中山大学第二课堂特色院系“测地观天”科技文化节系列活动

物理与天文学院第二届“格物论坛”

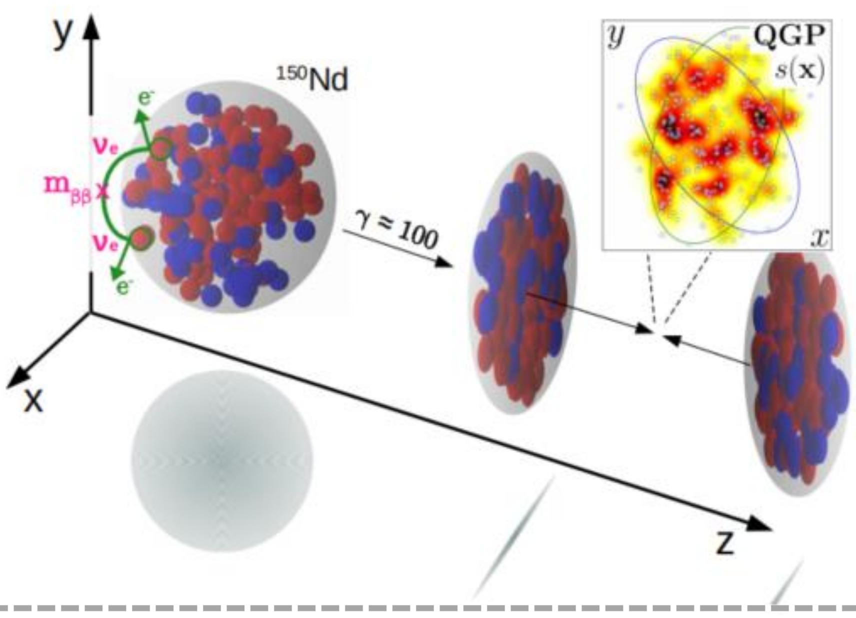
Benchmarking nuclear matrix elements of $0\nu\beta\beta$ decay with high-energy nuclear collisions

中山大学物理与天文学院物理系

姓名：李义　　导师：尧江明 教授

Introduction

- Neutrinoless double-beta decay (0νββ) plays a crucial role in determining whether neutrinos are Dirac or Majorana particles and in shedding light on the origin of matter-antimatter asymmetry in the universe.
- The nuclear matrix elements (NMEs) connect the observed half-lives of 0νββ decay to the underlying neutrino masses; however, predictions from different nuclear models can vary by factors of three or more, leading to significant theoretical uncertainties. Reducing these uncertainties remains a central challenge in both the design and interpretation of experiments aimed at discovering 0νββ decay.
- Exploring correlations between NMEs and experimentally accessible observables offers a promising approach to constraining and reducing these uncertainties.
- This work: we study the correlation between the NME of 0νββ decay ^{150}Nd → ^{150}Sm and the geometric properties of the quark-gluon plasma (QGP) that are produced in the ultra-central relativistic heavy-ion collision (HIC) of ^{150}Nd + ^{150}Nd.



Methods

Relativistic energy density functional (EDF)

- The EDF is composed of kinetic energy, electromagnetic energy and interaction energy

$$E[\tau,\rho,\nabla\rho;\mathbf{C}] = \int d^3r\left[\tau(\boldsymbol{r}) + \mathcal{E}^{\rm em}(\boldsymbol{r}) + \mathcal{E}^{\rm int}(\boldsymbol{r})\right].$$

- The NN interaction EDF

$$\begin{aligned}\mathcal{E}^{\rm int}(\boldsymbol{r}) = & \frac{\alpha_S}{2}\rho_S^2 + \frac{\beta_S}{3}\rho_S^3 + \frac{\gamma_S}{4}\rho_S^4 + \frac{\delta_S}{2}\rho_S\Delta\rho_S \\ & + \frac{\alpha_V}{2}j_\mu j^\mu + \frac{\gamma_V}{4}(j_\mu j^\mu)^2 + \frac{\delta_V}{2}j_\mu\Delta j^\mu \\ & + \frac{\alpha_{TV}}{2}\boldsymbol{j}^\mu_{TV}\cdot(\boldsymbol{j}_{TV})_\mu + \frac{\delta_{TV}}{2}\boldsymbol{j}^\mu_{TV}\cdot\Delta(\boldsymbol{j}_{TV})_\mu\end{aligned}$$

