Neutron rich matter in heaven and on Earth

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Despite a length-scale difference of 18 orders of magnitude, the internal structure of neutron stars and the spatial distribution of neutrons in atomic nuclei are profoundly connected.

Where do the neutrons go? The elusive answer to such a seemingly simple question holds the key to fundamental new insights into the structure of both atomic nuclei and neutron stars. To place this question in the proper context we consider the nucleus of ²⁰⁸Pb, the most abundant isotope of lead containing 82 protons and 126 neutrons. As the heaviest known doubly-magic nucleus, ²⁰⁸Pb holds a special place in the nuclear physics community. Just as noble gases with filled electronic shells exhibit low levels of chemical reactivity, doubly-magic nuclei with filled proton and neutron shells display great stability. Being heavy, the Coulomb repulsion in 208Pb is important, ultimately leading to a large neutron excess. The Lead (Pb) Radius EXperiment (PREX) at the Thomas Jefferson National Accelerator Facility (JLab) was conceived with the sole purpose of measuring the location of the 44 excess neutrons [1]. In turn, a detailed knowledge of the neutron distribution in ²⁰⁸Pb illuminates the structure of a neutron star.

To understand how such challenging feat could be achieved, we invoke the liquid drop model of Gamow. Weizsäcker, Bethe, and Bacher developed shortly after the discovery of the neutron by Chadwick in 1932. In the liquid drop model the atomic nucleus is regarded as an incompressible drop consisting of two quantum fluids, one electrically charged consisting of Z protons and one electrically neutral containing N neutrons. The radius of the charged drop, indeed the entire proton distribution, has been accurately mapped since the advent of powerful electron accelerators in the 1950's. In contrast, our knowledge of the neutron distribution comes entirely from experiments involving strongly interacting probes, such as pions and protons. Unlike electromagnetic reactions involving weakly coupled photons, experiments with strongly interacting probes are difficult to decode due to a myriad of theoretical uncertainties. The PREX collaboration took advantage of the flagship parity-violating program at JLab to infer the radius of the neutron distribution in 208 Pb.

In a parity violating experiment one measures the difference in the cross section between right handed and left handed longitudinally polarized electrons. In a world in which parity would be exactly conserved, this parity violating asymmetry would vanish. However, the weak interaction violates parity, so an asymmetry emerges from a quantum mechanical interference of two Feynman diagrams: a large one involving the exchange of a photon and a much smaller one involving the exchange of a neutral weak vector boson Z^0 ; these two Feynman diagrams are depicted in Fig.1. Whereas photons couple to the electric charge and are therefore insensitive to the neutron distribution, the Z^0 boson plays the complimentary role. That is, the weak charge of the neutron is large as compared to that of the proton, which is suppressed by the weak mixing angle: $Q^p_{\rm wk} = 1 - 4 \sin^2 \theta_{\rm W} \approx 0.072$ [2]. The weak (or Weinberg) mixing angle $\theta_{\rm W}$ is a fundamental parameters of the standard model that emerges from the unification of the electromagnetic and weak interactions.

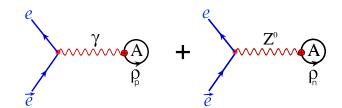


FIG. 1: **Probing the neutron distribution.** The quantum mechanical interference of the two Feynman diagrams generates a difference in the cross section between right and left-handed polarized electrons. The induced parity-violating asymmetry provides a powerful model independent tool to probe the neutron distribution of neutron-rich nuclei.

These facts make parity violating electron scattering an ideal tool to determine the neutron distribution. PREX has provided the first model independent evidence that the root mean square radius of the neutron distribution in ²⁰⁸Pb is larger than the corresponding radius of the proton distribution [1]. The difference between these two radii is known as the "neutron skin thickness", a dilute region of the nucleus populated primarily by neutrons.

