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RESEARCH HIGHLIGHT

Bridging nuclear physics across energy scales: from neutrinoless double-beta decay to high-energy heavy-ion collisions

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The challenge in searching for fundamental symmetry violation. Neutrinoless double-beta ($0\nu\beta\beta$) decay represents one of the most profound tests of fundamental symmetries in nature. This hypothetical nuclear process, in which two neutrons simultaneously decay into two protons with the emission of two electrons but no neutrinos, would demonstrate that lepton number is not conserved and confirm that neutrinos are their own antiparticles (Majorana particles). The observation of $0\nu\beta\beta$ decay would provide crucial insights into the absolute neutrino mass scale and could illuminate the origin of matter–antimatter asymmetry in the universe.

However, the design and interpretation of next-generation ton-scale experiments searching for this rare process face a critical bottleneck: the substantial uncertainties in nuclear matrix elements (NMEs) predicted by different nuclear theory models. These NMEs, which connect experimental observables to fundamental physics parameters like the effective neutrino mass, vary by factors of three or more across different nuclear structure calculations. This uncertainty translates to an order-of-magnitude ambiguity in the predicted half-life for a given neutrino mass, limiting our ability to extract meaningful physics from future potential experimental discoveries.

The challenge arises because NMEs are exquisitely sensitive to the many-body nuclear wave function of both the parent and daughter nuclei. Traditional calculations of the NMEs based on nuclear models that are tuned to describe low-energy nuclear structure data, such as energy levels and electromagnetic transition rates. These observables appear to be insufficient to strongly constrain the complex ground-state correlations that dominate the $0\nu\beta\beta$ decay process.

Heavy-ion collisions as nuclear structure diagnostics The paper by Li, Zhang, Giacalone, and Yao, in Physical Review Letters [1], presents an innovative approach to this long-standing problem by leveraging high-energy heavy-ion collisions as a complementary probe of nuclear structure. This connection might initially seem surprising, given the vast energy difference between nuclear decay processes (keV-MeV scale) and relativistic heavy-ion collisions (GeV-TeV scale). However, the key insight is that both phenomena are sensitive to the same underlying nuclear ground-state wave function, albeit through different physical processes.

In high-energy nuclear collisions, the ultrashort timescales involved effectively "freeze" the nuclear structure, creating a snapshot of the nucleon positions as they exist in the ground state [2, 3]. The subsequent formation and evolution of the quark-gluon plasma (QGP) retain memory of this initial spatial distribution through collective flow phenomena. Crucially, this approach enables the use of high-energy heavy-ion collisions to probe the very nuclear structure properties that are most sensitive to the NMEs (Fig. 1). The flow observables based on multi-particle correlation functions provide direct access to the same nuclear wave function properties that determine NMEs, offering sensitivities that are potentially orthogonal to those accessible through traditional low-energy experiments.

Methodology The authors employed a multireference covariant density functional theory (MR-CDFT) approach to investigate the ^{150}Nd $\rightarrow$ ^{150}Sm (Neodymium-150 to Samarium-150) transition, which is a promising $0\nu\beta\beta$ decay candidate. Their methodology involves varying nine parameters of the relativistic energy density functional within a space previously constrained by Bayesian analysis of low-energy nuclear data. This approach generates an ensemble of nuclear structure calculations that provides reasonable descriptions of known nuclear properties while spanning the theoretical uncertainty space.

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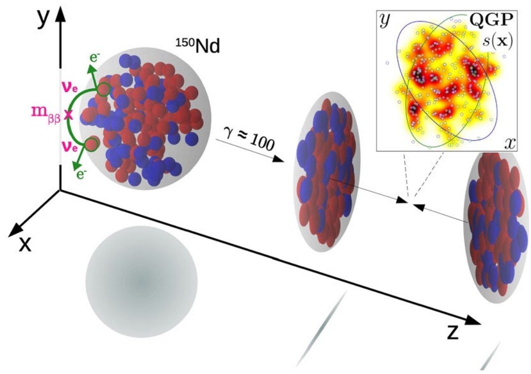