- The free parameters

$$\mathbf{C} = \{\alpha_S, \beta_S, \gamma_S, \delta_S, \alpha_V, \gamma_V, \delta_V, \alpha_{TV}, \delta_{TV}\}$$

MR-CDFT for nuclear low-lying states

- Nuclear wave functions are linear combinations of particle-number (N, Z) and angular-momentum(J) projected wave functions,

$$\left|\Psi_{I/F}(J_\nu^+,\mathbf{C})\right\rangle = \sum_q f_\nu^{JNZ}(\mathbf{q},\mathbf{C})\hat{P}^N\hat{P}^Z\hat{P}^J|\Phi(\mathbf{q},\mathbf{C})\rangle,$$

 where weight function f_ν^{JNZ} is determined by the variational principles.
- The mean-field wave functions $|\Phi(\mathbf{q},\mathbf{C})\rangle$ are determined by deformation constrained relativistic mean-field (RMF) + BCS theory.
- The NME of ground state to the ground state $0\nu\beta\beta$ decay is given by

$$M^{0\nu}(\mathbf{C}) = \left\langle\Psi_F(0_1^+,\boldsymbol{C})\middle|\hat{O}^{0\nu}\middle|\Psi_I(0_1^+,\mathbf{C})\right\rangle.$$

Development of SP-CDFT

- An emulator based on the eigenvector continuation method, capable of accurately reproducing MR-CDFT results for nuclear low-lying states with significantly reduced computational cost.
- The wave function $|\Psi^{JNZ}(J_k^+,\mathbf{C}_\odot)\rangle$ for the given parameter set $\mathbf{C}_\odot$ is expanded over the MR-CDFT wave functions $|\Psi^{JNZ}(J_\nu^+,\mathbf{C}_t)\rangle$ of the training set $\{\mathbf{C}_t\}$

