The PREX (Lead Radius) Experiment

Robert Michaels, July, 2021

(on behalf of the PREX collaboration, see hallaweb.jlab.org/parity/prex).

The size of a nucleus is one of its most basic properties. After 100 years of nuclear physics research one would hope that theory could predict the size of a nucleus with a high accuracy. For a heavy nucleus like lead, the size is thought to be determined by the neutrons since they are more numerous than the protons and thus form a "skin" around the nucleus. However, obtaining data about neutron distributions is elusive because neutrons do not have an electric charge. The PREX experiment, which ran in 2010 and again in 2019, has for the first time established the existence of this skin in a clean and model-independent way by measuring the "weak charge", as explained below. This provides a fundamental test of nuclear theory and has many applications to other areas of physics such as neutron stars.

Experiments at Jefferson Lab scatter electrons from nuclei and observe the scattering rate to deduce the structure of the nucleus. Electron scattering is a kind of "microscope" to view the nucleus. Most experiments use the electromagnetic interaction to probe the nucleus, but PREX uses the much more subtle weak nuclear interaction, one of four basic interactions in nature, the other two being the strong nuclear interaction, responsible for binding nuclei together, and gravity. Physicists have wanted to perform experiments like PREX for more than twenty years, but only recently, with the advent of Jefferson Lab accelerator technology and the precision control of the electron beam, has the experiment become feasible.

Effects of the weak interaction can be isolated by exploiting the well-established fact that only the weak interaction violates a "mirror symmetry"; this is called "parity violation". If one compares two experiments that are identical in every respect except that one is the mirror image of the other, the difference can only arise from the weak interaction. Preparing two such experiments is simple in concept: one must flip the spin of the electron incident on target. From the point of view of the target, the two spin states are mirror images, and one looks for a tiny difference in the scattering rate between these two states. However, the big challenge is that one must flip the spin very precisely without changing any other parameter of the beam, for example the energy or position. If these other parameters change by even a tiny amount, they lead to a change in scattering rate due to the electromagnetic interaction which would mimic the weak interaction effect. At Jefferson Lab, we have succeeded in controlling the beam positions at the level of 5 nanometers between flips of the spin , when averaged over a week of running. Thus, the two beams corresponding to the two spin orientations are identical

at a level that approaches the size of an atom, a major accomplishment made possible by Jefferson Lab accelerator technology and expertise.

Another challenge of the PREX experiment is that the weak interaction is intrinsically weak, and thus it requires a very intense beam and a long running time (about a month) to obtain a useful statistical precision. Fortunately, Jefferson Lab's high-intensity, precisely controlled electron beam makes it uniquely suited to these types of experiments.

The lead target posed significant technical challenges: the heat and radiation produced in the electron beam. Since lead has a relatively low melting point we coated the lead with diamond, which has much higher thermal conductivity and carries away the heat. However, the diamond eventually degrades in the electron beam and the targets would fail (melt). The targets had a lifetime of about one week. To mitigate this, we deployed 10 targets in order to cycle through fresh ones. Another challenge was the large amount of radiation produced by the target. To mitigate this, extensive simulations were performed to design a shielding arrangement to protect electronics equipment in the hall which could get damaged by the radiation.

The PREX experiment ran first in 2010 and was followed by a second run in 2019 with improved designs. The collaboration also performed the same kind of measurements on a calcium target (⁴⁸Ca), the CREX experiment, with similar physics aims but on a lighter neutron-rich nucleus.

The major advantage of the weak interaction is that it is sensitive to neutrons. Every particle has a weak charge that participates in the weak interaction and is the analog of the more familiar electric charge, the participant in the electromagnetic interaction. The electric charge of the neutron is zero, and hence the electromagnetic interaction does not see neutrons very well. The proton electric charge, on the other hand, has one unit of positive electric charge, while the electron has one unit of negative charge. In contrast, the weak charge of the neutron is about 13 times larger than the weak charge of the proton, making the weak interaction the ideal probe for finding where neutrons are inside a nucleus.

Information about the location of neutrons inside a nucleus has been historically elusive. Past experiments have tried scattering particles such as protons or pions from nuclei, but the extraction is not as clean as for electron scattering because the strong nuclear interaction responsible for the scattering obscures the interpretation. Electron scattering is the tool of choice for providing clean data on the structure of nuclei, because electrons to do not participate in the strong nuclear force, and because the electromagnetic and weak interactions, in which electrons do participate, are rather well understood. Since neutron data has been so difficult to obtain, theoretical models of nuclear structure are constrained mainly by data other than neutron distributions. Thus, the PREX result on the neutron skin of lead provides a powerful independent check of these theoretical models.

Highly precise information about the neutron skin has a fundamental impact not only on nuclear theory, but on other areas of physics as well. In atomic physics, experimenters are hoping to check the theory of the weak interaction itself with a precision sufficient to see if extensions to the theory such as "supersymmetry" are relevant. However, the atomic physics community needs the PREX result as an input to interpret their results, because the atomic measurements are sensitive to where the neutrons are located in the nucleus. In another area of application, heavy ion collision experiments probe nuclear matter at a higher density than that of ordinary nuclei. Neutron skin data calibrates how the pressure of neutron-rich matter changes with the density of neutrons. This provides vital input to theory which can then be used to predict the results from the heavy ion research community.

For the same reasons, PREX can impact the astrophysics of neutron stars, the most exciting of the applications of our work. A neutron star is the remnant of a supernova explosion and is one of the possible final states a star can come to after expending its fuel. Up until recently, neutron stars have been purely theoretical constructs and thought to be made up of predominantly neutrons. However, within the past ten years, the field of neutron star astronomy has been making rapid advances in its ability to observe the properties of neutron stars such as their mass and size (i.e. radius), which can then be compared to theoretical expectations. The theoretical models must be calibrated by precise measurements of the neutron skin of nuclei on Earth, which is where PREX plays a role. As an example of the physics that's at stake, if the mass-radius relationship of neutron stars turns out to be inconsistent with expectations, it would hint at an exotic form of the dense matter in these stars, for example that they are made up largely of free quarks instead of neutrons. Quarks are the building blocks of both protons and neutrons, but quarks have never been observed in a free form in matter. On Earth, the quarks are inextricably bound together to form protons and neutrons.

In summary, the PREX experiment has established the existence of a neutron skin in the lead nucleus for the first time. Precise measurements of this skin thickness makes an important impact on the field of nuclear physics and has many applications to other fields of current physics research which needs information about neutron distributions. These measurements were only made possible with the advent of the Jefferson Lab high-intensity, high-quality electron beam. New measurements performed in 2019 have significantly improved the precision of the ²⁰⁸Pb results and applied the technique to another nucleus (⁴⁸Ca) to increase the impact of this science.

The most recent PREX result was published in The Physical Review in Feb 2021. Here is the reference: PRL 126 (2021) 17, 172502. As of this writing the CREX results are not yet published.