ARUNA: Advancing Science, Educating Scientists, Delivering for Society

ARUNA, the Association for Research at University Nuclear Accelerators is an association of twelve university-based accelerator laboratories in the USA and the scientists performing nuclear research at them.

ARUNA, the "Association for Research at University Nuclear Accelerators" (http://aruna.physics.fsu.edu) was founded in 2010 with the goals to optimize the use of university-based accelerator facilities in the USA, to increase the opportunities for education around them and to document their scientific impact as an integral part of the U.S. nuclear science enterprise. The diversity of approaches provided by these laboratories is a critical asset for the field, which is presently growing around the science opportunities provided by the Facility for Rare Ion Beams, FRIB. ARUNA laboratories provide a highly creative, nurturing scientific environment with many opportunities for students to acquire the essential skills required for a well-trained "nuclear" workforce.

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. 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 provide intellectual leadership by developing new concepts and techniques applicable both at their local and at the national user facilities, furthermore, they are at the core of the user communities at the national facilities. ARUNA laboratories and their broader intellectual and scientific networks provide the link between disciplines that foster new ideas and innovations. Without their continuous and strengthened support, nuclear physics may well disappear as an academic field from many university campuses.

ARUNA laboratories have developed unique capabilities in mono-energetic neutrons and high-intensity mono-energetic photon beams. They have developed techniques for generating and utilizing heavy-ion beams or high-intensity low-energy beams, which will be an important asset towards 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 US experimental portfolio. ARUNA facilities are also characterized by their flexibility in performing long-term experiments and pursuing programs that are not possible within the environment and time constraints of the national user facilities.

ARUNA laboratories are leading contributors to the “nuclear” workforce training in the USA. The ARUNA graduate students and postdocs can take ownership of complete scientific projects from inception to publication and acquire a diversity of skills that would not be provided if they only did their experimental work at national laboratories. Through their location on university campuses, ARUNA laboratories also attract undergraduates into the field and enable their involvement in forefront research projects early in their careers. Consequently, a large fraction of today's nuclear physics research community has been trained at university facilities.

Resolution

In order to ensure the long-term health of the field and the education of the next generation of scientists, it is critical to maintain balance between the ARUNA facilities and the major national user facilities, in science, operations and new initiatives. Under this condition the ARUNA laboratories will continue to flourish and provide a diversity of approaches for forefront science while nurturing the scientists of the future.

- Science programs at ARUNA Laboratories provide a diversity of topics and approaches to nuclear science. We recommend that ARUNA facilities are operated to maximize the scientific return from their capabilities.
- ARUNA laboratories provide unique and complementary resources, including neutron beams, gamma-beams and high-intensity ion beams, with the flexibility to nimbly react to scientific opportunities.
- ARUNA laboratories provide unique hands-on training environments to the next generation of nuclear scientists and cast a wide net in the search for talent in some of the strongest Physics graduate programs in the country.
- Upgrades and new initiatives will amplify the contributions of ARUNA labs to the community.
- ARUNA labs develop critical equipment benefiting both ARUNA labs and national facilities. Collaboration on technical developments between National and ARUNA facilities at less than full-cost-recovery levels would enhance the scientific impact of ARUNA laboratories.
- ARUNA laboratories benefit the national nuclear enterprise through significant additional university contributions and commitments.

Introduction

ARUNA (Association for Research at University Nuclear Accelerators) is an association of the accelerator laboratories at Florida State University, Hope College, James Madison University, Ohio University, Texas A&M University, TUNL (Duke University, University of North Carolina at Chapel Hill, North Carolina State University, North Carolina Central University), Union College, the University of Kentucky, the University of Massachusetts Lowell, the University of Notre Dame, University of Washington and Western Michigan University. It was founded in 2010 to enhance communication and exchange between the partner institutions and to strengthen the research and educational opportunities at these laboratories.