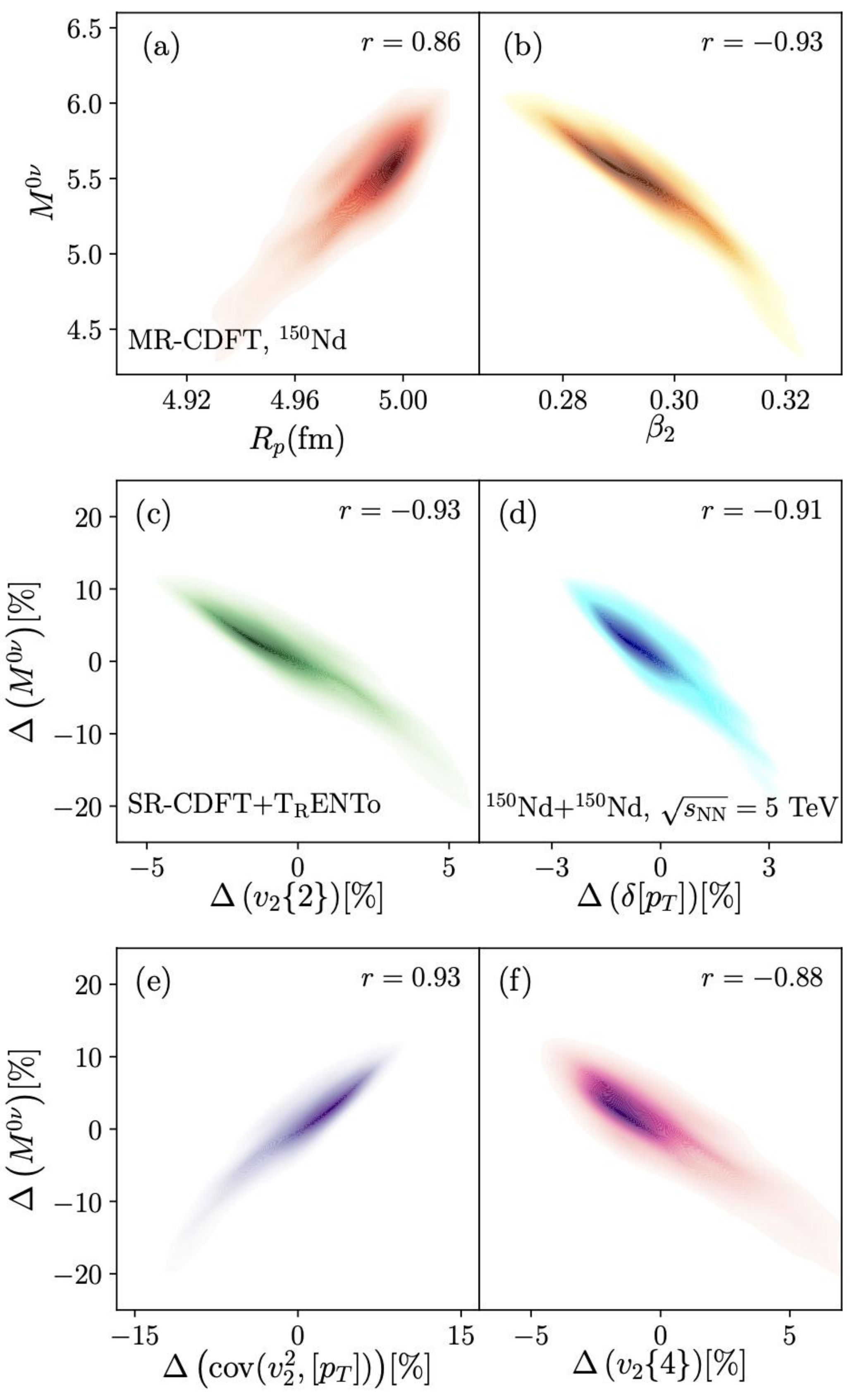
$$\left|\Psi^{JNZ}(J_k^+,\mathbf{C}_\odot)\right\rangle = \sum_{\nu=1}^{k_{max}}\sum_{t=1}^{N_t} f_{k,\mathbf{C}_\odot}^{JNZ}(\nu,\mathbf{C}_t)|\Psi^{JNZ}(J_\nu^+,\mathbf{C}_t)\rangle.$$

T_RENTo for heavy-ion collisions

- The nuclear density as input for the $\mathrm{T_RENTo}$ model for the high-energy ^{150}Nd + ^{150}Nd collisions.
- Computing the spatial ellipticity ε_2 and the ratio of total energy to total entropy E/S of the QGP, ultimately yielding the final-state elliptic flow v_2 and average transverse momentum $[p_T]$ of the collective flow.

Results

$$\frac{dN_{\rm ch}}{d^2\mathbf{p}} \propto \frac{dN_{\rm ch}}{p_T\,dp_T}\left(1 + \sum_{n>1} 2\,v_n\cos n(\phi-\phi_n)\right)$$



- Spreads of the NMEs and the observables in ^{150}Nd + ^{150}Nd collision by 1k parameter sets, which predict different B(E2) values for ^{150}Nd.
- The existence of strong correlations between the value of the NME of 0νββ decay and quantities accessible at colliders.

Summary, Conclusion & Outlook

Summary &Conclusion

- We have conducted the first statistical analysis of the correlation between NMEs of 0νββ decay and observables from HIC using covariant density functional theory (CDFT).
- Our study reveals strong correlations between the NMEs and specific HIC observables, whose precise experimental measurement could serve as a valuable benchmark for the prediction of the NMEs in the future.

Outlook

- Extension to other candidate nuclei of 0νββ decay.
- Exploration of the correlation between the NMEs with other observables, such as the vector meson production cross section in the HIC.

References:

[1] Y. Li, X. Zhang, G. Giacalone, J.M. Yao, arxiv: 2502.08027 (2025)

[2] X. Zhang, C.C. Wang, C.R. Ding, J.M. Yao, arxiv:2408.13209 (2024)

[3] J.M.Yao et al., Prog. Part. Nucl. Phys. 126, 103965 (2022)