Snowmass 2021 Letter of Interest:
Insights from Quantum Information Science into Dark Matter Direct Detection Experiments

Primary topical groups:

CF1 (Dark Matter: Particle-like)
CompF6 (Quantum Computing)

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Abstract: Quantum information science has the potential to improve greatly the knowledge about normal matter - dark matter interactions that can be extracted from experiments that perform direct detection of dark matter.

Background on Dark Matter searches: Many direct dark matter (DM) searches seek to measure WIMP-induced nuclear recoils. The primary sensitivity that direct DM experiments report is on the spin-independent coherent WIMP-nucleon cross section, where protons and neutrons are treated identically, and this interaction is assumed to be the only scattering occurring. For odd-numbered target nuclei with intrinsic spin, the spin-dependent cross sections for WIMP-proton and WIMP-neutron scattering are also reported, again with the simplified approach that the upper limit is placed on all interactions only via that particular channel [1]. This spin-independent/spin-dependent (SI/SD) simplification has some significant physics consequences, suggesting for example that DD experiments are essentially blind to vast classes of dark matter interactions involving derivative couplings.

Recent work showed that the naive SI/SD analysis generally underestimates DD sensitivities by two orders of magnitude: this emerges from a proper effective field theory (EFT) treatment of low-energy WIMP scattering, which has been worked out in a non-relativistic framework for use by DD experiments [2–5]. The nuclear response is computed by folding the single-nucleon reduced density matrix with the one-body matrix elements of operators derived in EFT. Thus DD experiments are far more powerful than previously realized, placing six (not two) independent constraints on dark matter theories. This has important consequences because current analyses employ cuts to maximize signal/noise ratio for SI/SD interactions and eliminate kinematic regions where the additional nuclear responses peak, thus missing some of the essential physics. The variety of operators - most of which are familiar, related to orbital angular momentum, axial charge, etc. - also profoundly changes the comparisons between different experiments. The relative sensitivity of experiments using different nuclear targets can vary by several orders of magnitude under changes in the underlying WIMP interaction. The experimental community has changed their analysis protocols and cuts, embracing the EFT approach to enlarge the extractable physics.

To take full advantage of current and planned DD experiments as described above, one must have a firm grasp on both the theory of the interaction of dark matter and neutrinos with detectors, and the uncertainty in that theory. While the base theory of the interaction with protons and neutrons is firm - EFT for dark matter, vector-axial vector (V-A) theory for neutrinos- actual targets are complex nuclei with complex responses that can change drastically from isotope to isotope. Uncertainty quantification (UQ) has begun to be implemented into the theory of atomic nuclei [6–9], including work by our collaboration [10], based in part upon the realization that correct assessment of any experiment that rests upon models needs UQ.

Background on quantum algorithms for effective field theory: Although practical quantum computing is still very much in its infancy, pioneering work has demonstrated the potential applicability and utility of quantum emulations of atomic nuclei, especially those relevant to interpreting experiments in high energy physics. For example, EFTs, where one characterizes the nuclear interaction by a ratio of the momentum scale to a momentum cutoff, has proven to be a useful workhorse in classical nuclear physics calculations. In particular, EFTs in the harmonic oscillator basis are powerful because they allow for UV convergence to be built in by construction, while IR convergence is recovered by enlarging the available kinetic energy dynamic range of the model [11]. Recently, an example of approximating the ground state of light nuclei described by this type of EFT was provided in Ref. [12]. Devices with order of 100 qubits are imminent, and while they will not be capable of fault-tolerant quantum computing, they will enable many-body simulations. The simulations of nuclei for DD experiments are particularly well-suited for these near-term devices due to their effective many body physics.

Using near-term quantum computers to learn more from direct DM searches: Near-term quantum computers still have significant errors from both systematic and stochastic sources [13], and these errors must be understood and mitigated for quantum computers to yield results that are more accurate than approximate classical theories. This intermediate scale noise mitigation is different from the concept of quantum error correction. Noise mitigation does not rely on the concept of encoding quantum information into larger numbers of qubits in order to reduce logical error rates. Instead, it relies on the detection of systematic errors, the calibration of quantum devices to account for them, and the reduction of these errors by post-processing the data or by feeding forward onto the machine's native gate constructions. Designing the calculations so that the deleterious effects of hardware errors are minimized is another strategy that will be important for maximizing the usefulness of near-term hardware for the quantum simulations used for these applications.

Tailoring the software to mitigate limitations of the hardware has been applied successfully to gate-based quantum computations. For instance, when the hardware errors are predominantly phase errors, relatively small changes in the error correction algorithm yield fourfold increases in the threshold for successful quantum error correction [14]. It has also been shown that error correction schemes that employ unitary gates and re-initializations using no qubit measurements can be advantageous if measurement is very slow compared to the gate operation time, which again is often the case in practice [15–17]. For quantum simulations, the most obvious way to try to adapt the operations to minimize errors is to tailor the qubit encoding to minimize the effects of hardware errors on the calculation.

As a simple example of this strategy, if the dominant errors are phase errors and the Hamiltonian to be simulated consists predominantly of Ising interactions, then it is intuitively clear that the errors in the energy obtained are smaller when the qubit z-axis is aligned with the Ising z-axis. Nuclear interactions are significantly more complex than Ising spin interactions, which makes determining an optimal encoding for a given error structure a challenging yet interesting problem. One can approach this problem by benchmarking the quantum simulation results for small nuclei such as deuterium [12] and helium [18] to the results of classical computations. For these small nuclei, accurate classical computations can be performed, so this benchmarking procedure will enable us to characterize the quantum simulation errors and also to determine whether choosing an appropriate qubit encoding increases the accuracy of the quantum simulations for DD experiments.

Summary: Quantum simulations have the potential to improve qualitatively our ability to learn from DM DD experiments. To exploit fully these capabilities using near term quantum simulators, it is important to understand and mitigate errors and to design algorithms so that they have enhanced resilience to imperfections in the hardware. Combining recent advances in EFT with quantum simulation has the potential to enable the development of a much deeper understanding of DM from DD experiments than could be contemplated even a few years ago.

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