The ARUNA research programs presented in this white paper are characterized as nuclear astrophysics, low-energy nuclear physics, fundamental symmetries and applications. In many instances, such as astrophysics, environmental studies, materials science and particle physics, overlaps exist with research questions and applications of accelerator-based techniques. ARUNA scientists are primarily funded through DOE and NSF for the nuclear physics core program. Most ARUNA groups operate their facilities as a means to achieve the grant-funded scientific goals. The Texas A&M cyclotron, TUNL and the University of Washington are operated as U.S. DOE Centers of Excellence. The grant funding to ARUNA laboratories is strongly leveraged by the host universities, which, almost everywhere, over-match the operations budgets by providing staff positions, utilities, and other contributions. The universities consider their respective ARUNA laboratories as scientific flagships with a large role in innovative and independent research developments and a unique role in graduate and undergraduate student training.

The National Science Foundation has traditionally made education and training a cornerstone of their research support. The topic of workforce development and its impact on the DOE mission has also become a primary focus at the DOE Office of Science and has been addressed in a report to NSAC [1]. Several challenges in fulfilling the workforce needs of fundamental and applied nuclear science were identified. The report concludes that early exposure of undergraduate students to nuclear methods is a significant factor in addressing these needs. All ARUNA laboratories support undergraduate research projects, many host research groups from undergraduate colleges and two ARUNA accelerator laboratories are located at undergraduate institutions. Through these links, ARUNA laboratories are playing an important role in rejuvenating the nuclear workforce. Access to experimental facilities in low-energy nuclear science has fallen to a level, which endangers the diversity of approaches, the quality of education and the number of experimental nuclear science Ph.D's. awarded. ARUNA laboratories are needed to alleviate the impact of the nationwide consolidation in experimental facilities for low-energy nuclear science and nuclear astrophysics.

ARUNA scientists provide intellectual and scientific leadership in their research fields. They also play a leading role for the nation's nuclear physics endeavor, as users and innovators at national research facilities and through developments for these programs. Many of the scientific goals and developments in the low energy nuclear physics and astrophysics communities have been spearheaded, tested, and developed at ARUNA institutions.

The intellectual potential at work in ARUNA provides great benefits for the national nuclear physics program. ARUNA laboratories and their broader intellectual and scientific networks provide the link between disciplines that foster new ideas and innovations. Without their continuous and strengthened support, nuclear physics may well disappear as an academic field from many university campuses.

A) Scientific Focus on Nuclear Astrophysics

Nuclear astrophysics is a multifaceted sub-discipline of nuclear physics 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 and explosion. 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. On the nuclear physics side, the study of the nuclear reactions at very low energies with stable beams provides essential input to the understanding of nuclear reaction processes near the particle threshold. At these conditions, the reaction rates can be strongly affected by quantum effects ranging from wave function coupling and interference to cluster formation and electron screening. These phenomena may not only impact our simulation of stellar burning but also the nuclear processes taking place in inertial confinement plasmas. These quantum phenomena are presently being investigated by nuclear theorists to come to a better understanding of their impact on different burning environments. Reaction studies with radioactive beams provide not only information about the reaction path, but also give information about the collective structure of nuclei far of stability, ranging from level density to halo structure and their impact on capture and fission probabilities. Nuclear astrophysics is a field that serves on a fundamental level both the astrophysics as well as the nuclear physics communities.

The complexity and variety of astrophysical measurements necessitate 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 require the capabilities of radioactive-beam facilities, including the large-scale national laboratories. 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 seed and fuel material for explosive burning processes, however, depends critically on very-low-energy charged-particle reactions that facilitate the ignition. To address questions of explosive nucleosynthesis therefore also depends critically on reliable knowledge about the reactions involving stable nuclei. 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 rates are simply too slow to be measured directly and indirect techniques must be employed to extract the information needed to calculate a reaction rate. Such spectroscopic measurements, conducted at TAMU, TUNL, ND, OU and FSU also provide information relevant to explosive nucleosynthesis and the nuclear equation of state (EOS). 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.

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, beam-pulsing 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.

