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ARUNA: Advancing Science, Educating Scientists, Delivering for Society

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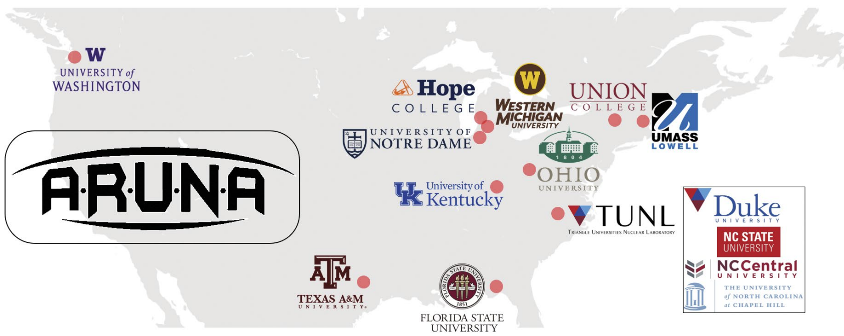

The Association for Research at University Nuclear Accelerators (ARUNA; http://aruna.physics.fsu.edu) is an association of 13 university-based accelerator laboratories in the United States and the scientists performing nuclear research at them. ARUNA was founded in 2010, with the goals to optimize the use of university-based accelerator facilities, increase the opportunities for education around them, and document their scientific impact as part of the U.S. nuclear science enterprise. ARUNA members believe that the diversity of approaches represented by their laboratories is a critical asset for a field that is presently growing fast around the science opportunities soon to be offered by the Facility for Rare Ion Beams (FRIB).

Scientists at the university-based ARUNA laboratories pursue research programs in nuclear astrophysics, low-energy nuclear physics, fundamental symmetries, and a rapidly growing number of nuclear physics applications, building bridges to other research communities. The ARUNA laboratories span a range of sizes and house a diverse portfolio of research instruments and programs (Table 1). All ARUNA facilities benefit from their location on university campuses and often are the flagship facilities at their host institutions. The faculty and scientists at these facilities represent an important intellectual resource for nuclear science in general. They not only provide new ideas for their local facilities but also contribute significantly to the user community around the national laboratories.

ARUNA laboratories have developed unique capabilities in mono-energetic neutrons and high-intensity mono-energetic photon beams. Other laboratories have developed techniques for generating and utilizing heavy-ion beams or high-intensity low-energy beams, which will be an important asset toward the development of the next generation of underground accelerators. Utilization of these probes is essential for addressing many of the scientific goals and challenges in low-energy nuclear physics and astrophysics. Three ARUNA laboratories have the capability to produce rare-ion beams and three have recently established research programs with high-resolution magnetic spectrographs, which had been identified as a missing resource in the U.S. experimental portfolio. ARUNA facilities are also characterized by their flexibility in performing long-term experiments or pursuing programs that are not possible within the environment of the national user facilities.

In addition, ARUNA laboratories provide important contributions to the "nuclear" workforce in the United States. Through their location on university campuses, they attract undergraduate and graduate students into the field, and they provide a unique training environment for students and postdocs. A large fraction of today's nuclear physics research community has been trained at university facilities.

The ARUNA facilities offer diverse capabilities, which have led to interinstitutional collaborations. An example is the Center for Excellence in Nuclear Training and University-based Research (CENTAUR), which facilitates collaborations between the ARUNA laboratories at Texas A&M University (TAMU), FSU, and ND. Other collaborations within ARUNA leverage the synergies between individual facilities and scientists. Nuclear astrophysics studies are strengthened by the collaborations between ND, TAMU, and OU, while nuclear structure studies combine the capabilities at the UK Accelerator Laboratory with ND and TUNL. Studies in fundamental symmetries leverage the expertise and facilities of TAMU, ND, and UW, while detector development is the beneficiary of the FSU–OU, UK–UML, and IU–WMU collaborations.

Scientific Focus on Nuclear Astrophysics

Nuclear astrophysics is a multifaceted subdiscipline of nuclear physics

Table 1. ARUNA laboratories with specific capabilities and science programs.

Accelerator facility	Flagship devices, capabilities	Science focus**
Florida State University (FSU) 9 MV Tandem + 8 MV Supercond. LINAC	Clover gamma-detector array, High-resolution spectrograph, Resolut in-flight RIB facility	NA: Primordial, CNO***-breakout, rp- process, ap-process reactions with RIB, spectrograph NS: Shell evolution, octupole collectivity
Hope College (HC) 1.7 MV Tandem	Ion-beam analysis setup	AP: Environmental sample analysis
Ohio University (OU) 4.5 MV Tandem	30-m-long neutron time-of-flight setup, light-ion scattering chambers	NR, NA: Statistical reaction analysis/models AP: Detector development
Texas A&M University (TAMU) K-150, K-500 Cyclotrons	MARS In-flight RIB facility, AGGIE, NIMROD, FAUST, MDM, TEXAT, DAPPER, Hyperion, TAMU trap, radiochemistry lab	NA: Surrogate reactions NS: Light nuclei, clustering NR: Heavy-ion collisions, super-heavy elements FS: Precision beta-decay measurements AP: Isotope production, radiation effects testing
*TUNL-HIGS 1.2 GeV Electron Storage Ring	Free-electron-laser, mono-energetic, polarized gamma-photon beam	NA: Inverse capture reactions, strength functions NS: Shape coexistence, triaxiality NS, NR: Few-body systems
*TUNL-LENA 2 MV Singletron, 230 kV ECR-accelerator	High-intensity low-energy accelerators, low-background detector systems	NA: Low-energy measurements, for hydrogen and helium burning
*TUNL-Tandem 10 MV Tandem	Light-ion reactions, high-resolution magnetic spectrograph	NS, FS: Nuclear matrix elements for $0\nu\beta\beta$ NS, NR: few-body systems NA: hydrogen burning, rp-process, hot CNO cycle
Union College (UC) 1.1 MV Tandem	PIXE, PIGE, Rutherford Scattering facilities	AP: Materials analysis
University of Kentucky (UK) 7 MV single-ended Van-de-Graaff accel. (vdG)	In-flight production of mono-energetic neutrons, (n,n'γ) spectroscopy	NS: Collective excitations, shape coexistence FS: Nuclear matrix elements for $0\nu\beta\beta$ NR: Neutron cross-sections
University of Massachusetts Lowell (UML) 5.5 MV single-ended vdG	1 MW Research Reactor, mono-energetic neutron facility, PIXE, implantation facility	AP: Detector development
University of Notre Dame (ND) 11 MV Tandem "St. Ana" 5 MV Pelletron	TwinSol in-flight RIB facility, high-resolution magnetic spectrograph, "St. George" Recoil Separator	NA: Quiescent CNO***, helium, carbon-burning, neutron-source reactions NA: Transfer reaction studies with RIB FS: Unitarity of CKM, $0\nu\beta\beta$-matrix elements AP: Actinide targets, materials analysis, detector development
University of Notre Dame (ND) "CASPAR" 1MV VdG at SURF	Deep-underground accelerator for background-free low-energy nuclear astrophysics experiments	NA: Low-energy experiments for hydrogen and helium burning, stellar neutron sources
University of Washington (UW) 9 MV Tandem	Cyclotron-radiation electron spectroscopy, HE6CRES	FS: Precision beta-decay measurements
Western Michigan University (WMU) 6 MV Tandem	PIXE, PIGE, X-ray spectrometer, Gamma Counting Station, SEE line	NS: Activation measurements, Hoyle State Studies NA: Study of p-nuclei and production, fusion AP: Materials science, detector development