Neutron skins

The development of a neutron rich skin in ²⁰⁸Pb has important consequences in constraining effective nuclear models that aim to describe within a single unified framework the dynamics of both atomic nuclei and neutron stars. The connection between the very small and the very large is particularly compelling given that a strong

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correlation has been established between the thickness of the neutron skin of ²⁰⁸Pb and the radius of a neutron star [3]. To elucidate the underlying dynamics behind such correlation we return to the liquid drop model where the nuclear binding energy is encoded in a handful of empirical parameters that represent volume, surface, Coulomb, and symmetry contributions:

$$B(Z, A) = a_{\rm v} A - a_{\rm s} A^{2/3} - a_{\rm c} \frac{Z^2}{A^{1/3}} - a_{\rm a} \frac{(N-Z)^2}{A} + \dots$$
 (1)

The volume term $a_{\rm v}$ scales with the total number of nucleons A=Z+N, underscoring both the short-range nature and saturation properties of the underlying nuclear force. Nuclear saturation, the existence of an equilibrium or "saturation" density of about $\rho_0\approx 0.15\,{\rm fm}^{-3}$, is a hallmark of the nuclear dynamics that is reflected in the nearly constant central density observed in atomic nuclei. The next three terms represent corrections to the energy due to the development of a finite nuclear surface $(a_{\rm s})$, the Coulomb repulsion among protons $(a_{\rm c})$ and, for asymmetric nuclei, quantum corrections due to the Pauli exclusion principle . This last term—the symmetry energy $(a_{\rm a})$ and especially its density dependence—plays a critical role in connecting the neutron skin thickness of atomic nuclei to the radius of a neutron star.

Although the liquid drop model is successful in describing the smooth behavior of the nuclear binding energy, in reality the atomic nucleus is not an incompressible liquid drop. So although highly insightful, the semi-empirical mass formula fails to capture the response of the liquid drop to changes in the density. This information is enshrined in the equation of state, which dictates how the energy depends on the overall density and neutronproton asymmetry of the system. In the thermodynamic limit and neglecting the long-range Coulomb interaction. the energy per nucleon at the equilibrium density is given entirely by the volume $a_{\rm v}$ and symmetry-energy $a_{\rm a}$ terms. The volume term $a_{\rm v}$ accounts for the dynamics of a symmetric system having equal number of protons and neutrons, while a_a penalizes the system for breaking the symmetry. So what happens as the system departs from its equilibrium position? Changes to the energy per nucleon with density are imprinted in the pressure. However, the contribution from the symmetric term to the pressure vanishes at the equilibrium density. Thus, the entire contribution to the pressure at saturation density is due to the symmetry pressure, a quantity that is often denoted in the literature by L and that it is closely related to the pressure at saturation of a system made entirely of neutrons; that is, $P_0 \approx L\rho_0/3$. As we now elaborate, it is this fundamental quantity that controls both the thickness of the neutron skin of atomic nuclei and the radius of a neutron star [4].

Connecting the very large to the very small

This brings us back to our original question of where do the 44 excess neutrons in ²⁰⁸Pb go? Although the liquid drop model favors the formation of a spherical drop

of uniform density, it is unclear what fraction of the excess neutrons should reside in the surface or in the core. Placing them in the core is favored by surface tension which tends to minimize the surface area, but disfavored by the symmetry energy which is larger at the core than at the surface. Conversely, moving them to the surface increases the surface tension but reduces the symmetry energy. Thus, the thickness of the neutron skin emerges from a tug of war between the surface tension and the difference between the symmetry energy at saturation density and at the lower surface density. This difference is nothing more than the symmetry pressure L. In particular, if the pressure is large, then it is energetically favorable to move the excess neutrons to the surface where the symmetry energy is low, resulting in a thick neutron skin [4].