High-Intensity Low-Energy Accelerators: The deep underground approach is being pursued by ND at the CASPAR underground accelerator at SURF (See Figure 1), following pioneering work at the LUNA facility in the Gran Sasso laboratory. Recent successes are the identification near threshold of cluster states in ^{10}B and ^{14}N via ^{6}Li(α,γ)^{10}B and ^{10}B(α,n)^{12}C respectively that facilitate a strong mass flow converting primordial material to the CNO range in the first generation of stars [2]. These results may affect the primordial lithium abundances. The measurement of the ^{14}N(p,γ) ^{15}O reaction over a wide energy range, coupled with an extensive R-matrix simulation [3] provided sensitive information for the recent observation of CNO neutrinos from the sun by BOREXINO for determining the solar metallicity. For the study of the ^{7}Be(α,γ) reaction, a ^{7}Be beam was developed at the 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 [4]. 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 [5].

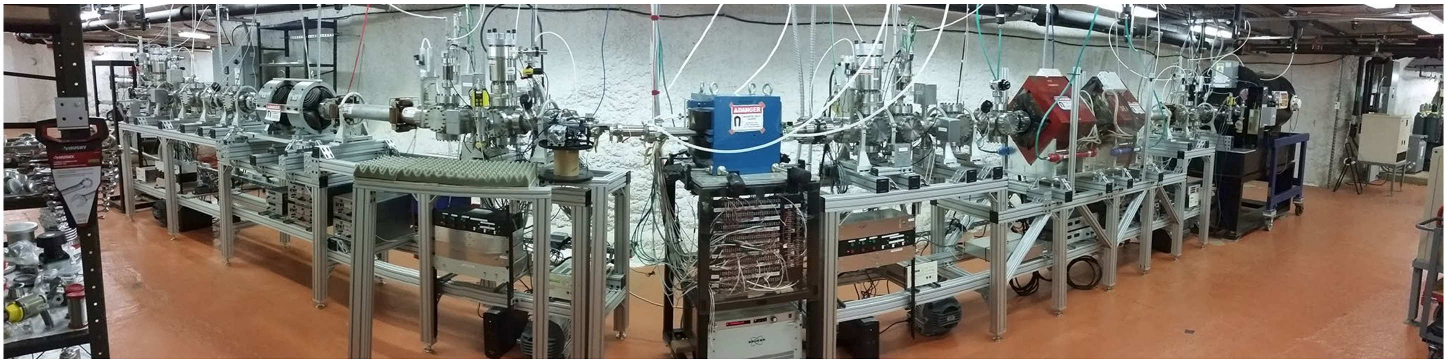


Figure 1: The CASPAR facility at the SURF underground laboratory, operated by the ND group.

Figure 2: The new 2-MV Singletron (left) and the redesigned ECR accelerator (right) at TUNL, each machine injecting ions into a dedicated beam line. The new LENA II facility at TUNL will deliver beams of exceptionally high intensity and sharp time-structure for experiments dedicated to nuclear astrophysics.

The ECR accelerator at TUNL's 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 related to ancient globular cluster stars, classical nova explosions, galactic radioactivity, and presolar stardust grains in primitive meteorites. Recent highlights are the measurement of the ^{29}Si(p, γ)^{30}P reaction to explain silicon isotopic ratios in presolar grains from stellar explosions [6,7], the identification of new resonances in the ^{30}Si(p,γ)^{31}P reaction to understand observed abundance correlations in globular cluster red giant stars [8], and a measurement of the ^{22}Ne(p,γ)^{23}Na reaction for explaining the nucleosythnesis in asymptotic giant branch (AGB) stars [9]. 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 [10]. The ^{22}Ne(α,n) reaction is being studied at the LENA facility and complementary studies have been performed at 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 not only determines the carbon oxygen ratio in our universe, but is also indicative for 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 [11].

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 is in particular not available at PAC-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.

Experiments addressing explosive nucleosynthesis: 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 radioactive-beam separator to probe critical reactions For Big-Bang nucleosynthesis, such as ^{7}Be(d,α) [4], reactions relevant to the break-out from the Hot-CNO cycle, such as ^{18}Ne(α,p) and the study of proton-capture (p,γ) reactions through the surrogate (d,n) reaction. Proton capture on neutron-deficient isotopes facilitates the rp-process in novae and X-ray bursts and affects the production of long-lived radioactive isotopes such as ^{22}Na and ^{26}Al in those environments. The ND group uses TriSol 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 [12]. A measurement with the ^{58}Ni(^{3}He,n)^{60}Zn reaction identified an unexpected structure in the level density with excitation energy which 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 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 [13].