*Triangle Universities Nuclear Laboratory—Duke University, University of North Carolina at Chapel Hill, and North Carolina State University. **NS: Nuclear Structure, NA: Nuclear Astrophysics, NR: Nuclear Reactions, FS: Fundamental Symmetries, AP: Applied Research. ***CNO: Carbon-Nitrogen-Ocygen cycles.

that pursues the origin of the elements and the chemical evolution of our universe, as well as the nature of the nuclear energy sources that stabilize stars and drive stellar evolution. This work is motivated by astronomical measurements and ever more detailed stellar models that challenge us to improve our understanding of the nuclear physics of stars. The complexity and variety of the astrophysical environments necessitates a broad portfolio of nuclear physics techniques and facilities. For example, studies of nuclear processes at the high temperatures and densities characteristic of stellar explosions ultimately require the capabilities of large-scale radioactive-beam facilities. In contrast, quiescent nucleosynthesis in stars requires a different kind of experimental approach and is primarily being pursued using high-intensity, low-energy accelerators at the ARUNA universities. The challenge is that the reactions of interest proceed at energies well below the Coulomb barrier and thus event rates are exceedingly low. Progress in direct measurements requires advancements in accelerator and detector technologies, techniques for reducing natural and cosmic-ray induced background events, and improved theoretical extrapolation techniques.

Even with this effort, some reactions are simply too rare to be measured directly and indirect techniques must be employed to extract the information needed to calculate a reaction rate. Such spectroscopic measurements, carried out at TAMU, TUNL, ND, OU, and FSU also provide information relevant to explosive nucleosynthesis and the nuclear equation of state. The seemingly disparate challenges of explosive and quiescent nucleosynthesis are in fact deeply interconnected in terms of technical developments and in their complementary scientific goals, since explosive nucleosynthesis cannot be reliably interpreted without a knowledge of the composition of the initial seed and the sources of the nuclear fuel in stars.

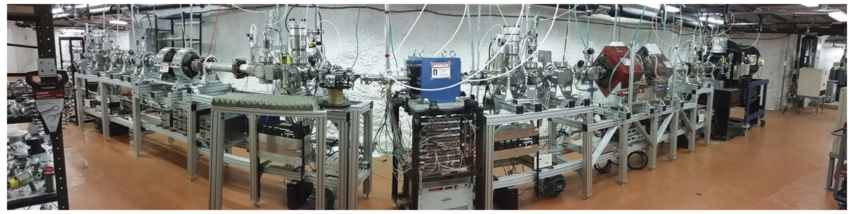

Figure 1. *The CASPAR facility at the SURF underground laboratory, operated by the ND group.*

The ARUNA institutions have developed a number of different but complementary experimental techniques to determine sub-Coulomb or near threshold reaction cross-sections, including: (a) direct underground accelerator studies, where two miles of rock serve as cosmic ray shielding, (b) high-current accelerators with digital coincidence and event identification techniques, (c) inverse kinematic techniques to detect and count the number of reaction products, and (d) indirect or Trojan Horse Methods (THM) that probe the structure of the compound nucleus at the threshold and translate this information into reaction cross-sections through reaction theory.

Unique Capabilities in ARUNA

The deep underground approach is being pursued by ND at the Compact Accelerator System for Performing Astrophysical Research (CASPAR) underground accelerator at Sanford Underground Research Facility (SURF) (see Figure 1), following pioneering work at the Laboratory for Underground Nuclear Astrophysics facility in the Gran Sasso laboratory. Recent successes are the identification near threshold of cluster states in ^{10}B and ^{14}N that facilitate a strong mass flow converting primordial material to the Carbon-Nitrogen-Oxygen (CNO) range in the first generation of stars. These results may affect the primordial lithium abundances. For the study of the ^{7}Be(α,γ) reaction, a ^{7}Be beam was developed at the Momentum Achromat Recoil Separator (MARS) facility at TAMU, probing resonance states in ^{11}C. FSU has studied the destruction of primordial Lithium through the ^{7}Be(d,α) reaction [1]. TAMU and OU have focused on a related study of the triple-alpha process using the neutron-induced inverse reaction to study the neutron-catalyzed decay of the Hoyle state, which determines the overall reaction rate [2].

