A Beam of Polarized Boron-10 Nuclei To Search for Exotic Gluons

William R. Milner[1], and Richard G. Milner[2]

1. Research Laboratory of Electronics, MIT–Harvard Center for Ultracold Atoms, and Department of Physics, MIT, Cambridge MA, USA 02139

2. . Laboratory for Nuclear science, and Department of Physics, MIT, Cambridge MA, USA 02139

Motivation

- A major thrust of twenty-first century nuclear physics is understanding how the quarks and gluons of Quantum Chromodynamics (QCD) give rise to the observed structure and properties of nuclei.
- A unique and innovative new accelerator, the Electron-Ion Collider (EIC), is being realized at Brookhaven National Laboratory, Upton, NY with the aim of opening up new windows on understanding QCD[1].
- Despite the fundamental role the gluon fills in QCD, direct measures of gluonic states in the nucleus remain elusive. As the electrically neutral gluon does not couple directly to the photon, it is probed only indirectly in electron scattering from hadrons.
- While to first order nuclei are bound states of protons and neutrons, as the spin of the nucleus increases, higher-order behavior in the nucleus becomes available in the form of *new* nuclear structure functions.

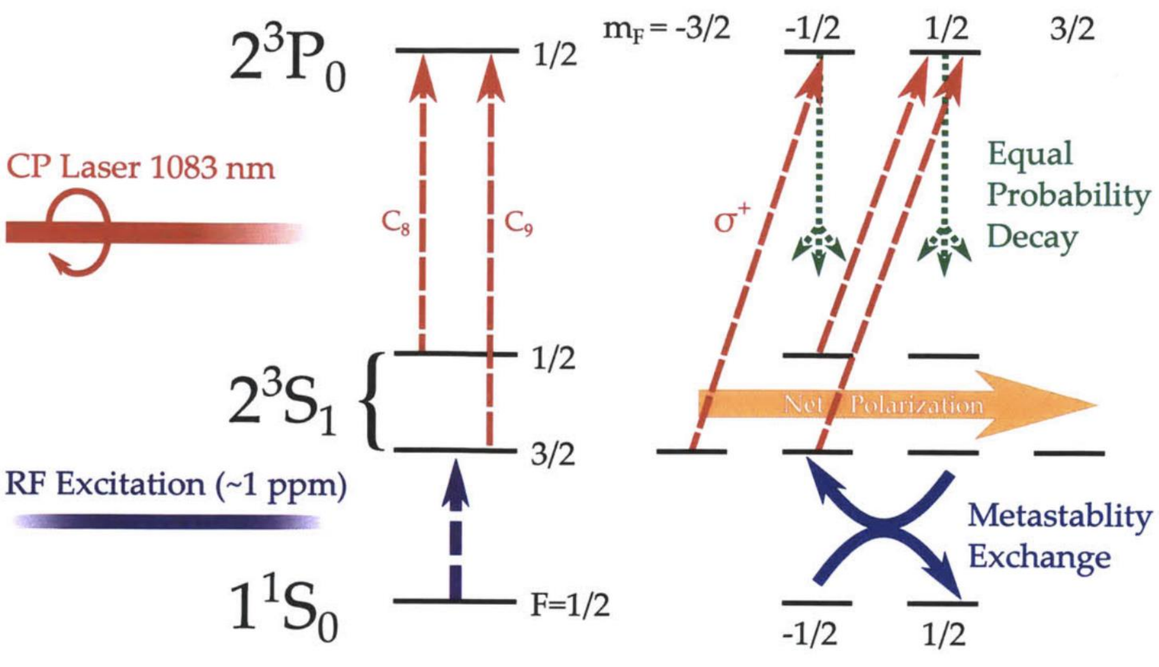
Nucleus	Nuclear Spin	Binding Energy per nucleon	Spin per nucleon
	I	MeV	
^{2}H	1	1.1	0.50
^{3}He	$\frac{1}{2}$	2.6	0.17
^{6}Li	1	5.0	0.17
^{7}Li	$\frac{3}{2}$	5.6	0.21
^{10}B	3	6.5	0.30
^{11}B	$\frac{3}{2}$	6.9	0.14
^{23}Na	$\frac{3}{2}$	8.1	0.07

Table I. Binding energy and spin properties of light nuclei.

