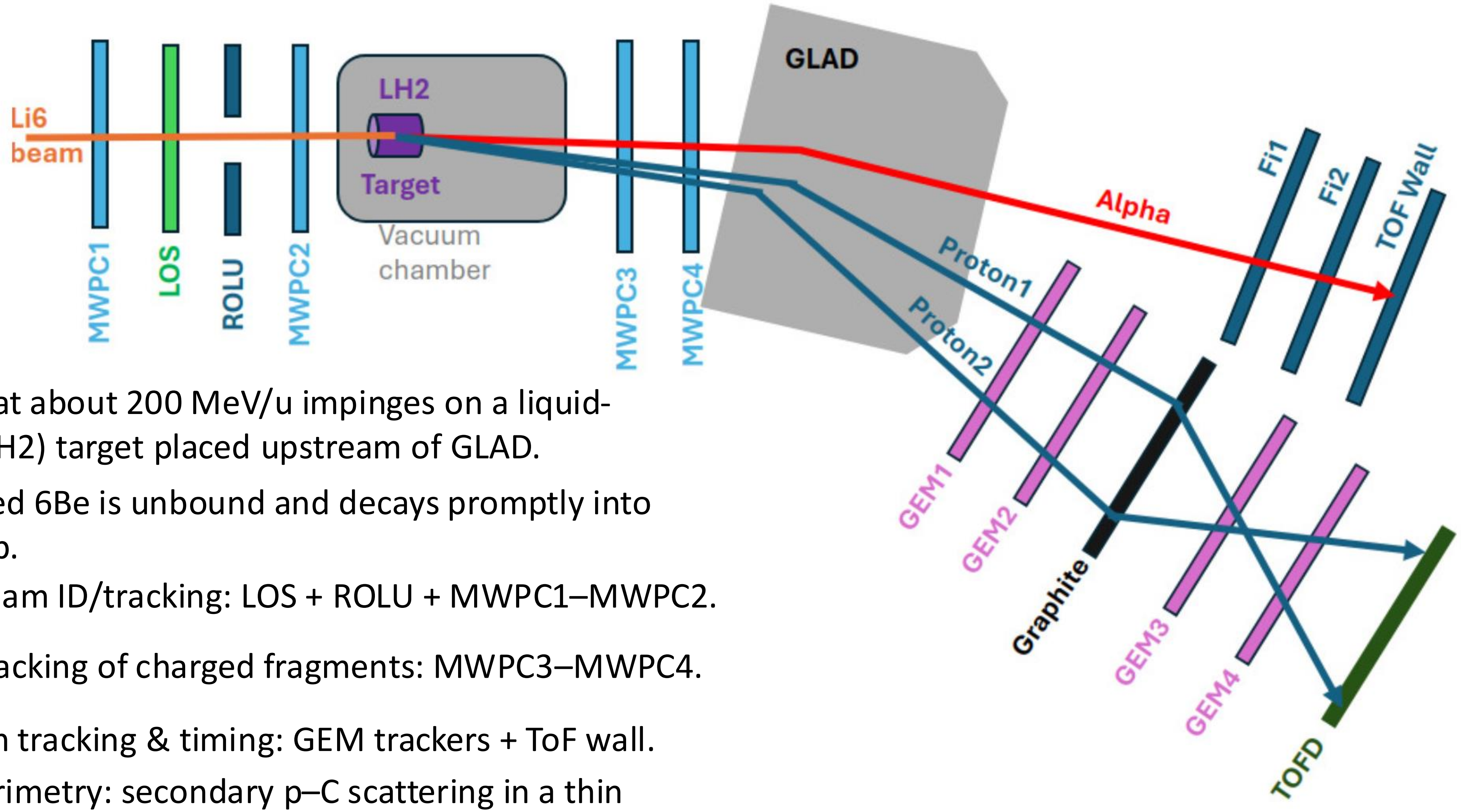
GLAD: the Large Acceptance Dipole magnet (R3B)



GLAD magnet

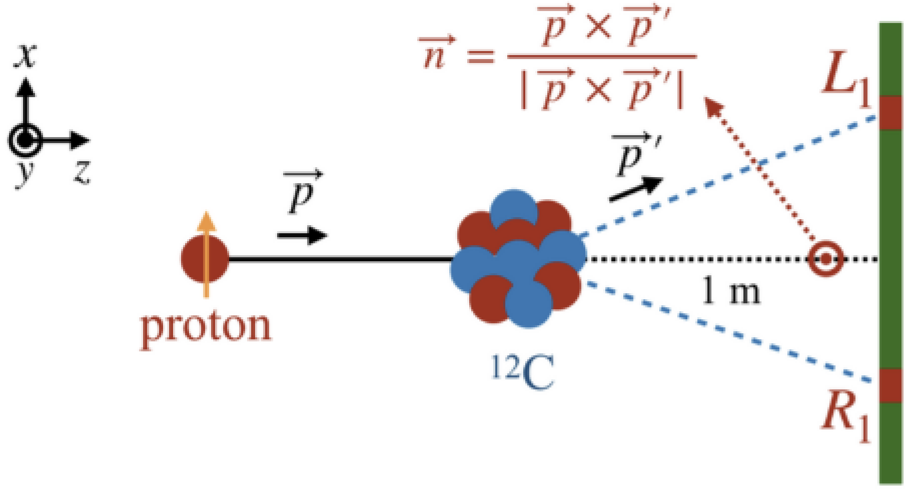
- **GLAD is a zero-degree superconducting dipole magnet** designed and constructed for the R^3B program at GSI/FAIR.
- It provides a **large vertical gap** with an angular acceptance of about **±80 mrad for neutrons**.
- The design uses **four tilted superconducting coils**; side coils reduce fringe fields to keep the **target region field low** for nearby detectors.
- The spectrometer has a **field integral ≈ 5 T·m**, enabling sizable deflection even for high-rigidity beams (up to the Super-FRS regime).
- With high-resolution tracking, GLAD can achieve a momentum resolution of about **$\Delta p/p \sim 10^{-3}$**.