B) 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 QCD-based interactions to the structure and reactions of light nuclei [14] and their reach towards 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 High Intensity Gamma-ray Source (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 3) [15].

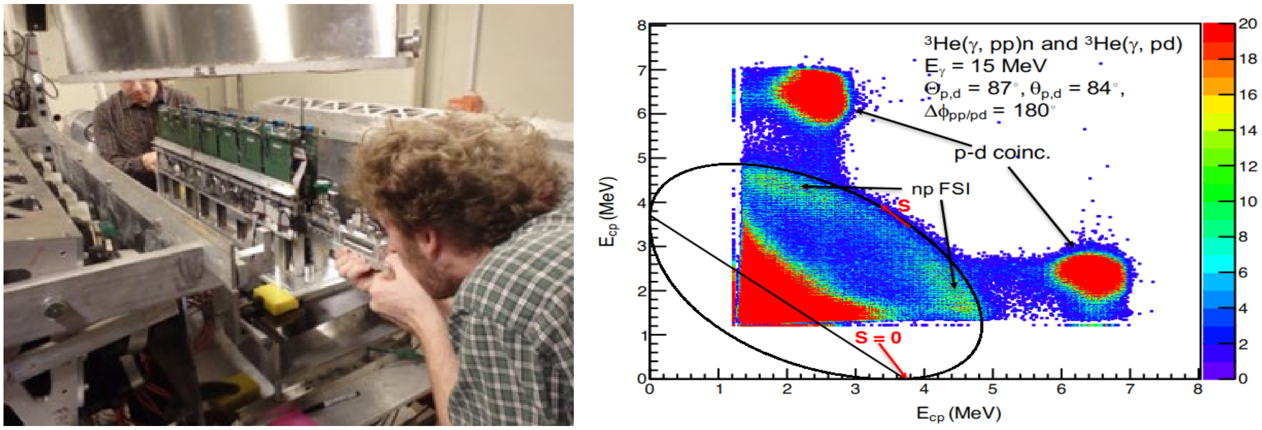


Figure 3: (Left) The target carriage and silicon strip detector arrays used in the kinematically complete measurements of two- and three-body photodisintegration. (Right) Two-dimensional histogram of the energies for the two charged particles detected in coincidence from the photodisintegration of ^{3}He in the HIGS experiment, reproduced from [15].

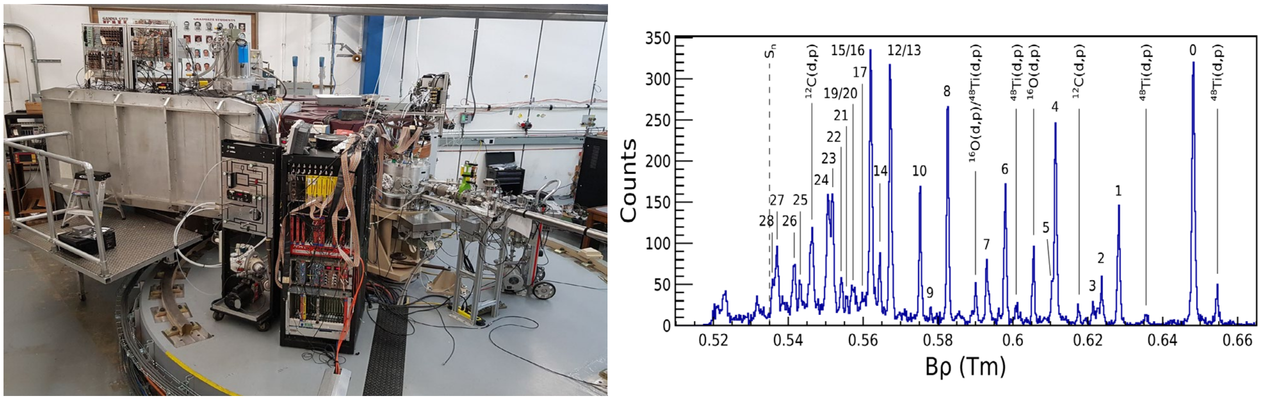


Figure 4: (Left) "Super"-Enge Split-Pole Spectrograph (SE-SPS), newly installed at the FSU laboratory. (Right) Spectrum of the $^{50}Ti(d,p)^{51}Ti$ reaction at 16 MeV acquired with the SE-SPS, which confirmed the existence of the *N=32* gap in the Ti isotopes.