The ECR accelerator at TUNL's Laboratory for Experimental Nuclear Astrophysics (LENA) facility produces the world's most intense proton beams for low-energy measurements and uses beam pulsing and coincidence techniques to reduce backgrounds. The focus is on understanding puzzling questions regarding hydrogen burning, such as the source(s) of abundance anomalies in globular clusters and interesting isotopic abundances in meteorites. LENA will be joined by a new 2 MV Singletron accelerator, designed specifically for studies of helium-burning reactions.

Helium burning produces neutrons via reactions such as ^{13}C(α,n) and ^{22}Ne(α,n). Both are critical for investigation of the s-process in stars, the i-process in early deeply convective stars, as well as the n-process in shock-driven core collapse supernova environments. The latter may be the source for light r-process elements in addition to the neutrino-driven wind environment, which will be driven by (α,n) reactions in the medium-mass range. This topic is pursued at many of the ARUNA laboratories. For example, ND and OU have studied ^{13}C(α,n), using R-matrix theory to couple data sets to derive a deeper understanding of the reaction mechanism [3]. The ^{22}Ne(α,n) reaction is being studied at the LENA facility and complementary studies have been performed at the High Intensity Gamma-ray Source (HIGS; TUNL) using nuclear resonance fluorescence to explore the contributions to the (α,n) and the competing (α,γ) channel. The low-energy resonances in the ^{22}Ne(α,γ) and ^{22}Ne (α,n) reactions that previously had only been observed in transfer studies were measured directly at CASPAR and will be supplemented by measurements in inverse kinematic with the St. George recoil separator at ND. The same resonances were mapped out via the THM method at TAMU, also demonstrating the versatility of this approach. A focus at OU has been measurements of (α,n) reactions on more massive isotopes, such as ^{27}Al, ^{65}Cu, and ^{96}Zr, of interest for supernovae. Low-energy (α,n) measurements typically require intense beams and long running times that are provided by the ARUNA facilities. Without a reliable knowledge of these neutron sources, for the conditions at the stellar site, a reliable prediction of the contributions of the various neutron-driven nucleosynthesis processes to the production of heavy elements remains impossible.

The ^{12}C(α,γ)^{16}O reaction determines the late evolution of massive stars by setting the stage for ^{12}C+^{12}C and possibly ^{12}C+^{16}O fusion. The C/O ratio in white dwarfs influences the ignition conditions of type Ia supernovae. In addition, ^{12}C(α,γ) plays a crucial role in the determination of the black hole mass gap and the ignition conditions of pair-instability supernovae. It remains an enigmatic key for our understanding of all advanced nucleosynthesis processes as well as the origin of the biological elements carbon and oxygen. A reliable extrapolation requires not only low-energy studies but measurements over a wide energy range for all reaction channels. The ARUNA labs have added substantially to the existing data sets, by measuring not only the radiative capture, but also inverse particle reaction channels at ND and OU, as well as by extensive ^{16}O(γ,α) studies at HIGS. TAMU is probing the reaction by determining the alpha asymptotic normalization coefficient (ANC) of the ^{16}O ground state. The reaction is ^{20}Ne (^{12}C,^{16}O(g.s.))^{16}O(g.s.) performed at energies close to the Coulomb barrier. All these data have been compiled to develop a complete R-Matrix analysis over the entire energy range, which is presently considered the gold standard in the field [4].

The carbon-induced reactions, ^{12}C+^{12}C and ^{12}C+^{16}O, are the key for understanding all subsequent nucleosynthesis in massive stars. They dictate the ignition conditions of type Ia supernovae as well as the occurrence of superbursts on accreting neutron star binary systems. Direct measurements are presently pursued at ND and the data are being coupled to recent studies using the THM model technique developed at TAMU. To avoid Coulomb effects in the exit channel the experiment will be based on the ^{12}C(^{13}C,n)^{24}Mg* THM reaction probe.

Low-energy nuclear reactions on stable nuclei dictate the timescales of stellar evolution and produce the seed material for explosive processes. The experimental studies of these reactions require small, dedicated accelerator facilities, specialized detector systems and most of all, time and access. The latter, in particular, is not available at program-committee-driven national laboratories with large demands on beam time. ARUNA facilities fill this need, and they are uniquely situated to study a host of fundamental questions in the field through the complementarity of their experimental approaches and infrastructure, and their development of reaction models and other theoretical approaches.

Complementary Programs in ARUNA

ARUNA-based research also plays an important role for the study of explosive stellar events. The radioactive beam capabilities at FSU, ND, and TAMU have been crucial for the development of FRIB techniques, and they continue to maintain an active science program in nuclear astrophysics. FSU's program is based on the Resolut separator to probe critical reactions, such as ^{24}Al(p,γ) and ^{25}Al(p,γ), through surrogate reaction channels. Proton capture on these neutron-deficient aluminum isotopes facilitate the rp-process in novae and X-ray bursts and affect the production of long-lived radioactive isotopes, such as ^{22}Na and ^{26}Al, in those environments. The ND group uses TwinSol and TAMU researchers use MARS for indirect and direct reaction studies in the hot pp-chains and the hot CNO cycles for exploring the onset of nova explosions in white dwarf matter.

Studies of statistical nuclear properties, averaged over many levels, are a research focus at OU. These data typically involve measuring spectra to extract the level densities of the nuclei populated by the emitted particles. The overall goal is to improve statistical model predictions by inferring systematic regularities over the nuclear landscape. Recent results have challenged theoretical descriptions. For example, ^{7}Li-induced reactions on ^{68,70}Zn revealed ^{74,76}Ge level densities lower than expected by standard phenomenological predictions [5]. A measurement with the $^{58}Ni(^{3}He,n)^{60}Zn$ reaction identified an unexpected structure in the level density with excitation energy that defies theoretical description. Neutron, proton, and α decays from ^{59}Mn, the compound nucleus of $^{11}B+^{48}Ca$ fusion, suggest an enhanced imaginary isovector potential that may well impact neutron-capture on neutron-rich nuclides, such as in i-process and r-process nucleosynthesis.

