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CONSTRAINING THE PROPERTIES AND INTERACTIONS OF DARK MATTER

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EXECUTIVE SUMMARY

This project addresses the Grand Challenge research problem of understanding the nature of the mysterious dark matter that permeates the universe. In particular, to interpret the results of direct experimental searches for dark matter it is necessary to quantify the interaction of potential dark matter particles with the nuclei used as targets in the detectors. This is a hugely demanding computational task that requires significant resources.

RESEARCH CHALLENGE

Understanding the nature of dark matter is a defining challenge for contemporary particle and nuclear physics. This project will provide necessary theoretical input for interpreting dark matter searches that are currently being undertaken at laboratories around the world, and will allow optimal design of the next generation of such experiments. The interaction of a broad class of dark matter candidates with the nuclei used in direct detection experiments is governed by nuclear scalar matrix elements. In recent work, the research team determined the scalar matrix elements of light nuclei via first-principles calculations of the underlying interactions with the Standard Model, albeit with larger-than-physical values of the quark masses used in the study (allowing computationally cheaper calculations). These calculations revealed significant, and unexpected, order 10% nuclear effects in the scalar interactions in light nuclei. These significant effects in small nuclei potentially indicate even larger effects and uncertainties in the scalar matrix elements of the much larger nuclei, for example xenon, typically used in direct detection experiments. If these effects persist in a controlled study at the physical values of the quark masses, it will have significant implications for the interpretation of the results of current and future dark matter direct detection experiments around the world.

METHODS & CODES

This study has been undertaken within the framework of lattice QCD (quantum chromodynamics), which is a first-principles method of calculating strong interaction matrix elements numerically on a discrete four-dimensional spacetime. In this approach, Monte Carlo techniques are used to create a representative set, known as an ensemble, of configurations of the background gluon fields on the links defined between points on the spacetime lattice. This ensemble is then used to perform calculations of quantities of physical interest. As the only known direct method of studying QCD at the low energies relevant for hadronic and nuclear interactions, lattice QCD is an important source of information for tests of the Standard Model, and it provides results for various hadronic and nuclear matrix elements that are systematically improvable and model-independent. As such, it is the necessary tool for the calculations undertaken.

RESULTS & IMPACT

This project began in mid-2019. The codebase has been successfully implemented on Blue Waters and production runs have begun. The calculations that are running are producing the time series data that will allow the determination of the nuclear quantities that govern the interactions of dark matter with light nuclei. Additionally, data structures are being generated that form the first step in calculations of nucleon–nucleon scattering and studies of light nuclear spectroscopy. Once the calculations are complete, they will enable understanding of nuclear effects in dark matter interactions with nuclei that will have far-reaching impacts on current and future terrestrial searches for dark matter. The research team anticipates that the precision they will achieve with the runs that are in progress will be sufficient to influence the design of future experiments searching for dark matter.

WHY BLUE WATERS

Undertaking a controlled calculation of the interactions of dark matter with nuclei is a hugely demanding computational task that requires significant resources that would not otherwise be available to the project team.