Wuji Mi’s PUR application

Research: developing a Cs-based atomic magnetometer for dark matter research
Mentor: Professor Ibrahim Sulai

A: The research question, problem, or creative undertaking

Matter and energy in the form of protons, electrons, neutrons, and radiation account for only 5 percent of the energy density in the universe. The remaining 95 percent is in the form of so-called dark matter and dark energy. Dark energy accounts for 68 percent of the mass-energy budget of the universe, and dark matter accounts for 27 percent. Our research is concerned with testing a dark matter candidate that has a measurable spin interaction which may be detected with a Cs-based magnetometer.

B: Research Value

Dark matter is called dark because it is invisible. It does not interact with electromagnetic forces nor emits radiation. Consequently, observing dark matter is extremely tough. Fortunately, the dark matter still interacts with gravitational force and scientists managed to find evidence of its existence through this property. In a galaxy, tens of billions of stars will rotate around the center of the galaxy, forming huge spiral arms. According to Newtonian mechanics, the magnitude of gravitational force is inversely proportional to the square of the distance between the two objects, so the farther away from the edge of the galaxy, the smaller the gravitational force and the slower the rotation speed. Observations have shown that in observable galaxies, including the Milky Way, the rotational velocities of distant stars differ from the prediction of Newtonian mechanics. When the distance between the star and the center of the galaxy reaches a certain value, the rotation rate of galaxies[1] does not decrease but increases steadily with distance. One possible explanation is that Newtonian mechanics still need to be revised, while another explanation points out that scientists have undercounted part of the mass in the galaxy, that is, the lost mass. These masses cannot be observed, yet account for 95% of the total mass of the universe. Later, they are named the dark matter. No matter what the reason is, the appearance of this problem indicates that our current theoretical model is incomplete.

The standard model of particle physics describes the electromagnetic, weak, and strong nuclear forces. The three fundamental forces are conducted by basic particles like electrons and quarks, yet dark matter is not modeled by those particles. Some theoretical ideas suggest that dark matter is in the form of a bosonic scalar field, noted as Φ.

For a magnetic vector field B, there is a measurable energy E associated with the interaction of the spin vector with the magnetic field, which can be expressed as

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[1] https://en.wikipedia.org/wiki/Galaxy_rotation_curve

$E \propto \vec{S} \cdot \vec{B}$, where $\vec{S}$ is the atomic spin and $\vec{B}$ is the magnetic field. In comparison, the scalar field Φ does not have a direction, which means Φ can not interact with vectors like spin $\vec{S}$. Its gradients $\nabla\Phi$, however, may perform as a vector and interact with the spin vector and produce observable energy.

In theory, if the earth encounters a dark matter cloud that is not uniformly distributed, then the product of spin dots a nonzero gradient will give us some values, which means we can investigate such kinds of non-magnetic spin interactions with the help of the high sensitivity of OPMs (optical magnetometer) to spin dynamics.

By conducting this experiment, we will be able to detect or set limits on interactions of spins and certain classes of dark matter candidates. If we can directly detect dark matter, fundamental theorems including standard model and Newtonian mechanics will be challenged, and human understanding of the universe and space will be further improved. Therefore, the research value of this experiment can be profound.

C: Project description, including methods and anticipated outcomes.

To observe such anomalies, we need detectors to be as sensitive as possible. As the best detector under extreme conditions, a magnetometer like SQUID (superconducting quantum interference device) is capable of detecting fields one hundred billion times smaller than the Earth's. Such magnetometers work by measuring the spin precession frequency[2] of certain atoms in a magnetic field. As an atom's magnetic moment precesses with a frequency proportional to the magnetic field, we can measure the precession frequency to a high precision rather than directly measuring the magnetic field.

In a magnetometer that contains vapor of alkali atoms, the moments of atoms are all randomly aligned due to their intrinsic magnetic moments and therefore cancel each other out at the macroscopic level. By shining polarized light through the gas, the magnetic moments of individual atoms tend to become aligned in the same direction and hence a measurable magnetic moment is obtained. In this manner, the frequency of the atomic precession may be measured by the effect it has on the intensity of the light passing through the gas.[3]

Among all magnetometers, a Cs-based magnetometer can even surpass the sensitivity of SQUID and be operated at only 103 °C, which is about 100 °C lower than other potassium-based magnetometers. This is because Cs has the highest saturated vapor pressure of all alkali atoms, hence yielding significantly lower operating temperatures. Given its outstanding precision and working conditions, a Cs-based magnetometer becomes the ideal device for this research. However, the Cs atomic magnetometer is easily affected by pump laser noise and spin-exchange collisions. To eliminate the

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[2] https://en.wikipedia.org/wiki/Larmor_precession

[3] http://mfam.geometrics.com/atomicmagnetomet.html

magnetic field noise, we need to operate the magnetometer near-zero magnetic field at a high alkali-metal density. According to the research conducted by S. J. Seltzera and M. V. Romalis[4], who compared the output results of two magnetometers under unshielded and shielded conditions, a shielded magnetometer can yield a clearer picture of magnetic signal, reaching high optimal sensitivity. By building a magnetic shield with shielding materials like ferromagnetic metals, we can create an easier "path" for magnetic flux lines to follow so that they will not pass through the magnetometer and affect the results.

In this project, I will design and build the circuits for the atomic magnetometer. I will also design and 3D print non-magnetic components on the device and then shield the circuits in the lab so that the magnetometer will not be disturbed by outside magnetic fields. Then, I will do optical observation and analyze the spin interactions with the recorded data. As for the outcome, a deeper understanding of OPM and its working theory is anticipated. Besides, I will try to find the limitations on the sensitivity of the magnetometer like noise and fix them. We also expect to find more possible solutions for improving the sensitivity of the magnetometer by modifying the environmental conditions and advancing our understanding by operating and reading relevant essays. Over the summer, we plan to incorporate the MPC (Multi-pass cell, an element that is commonly used to increase the interaction length between atoms and light) into our magnetometers to amplify the Faraday rotation signal used to read out the precession angle of the atoms. By amplifying the signal scale 100 times stronger, we can measure the optical absorption of the rotation signal and precession angle of low-concentration samples. Research[5] has shown that it's feasible.

D: Sharing the Result

The Sulai Lab is part of the Global Network of Optical Magnetometers for Exotic Physics (GNOME). This is a network experiment scattered over the world. We will give regular updates to our collaborators in the GNOME. All results will be shared and published at the conferences, Kalman research symposium, Bucknell Department of physics summer research program.

E: The Mentoring Relationship

Professor Sulai will guide me to design and construct the magnetometer, and we will keep daily meetings over the summer. I will record the data and do analysis including calculations and programming stuff and the professor will check my works through discussions and daily collaboration meetings.

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[4] https://aip.scitation.org/doi/10.1063/1.1814434
[5] https://aip.scitation.org/doi/pdf/10.1063/1.1659297

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