The equation of state has a strong impact on the mass–radius relations of neutron stars and ranks among the most sought-after goals in nuclear physics. Understanding of the behavior of nuclear matter at densities away from saturation has also important implications on the physics of core-collapse supernovae, whose density and temperature regions are sampled in the lab with heavy-ion collisions. At TAMU, Fermi-energy heavy-ion collisions are studied with the Neutron Ion Multi-detector for Reaction Oriented Dynamics (NIMROD) detector array, which unravels the multitude of fragments created simultaneously. Experiments probe the N/Z degree of freedom with carefully chosen targets and beams, both stable and radioactive [6].

Scientific Focus on Nuclear Structure and Reactions

Nuclear structure research, one of the pillars of nuclear science, aims at achieving an understanding of the basic interactions that lead to the rich variety of phenomena observed in atomic nuclei, with the goal of developing a comprehensive description applicable to all nuclei (i.e., for stable systems as well as those at the very limits of existence).

Few-Body Reactions at TUNL

Ab-initio theories are connecting quantum chromodynamics–based interactions to the structure and reactions of light nuclei [7] and their reach toward heavier, more complex nuclei and higher predictive power is increasing rapidly. A research program at TUNL pursues measurements of light nuclei that provide direct tests of these theories, combining results of experiments using mono-energetic photon beams at HIGS (see below) and neutron-beams in the tandem laboratory at TUNL.

The TUNL HIGS is the highest-flux Compton γ-ray source in the world, generating mono-energetic, polarized photon beams with energies from 1 to 120 MeV. Intensities exceeding 10^9 photons per second, with energy resolutions of ~3%, are routinely available, thus making HIGS a world-class facility for photonuclear research. This facility permits the study of few-nucleon reaction measurements that probe the neutron–neutron force, and three-nucleon interactions, as well as off-shell features of nucleon–nucleon interactions. Recent studies include kinematically complete measurements of the photodisintegration of ^{3}He (see Figure 2) [8].

Shell-Evolution Studies at FSU

Nuclear structure investigations at FSU exploit the recently installed "Super" Enge Split Pole Spectrograph as well as an array of Compton suppressed germanium detectors to be soon augmented by the Clarion-2 array, which is being assembled in collaboration with Oak Ridge National

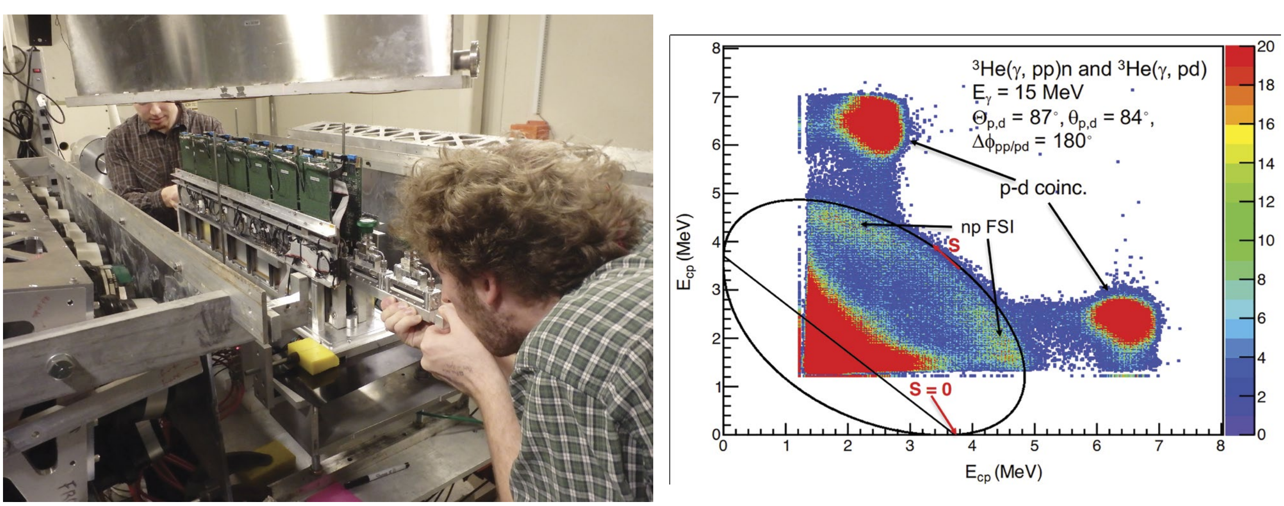

Figure 2. *(Left) The target carriage and silicon strip detector arrays used in the kinematically complete measurements of two- and three-body photodisintegration. (Right) Two-dimensional histogram of the energies for the two charged particles detected in coincidence from the photodisintegration of ^{3}He in the HIGS experiment, reproduced from Ref. [8]. under the creative common license https://creativecommons.org/licenses/by-nc-nd/4.0/.*

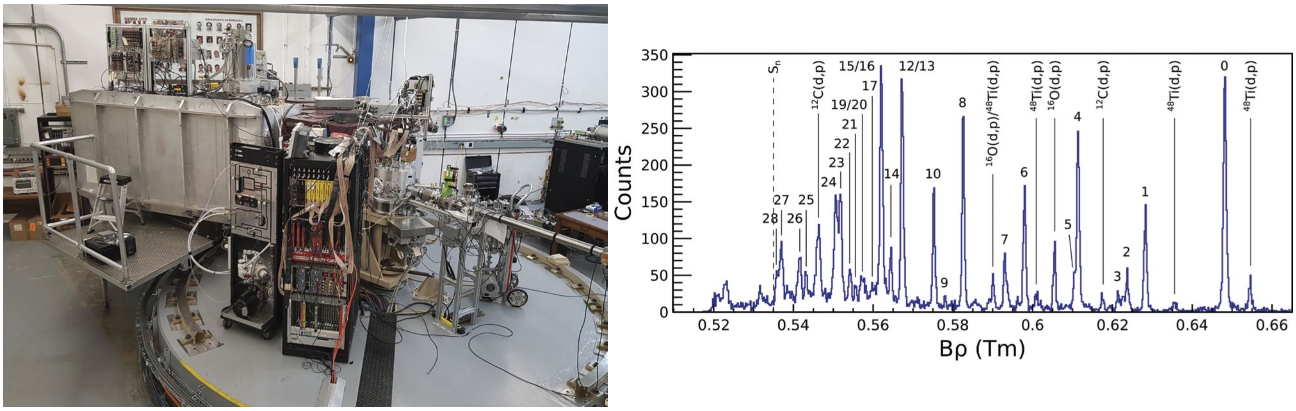

Figure 3. *(Left) "Super"-Enge Split-Pole Spectrograph (SE-SPS), newly installed at the FSU laboratory. (Right) Spectrum of the ^{50}Ti(d,p)^{51}Ti reaction at 16 MeV acquired with the SE-SPS, which confirmed the existence of the N = 32 gap in the Ti isotopes.*