Our experimental setup



- A 6Li beam at about 200 MeV/u impinges on a liquid-hydrogen (LH2) target placed upstream of GLAD.
- The produced 6Be is unbound and decays promptly into alpha + p + p.
- Incoming beam ID/tracking: LOS + ROLU + MWPC1–MWPC2.
- Pre-GLAD tracking of charged fragments: MWPC3–MWPC4.
- Downstream tracking & timing: GEM trackers + ToF wall.
- Proton polarimetry: secondary p–C scattering in a thin carbon analyzer + tracking/timing.
- Reconstruction: neutron at 0° not detected; kinematics constrained from measured alpha + p + p.

Expected observables and preliminary simulations



- The polarized cross section can be written as

$$\frac{d\sigma}{d\Omega}(\theta_{sc}, \varphi_{sc}) = \frac{d\sigma_0}{d\Omega}(\theta_{sc}) \left[1 + A_y(\theta_{sc}) P_n \cos(\varphi_{sc} - \varphi_P)\right]$$

Analyzing power — the transverse polarization component

- The **single-proton azimuthal asymmetry** gives access to polarization:

$$\mathcal{A}_1(\theta_{sc}) = \frac{N_L - N_R}{N_L + N_R} \simeq A_y(\theta_{sc}) P_n$$

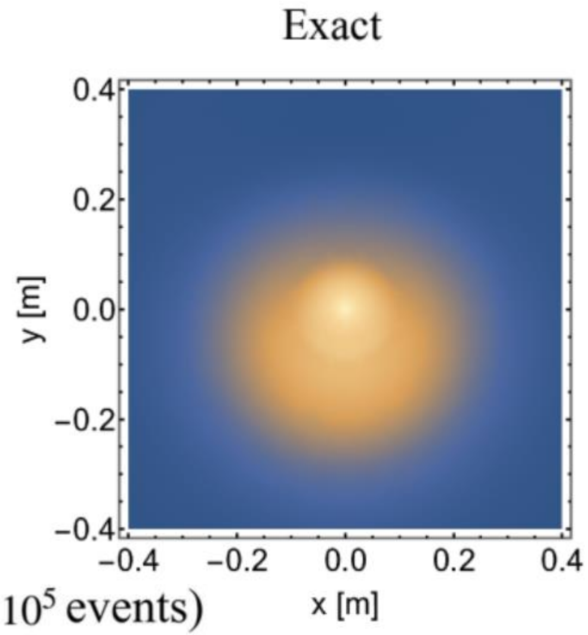
- For two protons we access the **spin-correlation tensor**

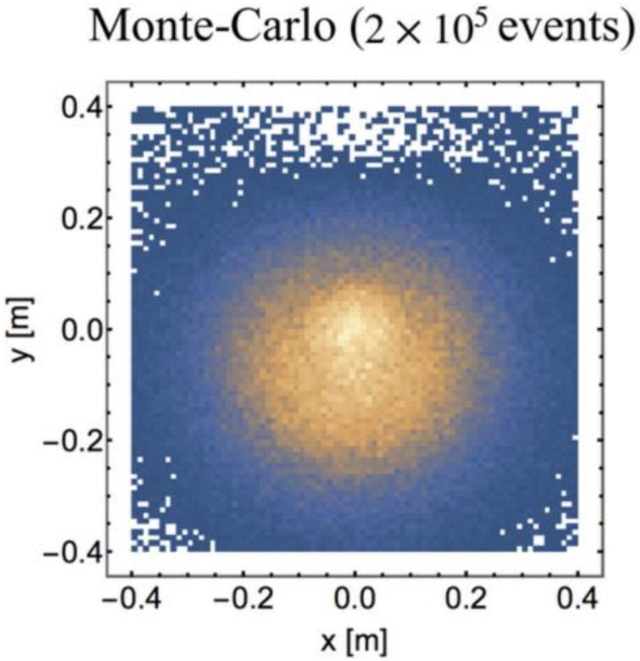
$$C_{ij} = \langle \sigma_i^{(1)} \sigma_j^{(2)} \rangle$$

- Proton polarimetry is based on **secondary p–C scattering** in a thin **graphite (carbon) analyzer**, reconstructed with **GEM tracking**.
- From the GEM hits we reconstruct the scattering angles **(θsc, ϕsc)** for each proton.

Expected observables and preliminary simulations

- Simulated polarimeter response shows the expected **left–right azimuthal modulation** after p–C scattering.
- Comparison of **analytic ("Exact")** intensity I(theta,phi) with **Monte-Carlo (2×10^5 events)** demonstrates the feasibility of extracting asymmetries within the detector acceptance.
- From measured asymmetries we can reconstruct **A1(θsc)** (single proton) and **Aij / Cij** (two-proton correlations).
- These observables can be directly compared with **three-body calculations of 6Be decay** and used to build **Bell-type combinations** of spin correlations.





Summary:

- We propose to probe spin entanglement in the unbound decay ^{6}Be →α+p+p, motivated by predicted CHSH violation.
- At R3B/GLAD, full reconstruction of α+ p+ p plus a downstream p-C polarimeter enables access to proton polarization and p-p spin correlations.
- Status: Letter of Intent submitted to GSI (Dec. 2025); feasibility studies and simulations are ongoing

- Letter of Intent submitted to GSI in Dec. 2025
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