Exotic gluon studies

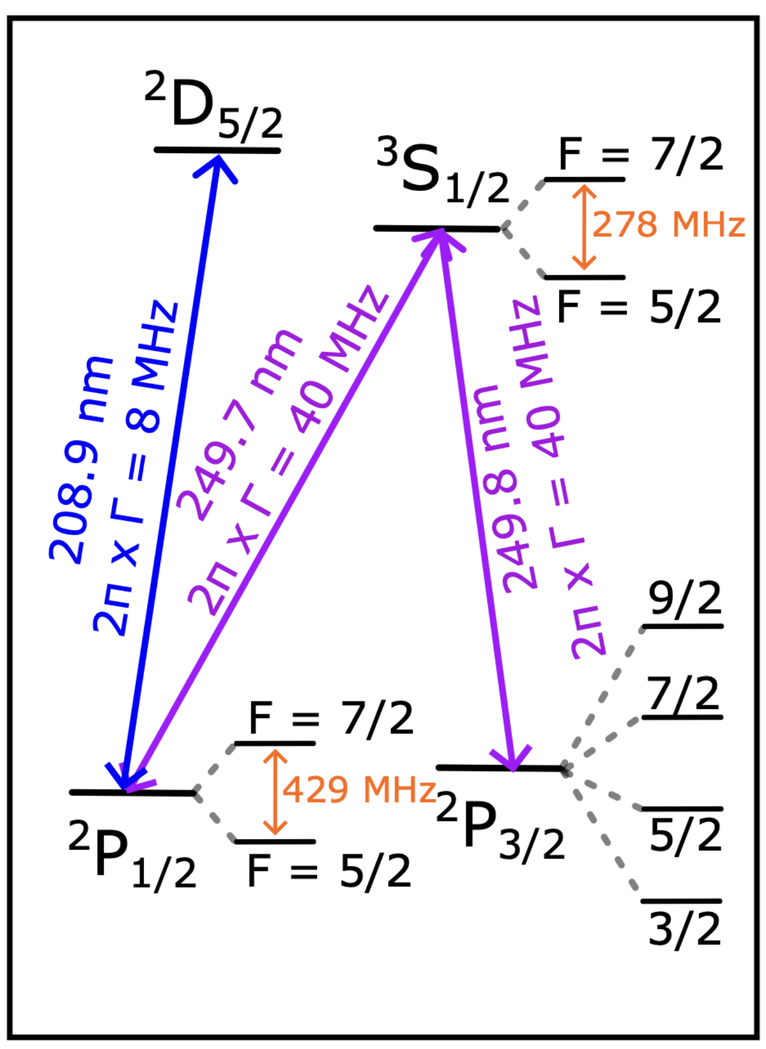
- In 1989, Jaffe and Manohar identified a new structure function which is sensitive to gluonic states in the nucleus but is free from contributions from the motion and binding of nucleons in the nucleus [2].
- A measurement of $\Delta(x, Q^2)$ would require an unpolarized electron beam of nuclear spin $I \geq 1$
- The nucleus should have significant binding, to enhance the amount of exotic gluons, but should not be too large, as spin effects will be diluted.
- One thus wants to optimize the nuclear spin *per nucleon*. **Boron-10** has the largest spin per nucleon of any nucleus beyond the deuteron.

Nuclear spin polarization



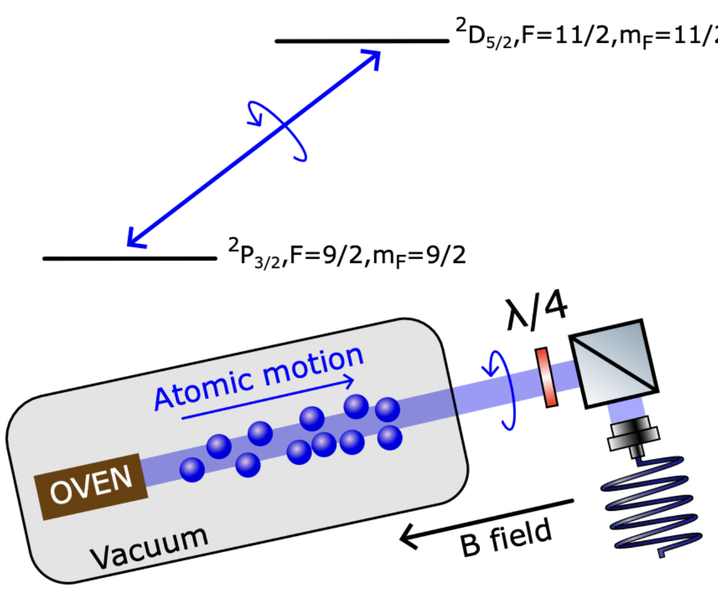
- Pioneering studies of nuclear spin polarization have been done with Helium-3. With one unpaired proton, ^{3}He is a prototypical spin ½ system.
- Metastable-exchange optical pumping (MEOP) has been successfully employed[3]. Here, a circularly polarized laser beam optically pumps atoms via driving the electronic transition $^{3}S_1$ to $^{3}P_0$. The hyperfine interaction $F = I \cdot J$ couples the electronic spin to the nuclear spin.
- Exchange collisions then occur, where ground ($^{1}S_0$) and metastable ($^{3}S_1$) atoms exchange electronic configurations and transfer the nuclear spin polarization to the ground state.