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, augmented to form the Clarion-2 array, which has been developed in collaboration with ORNL. An example of a recent measurement with the spectrograph is the study of the ^{50}Ti(d,p)^{51}Ti reaction (Figure 4) 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 [16].

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 – NRF), 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 5)

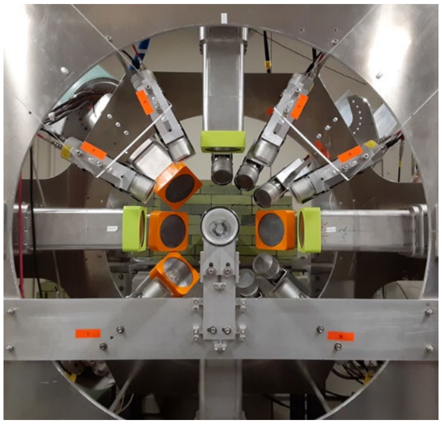


Figure 5: The Ge clover array installed at TUNL's HIGS facility

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 [17]. Recent work has focused on testing models, including effective interactions proposed for the description of neutron-rich systems, in stable nuclei. As an example 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 which confront these theoretical calculations.

Recent (^{3}He,n) measurements on ^{74,76}Ge at TUNL and ND [18] indicate populations of excited 0^+ states consistent with expectations from BCS theory. In addition, the recent observation of rigid triaxiality in the ground state of ^{76}Ge [19] 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 [20].

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. [21]

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.

C) Scientific 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 [22] and from searches for chirality-flipping interactions, in the form of scalar or tensor currents [23]. 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 [24]. 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. [25]). Next, the Superallowed Transition Beta Neutrino Decay Ion Coincidence Trap (St. Benedict) will be installed [26], 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 [27]. The TAMU Penning Trap (TAMUTRAP), by far the world's largest, has been built specifically for this purpose and has been commissioned [28]. The ability to manipulate ion motions and perform mass measurements has been demonstrated, and a light-ion guide and mass-separator in 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.

The accelerator program at UW concentrates on applying a new beta-spectroscopy technique, called cyclotron radiation electron spectroscopy (CRES), 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 [29]. The UW accelerator has already been used to provide sources of ^{6}He and ^{19}Ne, currently developing ^{14}O. An international collaboration [30] is working on the different aspects of the project. In order to pick up the 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.

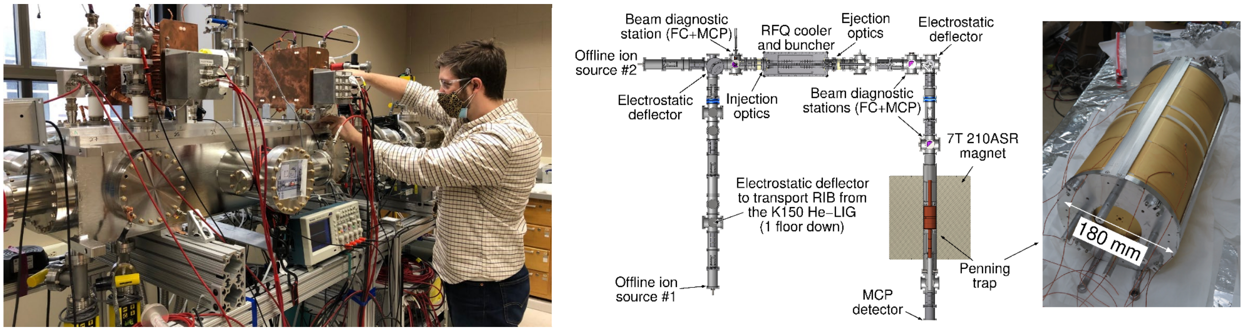


Figure 6: (Left) The St. Benedict radio-frequency quadrupole cooler and buncher currently being commissioned using an off-line ion source. (Right) TAMU ion trap facility with the world's largest Penning trap, TAMUTRAP.