Laboratory (ORNL). An example of a recent measurement with the spectrograph is the study of the ^{50}Ti(d,p)^{51}Ti reaction (Figure 3) that led to the determination of single-neutron energies for the $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ orbitals and confirmed the presence of a N = 32 gap in Ti isotopes. The γ-ray spectroscopy group has been exploring the properties of excited states in nuclei between ^{17}O and ^{40}Ca, focusing on negative-parity states involving an odd number of particles crossing from the sd- to the fp-shell for which effective interactions had not been thoroughly tested. The use of neutron-rich beams such as ^{14}C and ^{18}O, along with ^{26}Mg and ^{18}O neutron-rich targets has extended the reach to nuclei away from stability for which the available information is sparse. These systems also represent a bridge to the more exotic nuclei accessible only at rare ion-beam facilities. In collaboration with the FSU nuclear-theory group, a shell-model interaction was designed, which can reproduce 1p-1h and 2p-2h configurations in this mass region. The development entailed a comprehensive fit of two-body matrix elements to more than 200 new data points yielding the "FSU" interaction, which is available to the larger community [9].

Collective Structure and Shape-Coexistence Studies at TUNL and UK

The beams of mono-energetic photons available at TUNL-HIGS also provide quantitative probes of collective nuclear structure. By scanning stable nuclei with photons of a precise energy (nuclear resonance fluorescence), it is possible to identify nuclear levels from the ground state to the particle binding energy and to determine their properties such as energy, spin, and parity, as well as their deexcitation pathways and, in some cases, lifetimes. With this approach, the HIGS program, which focuses on stable nuclei, is complementary to research on exotic nuclei at other facilities. A 'clover array' consisting of 8 high-purity germanium (HPGe) detectors of the clover type and 12 low-background CeBr3 scintillators has recently been commissioned (see Figure 4)

The neutron and photon scattering reactions performed at UK and TUNL-HIGS are well suited to address other important issues in nuclear structure and have contributed significantly to our knowledge of nuclear shape coexistence, which has now been identified in many mass regions and appears to be a commonly occurring nuclear phenomenon [10]. Recent work has focused on testing models, including effective interactions proposed for the description of neutron-rich systems, in stable nuclei. As an ex-

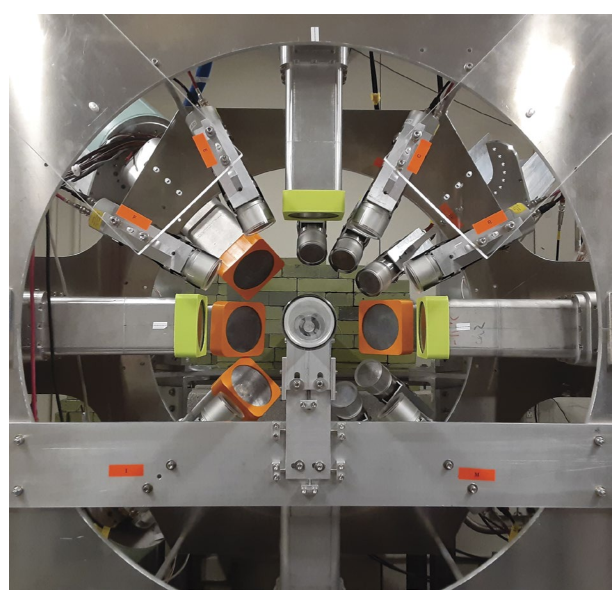

Figure 4. *The Ge clover array installed at TUNL's HIGS facility.*

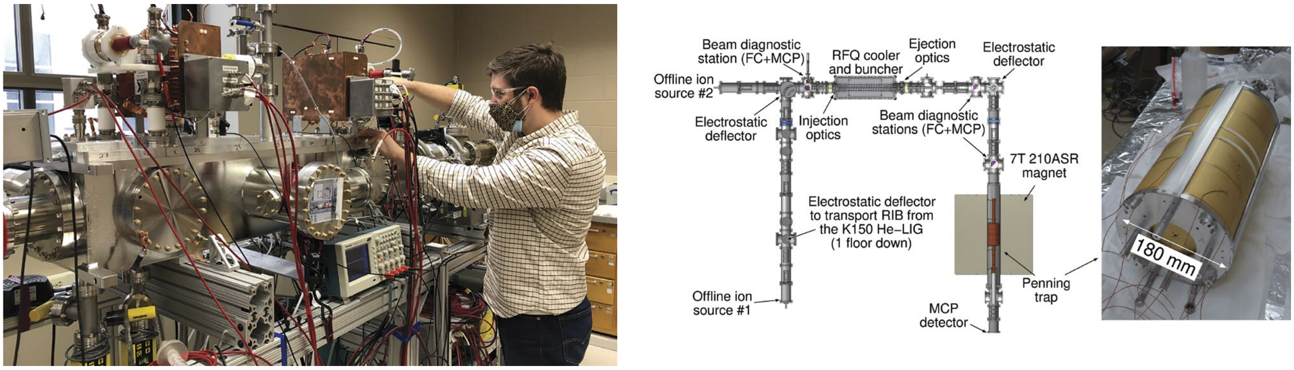

Figure 5. *(Left) The St. Benedict radio-frequency quadrupole cooler and buncher currently being commissioned using an off-line ion source. (Right) TAMU ion trap facility with the world's largest Penning trap, TAMUTRAP.*