Boron-10



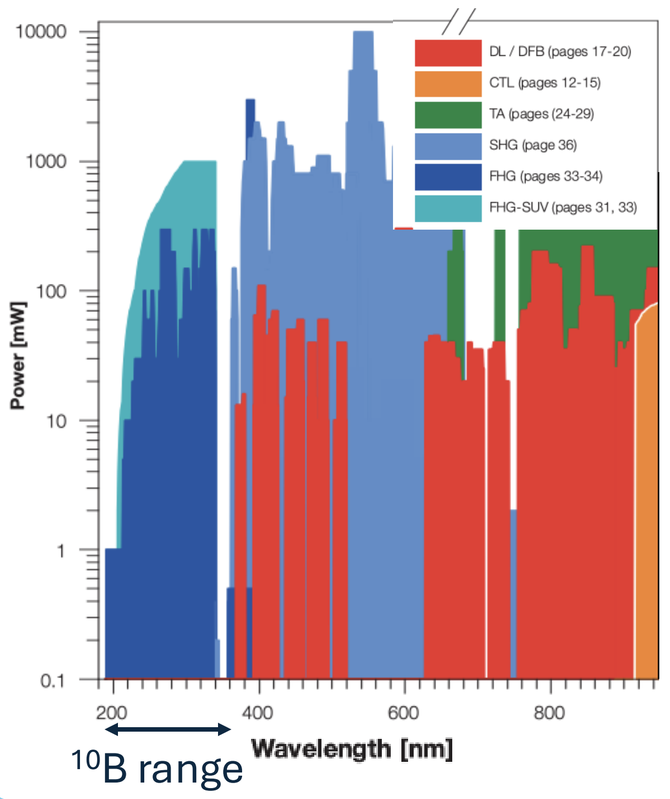
- Utilizing optical pumping techniques on new nuclei with high spin can open the door to study exotic gluons.
- Boron is a group-III element, whose electronic properties match Indium, Aluminum, Gallium. Optical pumping and high nuclear-spin polarization has been achieved on Indium[4, 5].
- The $|^2P_{3/2}, F = 9/2\rangle$ to $|^2D_{5/2}, F = 11/2\rangle$ transition is attractive, as it possesses a *closed* transition, with unity Clebsch-Gordan coefficient.
- Continuous–wave lasers at ~ 200 nm are commercially available at low power.

Experimental scheme



- The $|^2P_{3/2}, F = 9/2, mF = 9/2\rangle$ to $|^2D_{5/2}, F = 11/2, mF = 11/2\rangle$ transition is a closed transition. Repumping light is required to pump the atoms into the $^{2}P_{3/2}$, F = 9/2 manifold.
- We use circularly polarized light, with a quantization axis provided by an external B field aligned with the atomic beam. Slowing studied with Indium observed polarization > 50% with a similar pumping scheme.
- To use on the collider, it will be necessary to generate a polarized ion beam. Injection into an ion trap such as an Electron Beam Ionization Source is one possibility to achieve this.

Technical challenges



- Laser wavelengths for optical pumping appear to be achievable with commercial lasers [6]. ~mW optical powers should be sufficient to saturate the electronic transition.
- Obtaining high beam flux and making setup compatible with collider infrastructure will likely be the main technical challenge. Peak fluxes achieved (10^{10} atoms/cm^2/s) will need to be increased.
- Maintaining high nuclear spin-polarization during ionization will also be important. This is also an outstanding challenge for ^{3}He.

Outlook

- We propose a novel scheme to achieve nuclear-spin polarized Boron-10. Producing a beam of polarized ^{10}B would open the door to exciting new studies for searches of exotic gluons.
- Our experimental scheme uses commercially available equipment and a closed optical transition should be compatible with high nuclear spin polarization.
- Integrating this setup into the collider will require addition studies and can constitute an exciting research agenda.

References

1) Accardi, A., *et al., The European Physical Journal A* (2016)
2) R. L. Jaffe and Aneesh Manohar. *Phys. Lett. B,* (1989)
3) Gentile, Thomas R., *et al., Reviews of Modern Physics* (2017)
4) X. Yu, *et al., Phys. Rev. A* (2022)
5) X. Yu, *et al., Phys. Rev Res.* (2022)
6) Toptica catalogue

MIT-LNS is supported by the U.S. Department of Energy, Office of Nuclear Physics, under grant number DE-FG02-94ER40818

2025