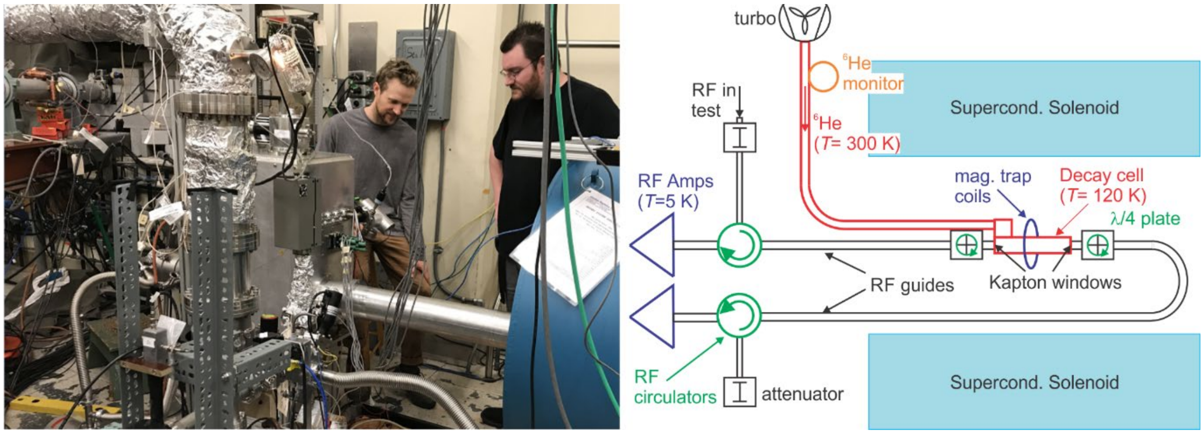


Figure 7: (Left) HE6CRES apparatus assembled at CENPA, University of Washington. (Right) Sketch of CRES setup, including delivery of radioactivity, magnets, and RF guides.

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, preparing detectors for FRIB experiments, and for development of detectors relevant to FRIB physics [35].

The prototype AT-TPC was tested extensively at Notre Dame before full construction of the AT-TPC was undertaken at NSCL. While not a detector, the SECAR recoil separator at FRIB was based upon the success design, construction, and use of the St. George recoil separator at ND. The ANASEN active-target detector was developed at FSU by a collaboration of FSU and Louisiana State University scientists and is being employed both at FSU and TRIUMF.

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 which 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 PIXE, PIGE, and 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 PFAS compounds in consumer products and environmental samples [31].

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. [32]

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 [33].

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 [34].

The ARUNA Network: Internal and External Collaborations

The ARUNA facilities offer diverse capabilities, which have led **to inter-institutional collaborations**. An example is the NNSA-funded "CENTAUR" Center for Excellence in Nuclear Training And University-based Research, which facilitates collaborations between the ARUNA laboratories at 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, FSU-LSU, UK-UML, and Indiana University-WMU collaborations.

ARUNA facilities are frequently used by **external collaborators**, who make use of unique capabilities at ARUNA labs and often pursue long-standing programs of research at them. A close collaboration between the nuclear science group at Louisiana State University and FSU has formed around the ANASEN active target detector, the SE-SPS Spectrograph and the SABRE Silicon detector array, which were developed and used at the FSU laboratory. Recently, a collaboration between Oak Ridge National Laboratory and FSU has developed and commissioned the Clarion-2 Gamma-detector array at the FSU laboratory and used it in a first round of experiments. This device will also be available to external collaborators and a workshop to organize future program has been held at the 2022 Low-Energy community meeting.

The ND laboratory has been used by researchers from Oak Ridge National Laboratory for their radioactive-beam program. The TUNL Tandem laboratory has been hosting a long-standing collaboration with researchers from Los Alamos National Laboratory, studying fission with the neutron-beam facility there.

