Magnetic moments of light nuclei from lattice QCD†

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The structure and dynamics of nuclei have been extensively probed using electromagnetic interactions. Magnetic moments historically helped support a picture of light nuclei as collections of weakly interacting nucleons, which led to the phenomenologically successful shell-model description of nuclei. At a fundamental level, however, nuclei are bound states of the quark and gluon degrees of freedom of QCD. Nuclear forces emerge from QCD as a consequence of confinement and chiral symmetry breaking. Yet, nuclei are not simply collections of quarks and gluons determined by global quantum numbers; rather, nuclei have the structure of interacting nucleons, and this feature remains to be understood at a deep level. Knowledge of the quark structure of nuclei, moreover, is required to turn nuclei into laboratories for probing fundamental symmetries, and pushing the limits of the Standard Model.

We have computed magnetic moments of the lightest few nuclei using lattice QCD. These calculations, the first of their kind, have been performed at unphysical light-quark masses. All three light-quark masses in our computation were set equal to the physical strange quark mass. At this $SU(3)$ flavor-symmetric point, the resulting pion mass is $m_\pi \approx 800\,\texttt{MeV}$. Further details of the lattice action and gauge configurations are found in Ref.[2]. To compute magnetic moments, $U(1)_{\mathcal{Q}}$ gauge links giving rise to a uniform magnetic field were post multiplied onto each QCD gauge field. While quenching sea quark electric charges is an approximation, there are no contributions to magnetic moments resulting from coupling the magnetic field to sea quarks in our computation This fact owes to the three degenerate quark flavors with their non-singlet electric charge matrix, $\mathcal{Q} = e\,\texttt{diag}\left(+\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}\right)$. Sub-percent QED effects, however, have been neglected in our computation. The combined gauge fields were used to compute up and down ($\equiv$ strange) quark propagators, which were then contracted to form the required nuclear correlation functions using the techniques of Ref.[3]. Finally nuclear correlation functions were projected onto spin components with respect to the direction of the magnetic field.

† Condensed from Reference[1]

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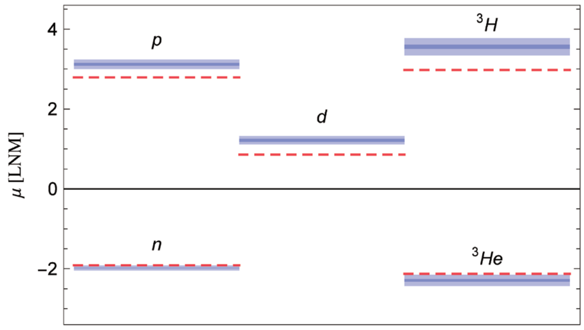

Fig. 1. Nuclear magnetic moments computed using lattice QCD at the $SU(3)$ flavor-symmetric point[1]. Results in lattice nuclear magnetons [LNM] (blue bands) are remarkably close to experimentally measured moments in physical nuclear magnetons (dashed red lines). Despite deep binding found at this unphysically large quark mass, magnetic moments of light nuclei are close to those predicted from simple shell-model configurations.

The ground-state energy of a non-relativistic hadron having mass M, and charge Qe is given by

$$E(\vec{B}) = M + \frac{e}{2M}|Q\vec{B}| - \vec{\mu}\cdot\vec{B} + \mathcal{O}(B^2). \qquad (1)$$

The field-dependent terms appearing above are due to the lowest Landau level and Zeeman interaction, which is proportional to the hadron's magnetic moment, μ. To isolate magnetic moments with good statistical precision, the long Euclidean-time limit of correlator ratios was utilized. For a spin-half hadron, e.g., we consider the ratio

$$\mathcal{R}^{(B)}(\tau) = \frac{C_\uparrow^{(B)}(\tau)}{C_\downarrow^{(B)}(\tau)} \Bigg/ \frac{C_\uparrow^{(0)}(\tau)}{C_\downarrow^{(0)}(\tau)} \sim e^{-2\mu|B|\tau}, \qquad (2)$$

as a function of the applied magnetic field. Extracted magnetic moments are shown in Fig. 1 in lattice nuclear magnetons, i.e. units of $\frac{e}{2M_N}$, where M_N is the lattice nucleon mass, $M_N \approx 1.6\,\texttt{GeV}$. When scaled in this fashion, results are remarkably close to experimental values. In particular, evidence for shell-model configurations suggests that this property of nuclei may extend over a broad range of quark masses.

References

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