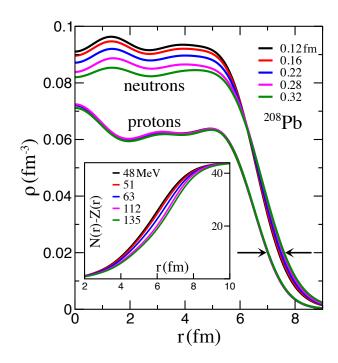


FIG. 2: Where do the excess neutrons go? Neutron and proton densities in ^{208}Pb as predicted by a variety of models with differing values for the neutron skin thickness (see legend). The inset displays the running sum and indicates how models with larger values of the symmetry pressure L (see legend) are more effective in pushing the 44 excess neutrons to the surface.

These facts are nicely illustrated in Fig. 2, which displays neutron and proton densities for ²⁰⁸Pb as predicted by a variety of models that successfully reproduce properties of finite nuclei and neutron stars. Given that the proton (or rather the "charge") distribution of ²⁰⁸Pb has been measured with remarkable precision, no significant spread is observed in the model predictions. Instead, challenging parity-violating experiments are required for a clean measurement of neutron densities. And whereas PREX has provided an important first step, the precision attained was insufficient to distinguish between the

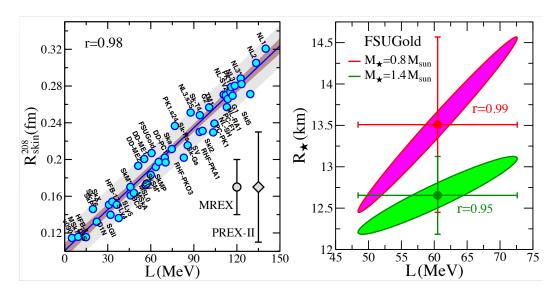


FIG. 3: Connecting the very small to the very big. Despite a difference in size of 18 orders of magnitude, the symmetry pressure L controls both the neutron skin thickness of 208 Pb as well as the radius of a neutron star. On the left hand panel a large set of highly successful models are used to illustrate the correlation between L and $R_{\rm skin}^{208}$; figure adapted from Ref. [5]. The right hand panel displays the correlation between L and neutron star radii for one of these models: "FSUGold" [6].

various competing models. This results in a large model spread for the neutron densities and consequently also for the neutron skin thickness, whose values are indicated in the legend and schematically depicted by the region between the two arrows. The inset in Fig. 2 isolates the spatial distribution of the 44 excess neutrons in the form of a running (or partial) sum. This running sum, which naturally terminates at 44, represents the total number of excess neutrons accumulated up to a distance r. That models with a large symmetry pressure L (see legend) push the excess neutrons farther out to the surface is clearly evident from the figure.

To validate the strong correlation between the neutron skin thickness of 208 Pb $(R_{\rm skin}^{208})$ and the symmetry pressure L, we show in Fig. 3 predictions from a large number of theoretical models, all similar in spirit to the ones displayed in Fig. 2 [5]. With a Pearson-r correlation coefficient of nearly one, the alluded correlation is very strong indeed. This indicates how a fundamental parameter of the equation of state of neutron-star matter can be measured in a terrestrial laboratory. The error bars in the figure indicate the precision anticipated for the upcoming PREX-II (at JLab) and MREX (at Mainz) campaigns.

Remarkably, it is the same symmetry pressure that determines the radius of a neutron star; see right-hand panel in Fig. 3. In this case, however, the symmetry pressure pushes against the immense gravitational attraction encountered in the stellar interior. Yet regardless of whether pushing against surface tension or against gravity, both $R_{\rm skin}^{208}$ and the radius of a neutron star are sensitive to the symmetry pressure in the vicinity of saturation density. Thus, despite a difference in size of 18 orders in magnitude, a powerful "data-to-data" relation emerges: The thicker the neutron skin thickness of 208 Pb,

the larger the radius of a neutron star. This correlation is particularly strong for low mass neutron stars where the interior density is only slightly larger than saturation density. Indeed, as shown in the right-hand panel in Fig. 3, the correlation coefficient weakens slightly (from r=0.99 to r=0.95) in going from a 0.8 to a 1.4 solar mass neutron star.