The JMU laboratory has been collaborating with scientists from the University of Virginia using the 10-MeV electron beam.

Educating Scientists - Workforce Development

The ARUNA laboratories are focal points for attracting and educating the next generation of the nuclear workforce. Table 1 lists the 2015-2022 Ph.D. graduates in experimental nuclear science from ARUNA institutions. These graduates account for roughly one-fifth of the doctoral degrees granted in the USA in experimental nuclear science. 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 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., see Figure 8).

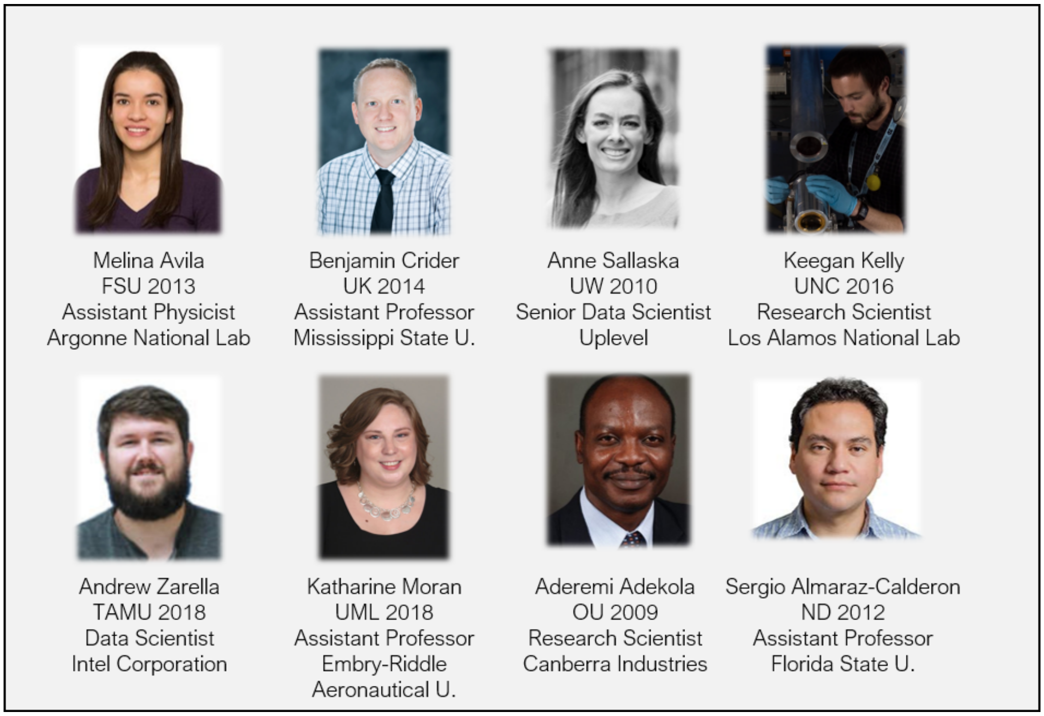


Figure 8: ARUNA Ph.D. recipients pursue a variety of career paths.

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 and James Madison University 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 NSF-funded Research Experience for Undergraduates (REU) programs hosted by the 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 students and dozens of 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 ARUNA collaboration, 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.

2016

- Mason Anders (Shlomo,TAMU)
- Jessica Baker (Wiedenhoever,FSU)
- Matteo Barbarino (Bonasera,TAMU)
- William Bauder (Collon,ND)
- Richard Behling (Melconian,TAMU)
- Joseph Belarge (Wiedenhoever,FSU)
- Amila Dissanayake (Kayani,WMU)
- Sean Finch (Tornow,Duke)
- Graham Giovanetti (Wilkerson,UNC)
- Emily Jackson (Lister,UML)
- Sean Kuvin (Wiedenhoever,FSU)
- Georgios Laskaris (Gao,Duke)
- Jacqueline MacMullin (Wilkerson,UNC)
- James Matta (Garg,ND)
- Larry May (Yennello,TAMU)
- Dmitriy Mayorov (Folden,TAMU)
- David Mc. Pherson (Cottle,FSU)
- Mike Mehlman (Melconian,TAMU)
- Scott Miller (Riley,FSU)
- Vikram Prasher (Chowdhury,UML)
- Sarah Shidler (Wiescher,ND)
- Rashi Talwar (Wiescher,ND)
- Justin VonMoss (Tabor,FSU)
- Brittany VornDick (Young,NCSU)
- David Zumwalt (Garcia,UW)