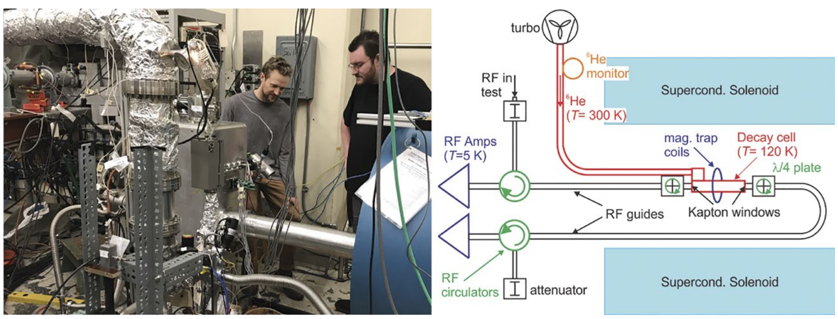

Figure 6. *(Left) HE6CRES apparatus assembled at the University of Washington. (Right) Sketch of Cyclotron Radiation Electron Spectroscopy (CRES) setup, including delivery of radioactivity, magnets, and RF guides.*

ample of the complementarity between experiments at HIGS and those at other facilities, recent results on the stable ^{64}Ni nucleus led to the observation of triple shape coexistence, a phenomenon observed earlier in neutron-rich Ni nuclei at exotic-beam facilities. Measurements at UK are planned in order to address remaining questions about this pivotal nucleus. In addition, all of the stable even-mass Ge nuclei have been examined in detail at UK to characterize the lowest excited 0^+ states and their related band structures to gain an understanding of configuration mixing in these nuclei. The development of capabilities for measuring lifetimes in heavy nuclei with the Doppler-shift attenuation method following the scattering of fast neutrons have played a key role in constraining the nuclear models of these nuclei. Increased collaboration with theorists has resulted in a deeper understanding of the unique data obtained and impacts research at other facilities.

Nuclear Structure Studies for 0νββ at TUNL, ND and UK

Evidence for neutrinoless double-beta decay (0νββ), which would confirm lepton-number violation in weak interactions and point directly to physics beyond the standard model, is the subject of several large international searches, with much of the work focused on the 0νββ candidates, such as ^{76}Ge, ^{130}Te, and ^{136}Xe. The discovery of 0νββ could also furnish information about the absolute neutrino mass scale, assuming that the nuclear matrix elements (NMEs) describing the decays can be accurately calculated. These decays pose significant challenges to nuclear structure theory, as the wave functions for the initial and final states must be determined to high precision but are seemingly beyond the current NME calculations. Complementary studies at TUNL and UK have addressed these difficulties by generating experimental data that confront these theoretical calculations.

Recent (^{3}He,n) measurements on ^{74,76}Ge at TUNL and ND [11] indicate populations of excited 0^+ states consistent with expectations from BCS-pairing theory. In addition, the recent observation of rigid triaxiality in the ground state of ^{76}Ge [12] implies an NME that is smaller than that calculated by assuming spherical symmetry. This work is buttressed by nuclear structure studies of the 0νββ parent–daughter pairs ^{76}Ge-^{76}Se, ^{130}Te-^{130}Xe, and ^{136}Xe-^{136}Ba at UK, which has emerged as the premier facility for nuclear structure studies with fast neutron inelastic scattering. A 7-MV single-stage electrostatic accelerator provides the capacity to produce high-quality, time-bunched mono-energetic neutrons, and detailed γ-ray spectroscopic techniques have enabled comprehensive descriptions of the low-lying, low-spin states of these stable nuclei, which are necessary to test model descriptions for NME calculations [13].

Cluster Structures Studied at TAMU

Gamow's theory of α decay proposed that α particles form within the nucleus prior to decay, fueling decades of theoretical and experimental study of clustering within atomic nuclei. One program at TAMU examines excited states with exotic deformations containing α-particle clusters, trying to validate predictions that such clustering can promote the production of angular-momentum-stabilized toroidal nuclei. An experiment performed with NIMROD, a 4π array composed of silicon detectors and CsI crystals, showed evidence of high excitation energy resonances in the 7α disassembly of ^{28}Si in collisions of ^{28}Si on ^{12}C. Cranked covariant density functional theory calculations support the view that these resonances may correspond to quanta of angular momentum giving rise to local energy minima for an α-clustered toroidal configuration in ^{28}Si [14].

Super-Heavy Element Research at TAMU

Elements 114 to 118 were discovered using ^{48}Ca projectiles bombarding targets of actinide elements in so-called warm fusion reactions. Unfortunately, the use of ^{48}Ca for new element discoveries is exhausted because targets of the appropriate elements are not available in sufficient quantities. Thus, for new elements to be discovered using projectiles with $Z > 20$, two avenues exist: (a) fusion with projectiles just above calcium or (b) multinucleon transfer with heavier beams. Studying the mechanisms of these reactions is an ongoing effort at TAMU. One avenue being examined is the survivability of the heavy deformed compound nuclei in reactions of ^{nat}Lu, $^{178,180}Hf$, and ^{181}Ta targets with medium-mass projectiles.

Science Focus: Tests of Fundamental Symmetries in Nuclear Systems

The ARUNA laboratories are ideally suited for some of the most sensitive experiments in search of new physics via β decay, from tests of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [15] and from searches for chirality-flipping interactions, in the form of scalar or tensor currents [16]. The efforts we describe aim at performing the most sensitive searches for new physics in the ARUNA labs. In these examples, the ARUNA labs produce short-lived radioactive isotopes with the accelerator and transfer them to the ion traps or a decay station.