Neutron stars

Neutron stars are fascinating dynamical systems where a convergence of disciplines is required for their understanding. Although the most common perception of a neutron star is that of a uniform assembly of neutrons packed to enormous densities, the reality is far different and much more interesting. While firmly established on theoretical grounds since 1939, it would take almost three decades for Jocelyn Bell, a talented young graduate student from Cambridge, to discover neutron stars [7]. Although it is well known that Jocelyn Bell was snubbed by the Nobel committee in 1974—the year that her doctoral advisor Anthony Hewish shared the Nobel prize in Physics with Martin Ryle—she has always displayed enormous grace and humility in the face of this controversy. Since then, Bell has been recognized with an enormous number of honors and awards, including the most recent 2018 Breakthrough Prize in Fundamental Physics. Renowned for her generosity and support for underrepresented minorities in science, Professor Bell has decided to donate the entirety of the 3 million dollar prize to promote diversity in the field.

The role that nuclear physics plays in elucidating the structure and composition of neutron stars is of paramount importance. Unlike white-dwarf stars that are entirely supported against gravitational collapse by the pressure from its degenerate electrons, an important source of pressure support for neutron stars comes from nuclear interactions. Indeed, in their 1939 seminal paper, Oppenheimer and Volkoff demonstrated that a neutron star supported exclusively by neutron degeneracy pressure will collapse into a black hole once its mass exceeds 0.7 solar masses. Today we know of at least two neutron stars with masses as large as two solar masses [8, 9]. To better understand the predominant role that nuclear physics plays in elucidating the structure and composition of a neutron star, we now embark on a brief journey of a neutron star; see sidebar I. Although the surface of the neutron star is largely insensitive to the nuclear dynamics, it is of observational importance because it provides significant constraints on the stellar radius. Assuming that the thermal emission from the surface follows a blackbody spectrum at a uniform temperature, then the stellar radius may be determined from the Stephan-Boltzmann law that relates the luminosity to the temperature and radius of the star. Unfortunately, the determination of stellar radii by photometric means has been plagued by large systematic uncertainties arising from unreliable distance measurements as well as distortions to the blackbody spectrum from a thin stellar atmosphere. In the past, these uncertainties revealed discrepancies in the extraction of stellar radii as large as 5-6 km. Fortunately, the situation has improved significantly through a better understanding of systematic uncertainties, important theoretical developments, and the implementation of robust statistical methods [10]. And while the uncertainty has now been reduced to about a couple of kilometers, a powerful new player has entered the game: gravitational-wave astronomy.

Multimessenger astronomy

The first direct detection of gravitational waves from a binary neutron star merger (GW170817) by the LIGO-Virgo collaboration has opened the new era of multimessenger astronomy [11]. Besides the detection of gravitational waves, electromagnetic counterparts associated with both a short gamma ray burst and a long-term kilonova powered by the radioactive decay of r-process elements were also detected; see the article by Anna Frebel and Timothy Beers in Physics Today, January 2018. Moreover, GW170817 has provided fundamental new insights into the nature of dense matter. Critical properties of the equation of state are encoded in the tidal polarizability, a neutron-star property that describes its tendency to deform in response to the tidal field induced by its companion. As the two neutron stars approach each other, the phase of the gravitational wave deviates from its point-mass nature that is characteristic of black holes. These deviations are imprinted in the tidal polarizability, a quantity that is highly sensitive to the stellar structure as it scales as the fifth power of the compactness, defined as the ratio of the stellar radius to the Schwarzschild radius. The Schwarzschild radius of the star, namely, the radius at which the star would become a black hole, is directly proportional to the stellar mass and for our Sun it is approximately equal to