Fig. 1 (Color online) Cartoon illustration of how the same fundamental property of the ^{150}Nd nucleus, **its ground-state nucleon distribution**, has consequences in two very different areas of physics. On the left, this distribution affects the probability of its neutrinoless double-beta ($0\nu\beta\beta$) decay. On the right, it determines the initial geometry of the quark-gluon plasma created when these nuclei are smashed together in high-energy heavy-ion collisions. The central idea is that experimental data from these collisions can refine our understanding of the nucleon distribution, which in turn would help reduce the uncertainty in prediction of the $0\nu\beta\beta$ decay. Adapted from Ref. [1]

For each parameter set, the authors calculated both the $0\nu\beta\beta$ decay NME and the intrinsic nuclear density distribution characterized by the quadrupole deformation parameter β_2. These nuclear densities then serve as input for high-energy collision simulations using the T$_\mathrm{R}$ENTo model, which describes how the initial nuclear geometry translates into the entropy density of the produced QGP. This study focuses on ultracentral collisions, where nuclear deformation effects are maximally expressed.

The connection between the initial nuclear structure and final-state observables relies on the established relationships from relativistic heavy-ion phenomenology. The spatial eccentricity of the QGP (ε_2) correlates strongly with the experimental elliptic flow coefficients (v_2), whereas the energy-to-entropy ratio (E/S) connects to the mean transverse momentum in each event ($[p_\mathrm{T}]$). These relationships allow the authors to predict how variations in nuclear structure would manifest in quantities experimentally accessible in the collider experiment.

Remarkable correlations across energy scales The central finding of this paper is striking: the correlations between NMEs and heavy-ion flow observables are comparable in strength to those found using traditional nuclear structure probes. Specifically, the Pearson correlation coefficient between the NME and quadrupole deformation parameter β_2 of ^{150}Nd is $r = -0.93$, whereas correlations with various flow observables range from $r = -0.88$ to $r = 0.93$. This suggests that heavy-ion collision measurements could provide constraints on NMEs that are competitive with, and complementary to, existing low-energy approaches.

Particularly intriguing is the strong correlation ($r = -0.78$) between the NME and the difference in quadrupole deformations between the ^{150}Nd and ^{150}Sm nuclei. This sensitivity to deformation differences suggests that comparative measurements using isobar collisions—involving both the parent and daughter nuclei of $0\nu\beta\beta$ decay candidates—could provide especially powerful constraints. This is mainly because the relative nature of such measurement allows for the cancelation of many systematic uncertainties that typically plague absolute measurements.

Future prospects While these initial proof-of-principle results are encouraging, several important extensions are needed to fully quantify the potential of this approach. First, the correlations observed within the MR-CDFT framework should be verified using other state-of-the-art nuclear structure theories, such as the *ab initio* in-medium similarity renormalization group (IMSRG) method. Different theoretical approaches may provide insights into the model-dependence of the nucleon correlations.

On the high-energy side, the T$_\mathrm{R}$ENTo model's linear response assumptions, while qualitatively established, represent a simplification of the complex dynamics involved in heavy-ion collisions. Future studies should incorporate full three-dimensional viscous hydrodynamic simulations to more accurately capture the relationship between initial nuclear structure and final-state observables. Additionally, the inclusion of other deformation modes (octupole, triaxial) could provide access to additional aspects of the nuclear wave function.

The experimental feasibility of this program appears promising. The required statistical precision for measuring flow observables in ultracentral collisions is well within the capabilities of current and planned detector systems at the Large Hadron Collider. Short dedicated runs of a few hours could provide sufficient statistics, and upcoming detector upgrades such as ALICE 3 will further enhance these capabilities. The potential addition of a second ion source would enable the crucial isobar collision measurements that could maximize the sensitivity to nuclear structure differences.

Summary This paper exemplifies how connecting methods at disparate energy scales can illuminate fundamental questions. By demonstrating that nuclear wave function properties governing rare decay processes also influence collective behavior at extreme temperatures and densities, the authors have opened a new pathway for constraining physics beyond the Standard Model.

With multiple ton-scale $0\nu\beta\beta$ experiments under construction, any method reducing NME uncertainties will directly impact our ability to interpret discoveries or constrain neutrino properties. The general principle—that collective phenomena in high-energy collisions can illuminate subtle features of many-body correlations in the colliding nuclei—may find applications across nuclear and particle physics. This intersection of nuclear structure theory, heavy-ion physics, and fundamental symmetry tests represents fertile ground for future discoveries in modern physics.

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