The ND program in fundamental symmetries aims at probing for beyond-the-standard-model physics through the unitarity test of the CKM matrix, which is currently under tension [17]. The goal is to improve the accuracy of the largest matrix element, V_{ud}, by performing precision measurements of superallowed mixed β-decay transitions. Unlike its more precisely determined superallowed pure Fermi counterpart, mixed decays require not only experimental information on Q-values, half-lives, and branching ratios, but also on the Fermi-to-Gamow-Teller mixing ratio in order to extract a value for V_{ud}. Over the past years, several half-lives, ranging from ^{11}C to ^{29}P, have been measured using the ND beta counter and radioactive ion beams separated by the TwinSol facility (see, e.g., Ref. [18]). Next, the Superallowed Transition Beta Neutrino Decay Ion Coincidence Trap (St. Benedict) will be installed [19] (Figure 5), which will aim at measuring the $\beta-\nu$ angular correlation parameter in order to extract the Fermi-to-Gamow-Teller mixing ratio for the first time in many superallowed mixed β decay transitions, with ^{17}F as the first measurement envisioned.

The fundamental symmetry group at TAMU continues to search for beyond-the-standard-model physics via the precision frontier. Table-top experiments measuring β-decay observables to <0.1% are sensitive to new interactions in a manner complementary to and competitive with high-energy physics searches. The β-delayed proton decays of several neutron-deficient nuclei offer a unique approach for measuring the $\beta-\nu$ correlation parameters and ft values [20]. The TAMU Penning Trap (TAMUTRAP), by far the world's largest, has been built specifically for this purpose and has been commissioned [21]. The ability to manipulate ion motions and perform mass measurements has been demonstrated, and a light-ion guide and mass-separator is under construction, with the purpose to deliver and transport the short-lived isotopes of interest ($^{20,21}Mg$, $^{24,25}Si$, $^{28,29}S$, $^{32,33}Ar$, $^{36,37}Ca$, $^{40,41}Ti$) to the TAMUTRAP facility (Figure 5).

The accelerator program at UW concentrates on applying a new beta-spectroscopy technique, called cyclotron radiation electron spectroscopy (CRES; Figure 6), to searches for chirality-flipping interactions. The CRES technique determines the beta energy from the frequency of microwave radiation emitted by betas in a magnetic field. CRES was proposed and applied to tritium betas (~20 keV) by the Project8 collaboration [22]. The UW accelerator has already been used to provide sources of ^{6}He and ^{19}Ne, currently developing ^{14}O. The He6–CRES collaboration has members from Argonne National Laboratory, North Carolina State University, Mainz University, Pacific Northwest National Lab, TAMU, Tulane University, and UW working on the different aspects of the project. In order to pick up faint microwave radiation, low-noise amplifiers working at cryogenic temperatures are needed. Groups from Argonne National Laboratory and TAMU are developing an ion trap and RF cooler/buncher system, to use in combination with the CRES apparatus. The goal of these developments is to develop CRES techniques to a level where they can be applied to a wide variety of nuclei at radioactive beam facilities.

Delivering for Society, Applications of Nuclear Methods

ARUNA laboratories also provide wide-ranging innovations and benefits for society. These efforts are synergistic with the science missions that drive the laboratories, relying on developing and using analytical techniques to support applications in medical isotopes, novel detector technology, radiation effects on electronics, and nuclear data for diverse applications. In addition to the faculty and technical staff, these local efforts involve undergraduate students, graduate students, and postdoctoral scholars, hence contributing to development of a highly skilled workforce. A wide variety of applications due to the diverse nature of the accelerator facilities is present throughout ARUNA.

Analytical Techniques

Programs using accelerator-based techniques for elemental or structural analysis, such as Proton Induced X-ray Emission (PIXE), Proton Induced Gamma-ray Emission (PIGE), and Rutherford Back Scattering (RBS) (UML, ND, TAMU, Union, Hope, WMU) engage many undergraduates. Students learn these valuable techniques and apply them in the lab, with their results providing a direct impact on society. One timely and very important example is the application of PIGE at ND as a rapid scanning method for Polyfluoroalkyll compounds in consumer products and environmental samples [23].

Neutron Beams

Institutions with neutron production capabilities (UK, OU, TUNL, UML) provide important and unique measurements of neutron-induced cross-sections to characterize materials and contribute to detector development. An example is the development of enriched C7LYC dual neutron-gamma scintillators for fast-neutron spectroscopy and digital pulse-shape analysis techniques. Neutron scattering cross-section data are critical in many applications, including advanced reactor design. Additionally, gamma rays emitted after neutron bombardment can be used for elemental analysis, thus expanding the suite of analytical techniques at ARUNA facilities.

Medical Isotopes

Isotopes for nuclear medicine, such as the Targeted Alpha Therapy Isotope At-211, an exciting new cancer treatment modality, are also produced at ARUNA accelerators. The production mechanism for this isotope requires 28-MeV alpha particles, which are only available at a few accelerators, including TAMU. In addition to production, novel chemical separations are being pursued [24].

Radiation Effects

An application that is significant for society is the ability to measure the response of space-based detector electronics to radiation before they are installed in space-based detectors. For example, over 100 parts for the controls of the SpaceX Dragon Crew capsule were tested with heavy-ion beams available from the K500 accelerator at TAMU. In addition, OU contributed to the development of next-generation X-ray telescopes by providing proton beams mimicking the conditions found in orbit [25].

Similarly, the WMU accelerator facility is used extensively to study irradiation effects on superconductors, with some interesting results. In particular, the disorder induced by proton irradiation has been found to increase the critical temperature in some superconductors [26].

Detector Development

Many of the ARUNA facilities have a significant amount of flexibility as they are university-based and not driven by external user programs. As such, new ideas, new detector schemes, and new techniques can be developed rapidly and efficiently as needs arise. One example is the WMU accelerator facility. Because of its close proximity to FRIB, it often serves as a staging area for preparing detectors for FRIB experiments and for development of detectors relevant to FRIB physics [27].