3 km. Pictorially, a "fluffy" neutron star having a large radius is much easier to polarize than the corresponding compact star with the same mass but a smaller radius. Given the sensitivity of the gravitational-wave signal to the neutron star structure, limits on the tidal polarizability inferred from GW170817 disfavor overly large stellar radii [12, 13], thereby providing a powerful complementary approach to the traditional photometric techniques. Moreover, by exploiting the true multimessenger nature of the binary merger, additional constraints have been obtained on both the maximum stellar mass and the minimum radius of a 1.6 solar mass neutron star [14, 15]. As displayed on the left-hand panel in Fig. 4, these credible constraints on limiting values of stellar radii and maximum masses are now starting to paint a compelling picture of the mass-vs radius relation.

A bright future

So how do all these new developments illuminate the connection between GW170817 and laboratory observables? In particular, given their sensitivity to the symmetry pressure, how do the inferred limits on stellar radii reflect on the neutron skin thickness of $^{208}\mathrm{Pb?}$ Seeing that GW170817 disfavors overly large stellar radii, we inferred a neutron skin thickness that is well below the central value measured by the PREX collaboration [12], a fact that is clearly illustrated on the right hand panel of Fig. 4. In an effort to reduce the experimental uncertainty by a factor of three, the follow-up PREX-II experiment is scheduled to run at JLab in 2019. After this and its sister campaign on ⁴⁸Ca are over, JLab will pass the baton to the Facility for Rare Isotope Beams (FRIB) that has as one of its main science drivers the study of exotic nuclei with very thick neutron skins. Also this year, the third operating run by the LIGO-Virgo collaboration is projected to begin with the promise of many more detections of binary neutron star mergers. If PREX-II confirms that the neutron skin thickness of lead is large, this will suggest that the symmetry pressure is also large (or "stiff") at the typical densities found in atomic nuclei. If at the same time the LIGO-Virgo collaboration validates the relatively small stellar radii suggested by GW170817, then this will imply that the symmetry pressure is small (or "soft") at about twice saturation density. The evolution of the symmetry energy from stiff at typical nuclear densities to soft at slightly higher densities may be transformative, as it may be indicative of an exotic phase transition in the neutron star interior. Note that in a recent re-analysis of GW170817 data the LIGO-Virgo collaboration obtained limits on the tidal polarizability even more stringent than reported in the original discovery paper.

The determination of the symmetry pressure L—and more generally the density dependence of the symmetry energy—has far reaching consequences in many areas of physics as diverse as precision tests of the standard model using atomic parity violation, the collision of heavy ions, and, of course, nuclear and neutron-star structure. Atomic parity violating experiments measure the weak charge of the nucleus, which depends on the value of the

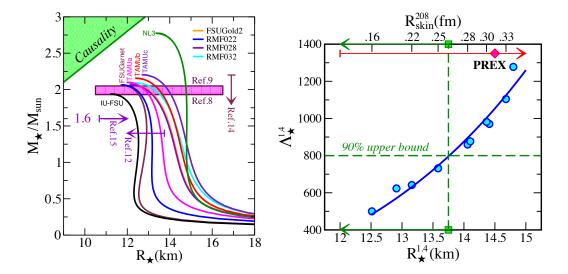


FIG. 4: Neutron rich matter in heaven and earth. The left-hand panel displays predictions for the holy grail of neutron star structure: the mass versus radius relation. All models reproduce a variety of nuclear properties, yet differ widely in their predictions of stellar radii. In references [8, 9] photometry was used to set lower limits on the maximum stellar mass. All other limits emerge from using both electromagnetic and gravitational-wave information from GW170817. On the right-hand panel the same theoretical models are used to predict the tidal polarizability and radius of a 1.4 solar mass neutron star as well as the neutron skin thickness of 208 Pb. Limits on the tidal polarizability inferred from GW170817 suggest that both $R_{\star}^{1.4}$ and $R_{\rm skin}^{208}$ are relatively small. On the other hand, the PREX experiment reported a fairly large value for $R_{\rm skin}^{208}$, albeit with large error bars. If the large value of PREX is confirmed, the tension could be resolved if a phase transition develops in the stellar interior. Figures adapted from Ref. [12].

weak mixing angle $\theta_{\rm W}$ at low momentum transfer. However, the search for "new physics" beyond the standard model is hindered by large uncertainties in the neutron radius which, as we have seen, is highly sensitive to L. Above saturation density, the symmetry pressure may be constrained by means of experiments involving the collision of heavy ions. Heavy-ion collisions is the only tool that can probe vast regions of the nuclear equation of state in terrestrial laboratories. Past experiments with very energetic heavy ions enabled to compress nuclear matter to several times nuclear saturation density and allowed to extract the equation of state of symmetric nuclear matter. Current uncertainties in the density dependence of the symmetry energy are large, yet ongoing international efforts at existing and future facilities, such as RIKEN in Japan, FRIB in the US, and GSI/Fair in Germany, are poised to probe neutron-rich matter at supra-saturation density and will offer a better understanding of the properties of dense neutron-rich matter.

Although the multimessenger era is still in its infancy, it is remarkable that the very first observation of a binary neutron star merger is already providing a treasure trove of insights into the nature of dense matter. In the new era of multimessenger astronomy the strong synergy between nuclear physics and astrophysics will grow even stronger. As illustrated in the second sidebar, ultra sensitive gravitational wave observatories, earth- and spacebased telescopes operating at a variety of wavelengths, and new terrestrial facilities probing atomic nuclei at the limits of their existence are poised to answer two of the

eleven science questions for the next century [16]: What are the new states of matter at exceedingly high density and temperature and How were the elements from iron to uranium made? The future is very bright indeed!

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- S. Abrahamyan et al., Phys. Rev. Lett. 108, 112502 (2012).
- [2] D. Androi et al., Nature 557, 207 (2018).
- [3] C. J. Horowitz and J. Piekarewicz, Phys. Rev. Lett. 86, 5647 (2001).
- [4] C. J. Horowitz et al., J. Phys. G41, 093001 (2014).
- [5] X. Roca-Maza et al., Phys. Rev. Lett. **106**, 252501 (2011).
- [6] B. G. Todd-Rutel and J. Piekarewicz, Phys. Rev. Lett 95, 122501 (2005).
- [7] A. Hewish, S. Bell, J. Pilkington, P. Scott, and R. Collins, Nature 217, 709 (1968).
- [8] P. Demorest et al., Nature 467, 1081 (2010).
- [9] J. Antoniadis et al., Science **340**, 6131 (2013).
- [10] F. Özel and P. Freire, Ann. Rev. Astron. Astrophys. 54,

- 401 (2016).
- [11] B. P. Abbott et al. (Virgo, LIGO Scientific), Phys. Rev. Lett. 119, 161101 (2017).
- [12] F. J. Fattoyev, J. Piekarewicz, and C. J. Horowitz, Phys. Rev. Lett. 120, 172702 (2018).
- [13] E. Annala, T. Gorda, A. Kurkela, and A. Vuorinen, Phys. Rev. Lett. 120, 172703 (2018).
- [14] B. Margalit and B. D. Metzger, Astrophys. J. 850, L19 (2017).
- [15] A. Bauswein, O. Just, H.-T. Janka, and N. Stergioulas, Astrophys. J. 850, L34 (2017).
- [16] Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (The National Academies Press, Washington, 2003).

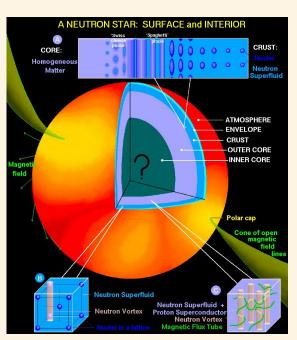
Anatomy of a Neutron Star

A neutron star is a gold mine for the study of physical phenomena that cut across a variety of disciplines, from particle physics to general relativity. With masses comparable to that of our Sun but radii of only 10-15 km, neutron stars are unique laboratories for the study of phenomena that lie well outside the realm of terrestrial laboratories.