Educating Scientists: Workforce Development

The ARUNA laboratories are focal points for attracting and educating the next generation of the nuclear workforce. Roughly one-fifth of the doctoral degrees granted in the United States in experimental nuclear physics are awarded to ARUNA institution graduates. Annually, a further 140 undergraduate students perform research within an ARUNA laboratory, while dozens more participate in accelerator-based research as a part of their coursework. The roughly three-dozen postdoctoral research associates working at ARUNA laboratories each year are key to workforce development, both as mentors and recipients of mentorship. Each of these individuals benefits from the unique experiences and development opportunities afforded by a university-based accelerator.

The scale and location of university-based accelerators enable students to engage in every stage of experimental nuclear research, from experiment design, equipment development, and executing experiments, through data analysis and interpretation. Skills acquired include bread-and-butter nuclear detection techniques of use for applications as well as fundamental science, and the management and

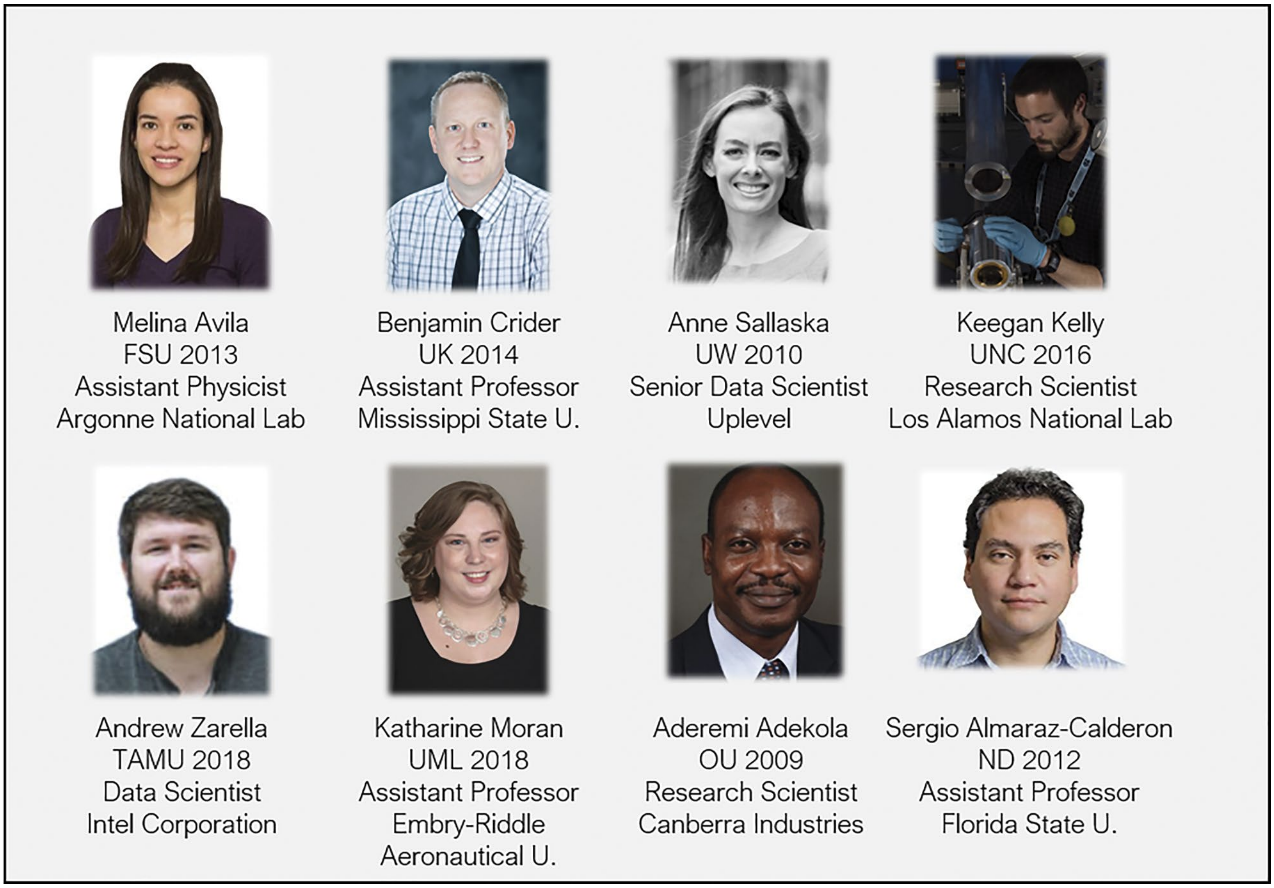

Figure 7. *ARUNA Ph.D. recipients pursue a variety of career paths.*

analysis of large, complex data sets. This hands-on, immersive research experience, which is increasingly rare in nuclear science, prepares ARUNA students for a wide variety of future careers, including positions at national laboratories, data science firms, and institutes of higher education (e.g., Figure 7).

Undergraduate research is a hallmark of ARUNA laboratories. These young researchers are frequent members of research teams and many lead their own experimental efforts. The programs at Union College and Hope College are driven entirely by undergraduate researchers, publishing student-authored work in top-tier journals. Beyond the school year, several dozen undergraduates are involved in the National Science Foundation–funded Research Experience for Undergraduates programs hosted by ND, TAMU, and TUNL. Several more undergraduates are engaged through informal research partnerships, such as the long-running collaborations between UK and the University of Dallas and ND and the University of Wisconsin–-La Crosse. For many students, this is their first opportunity to perform research with state-of-the-art laboratory equipment. Some students are able to engage even earlier, for instance through Union College's annual workshop for high school students and physics teachers, which has reached well over 100 high school students and dozens of high school teachers. Another example is FSU's week-long summer camp on nuclear medicine and science, which is open to both middle and high school students. Through collaboration within ARUNA, this program will soon be replicated at TAMU. The educational impact of ARUNA institutions is multiplied by the integration of experiments using local accelerators into the physics curriculum. Formal laboratory courses involving accelerator-based experiments are available at Hope College, OU, the TUNL universities, and Union College. Laboratory courses at all other ARUNA universities benefit from the state-of-the-art equipment and expertise available for more traditional laboratory courses in nuclear physics and related topics.

In short, ARUNA institutions are an efficient and effective component of nuclear science education and workforce development in the United States.

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