As illustrated in the figure, the stellar composition at the highest densities encountered in the inner core is unknown. Depending on the unknown compressibility of neutron rich matter, the stellar core may harbor exotic states of matter, such as deconfined quark matter — a novel state of matter in which quarks are allowed to roam freely at these enormously high densities. Yet at present the canonical picture of the stellar core is that of a uniform liquid consisting of neutrons, protons, and neutralizing leptons (electrons and muons) in chemical equilibrium. The stellar core accounts for practically all the mass and about 90% of the size of a neutron star.

Above the uniform core lies the non-uniform stellar crust, a region of about 1 km that develops as a consequence of the short-range nature of the nuclear force. Indeed, at the sub-saturation densities of the stellar crust it becomes energetically favorable for neutrons and protons to cluster into complex nuclei that display highly exotic shapes, often referred to as "nuclear pasta".

The outermost surface of the neutron star constitutes the very thin atmosphere that is composed of hydrogen, but may also contain heavier elements such as helium and carbon. To date, most of the information on neutron-star radii has been obtained from the thermal emission from its surface, often assumed to be that of a black body spectrum. Unfortunately, complications due to both distortions to the black body spectrum and distance measurements make the determination of stellar radii a challenging task. Yet, the discovery of gravitational waves from GW170817 has opened a new window into the study of neutron star properties that will nicely complement electromagnetic observations.



A scientist rendition of the structure and composition of a neutron star. Courtesy of Dany Page.

Heaven and Earth

The neutron skin thickness of atomic nuclei offers valuable insights into the nature of neutron rich matter. Parity violating electron scattering, a sensitive and powerful experimental tool perfected at the Thomas Jefferson National Accelerator Facility (JLab) has been used to provide the first model-independent evidence in favor of a neutron rich skin in ²⁰⁸Pb. In 2019, the neutron skin thickness of ²⁰⁸Pb and ⁴⁸Ca will be measured with enough precision to constrain both nuclear models and the symmetry pressure *L*. To accomplish this ambitious program, state of the art equipment — like the five-story high spectrometer shown in the figure — are essential.



Almost a year ago, back in August 17, 2017, the LIGO-Virgo collaboration detected gravitational waves from the merger of two neutron stars (GW170817). In one clean sweep GW170817 has provided critical insights into the synthesis of the heavy elements and on the nature of neutron-rich matter — fundamental questions at the core of FRIB's mission. The start of the third operating run is projected to begin in early 2019 and many more binary neutron star mergers are anticipated, as LIGO works its way to full design sensitivity. The figure shows an aerial view of the Livingston interferometer.



Two of the main science drivers of the Facility for Rare Isotope Beams (FRIB) currently under construction at the campus of Michigan State University, are the study of the heaviest of elements and the production of exotic nuclei with very thick neutron skins. In particular, FRIB will measure the neutron skin thickness of short-lived isotopes using strongly interacting probes. To ensure the success of such challenging program, the upcoming electroweak measurements at JLAB will be instrumental in supplying critical calibrating anchors. A view of progress on FRIB's high-power superconducting linear accelerator, which will accelerate heavy ions and produce rare isotopes by in-beam fragmentation.



The Neutron star Interior Composition Explorer (NICER) is part of NASA's program dedicated to study the exotic structure and composition of neutron stars. Launched on June 2017 aboard SpaceX's Falcon 9 rocket, NICER was successfully deployed to the International Space Station; see figure. NICER is the first NASA mission designed specifically for the study of neutron stars. By measuring radii of neutron stars, NICER will provide some of the most stringent tests of the equation of state of neutron rich matter. NICER represents a powerful complement to LIGO in the brand new era of multimessenger astronomy.