2016

- Shamim Akhtar (Brune,OU)
- Marisa Alfonso (Folden,TAMU)
- Anthony Battaglia (Aprahamian,ND)
- Johnathan Button (Youngblood,TAMU)
- Zilong Chang (Gagliardi,TAMU)
- Murat Dag (Tribble,TAMU)
- Sushil Dhakal (Brune,OU)
- Rutger Dungan (Tabor,FSU)
- Ben Fenker (Melconian,TAMU)
- Kyong Han (Ko,TAMU)
- Nathan Holt (Rapp,TAMU)
- Ran Hong (Garcia,UW)
- Min Huang (Gao,Duke)
- Keegan Kelly (Champagne,UNC)
- Feng Li (Ko,TAMU)
- Alexander Long (Wiescher,ND)
- Wenting Lu (Collon,ND)
- Stephanie Lyons (Wiescher,ND)
- Karen Ostdiek (Collon,ND)
- Cody Parker (Brune,OU)
- Yuan Qiu (Chowdhury,UML)
- Jack Silano (Karwowski,UNC)
- Mallory Smith (Aprahamian,ND)
- Sidharth Somanathan (Fries,TAMU)
- Pei-Luan Tai (Tabor,FSU)
- David Ticehurst (Howell,UNC)
- James Trimble (Henning,UNC)
- Tyler Werke (Folden,TAMU)
- Kevin Wierman (Wilkerson,UNC)
- Jun Yan (Wu,Duke)
- David Ticehurst (Howell,UNC)
- James Trimble (Henning,UNC)
- Tyler Werke (Folden,TAMU)
- Kevin Wierman (Wilkerson,UNC)
- Jun Yan (Wu,Duke)

2018

- Nadyah Alanazi (Voinov,OU)
- Bilal Amro (Lister,UML)
- Jonathan Barron (Riley,FSU)
- Miguel Bencomo (Hardy,TAMU)
- Clark Casarella (Aprahamian,ND)
- Dustin Combs (Young,NCSU)
- Patrick Copp (Lister,UML)
- John Dermigny (Iliadis,UNC)
- Brent Fallin (Turkington,Duke)
- Xiao Fang (Wiescher,ND)
- Lauren Heilborn (Yennello,TAMU)
- Ed Lamere (Couder,ND)
- Mike Moran (Couder,ND)
- Katherine Moran (Lister,UML)
- Chao Peng (Gao,Duke)
- Austin Reid (Huffman,NCSU)
- Andrea Richard (Crawford,OU)
- Nabin Rijal (Wiedenhoever,FSU)
- Pathirannehelage Nuwan Sisira Kumara (Tanis,WMU)
- Yifeng Sun (Ko,TAMU)
- Andrew Zarrella (Yennello,TAMU)
- Yang Zhang (Gao,Duke)

2019

- Brittany Abromeit (Tabor,FSU)
- Maria Anastasiou (Wiedenhoever,FSU)
- Yelena Bagdasarova (Garcia,UW)
- Chelsea Bartram (Henning,UNC)
- Giacamo Bonasera (Shlomo,TAMU)
- Yingying Chen (Wiescher,ND)
- Roman Chyzh (Tribble,TAMU)
- Andrew Cooper (Champagne,UNC)
- Eric Dees (Young,NCSU)
- Xiaojian Du (Rapp,TAMU)
- Katrina Elizabeth Koehler (Famiano,WMU)
- Forrest Friesen (Howell,Duke)
- Gwenaelle Gilardy (Couder,ND)
- Thomas Gilliss (Wilkerson,UNC)
- Rekam Giri (Brune,OU)
- Matt Hall (Bardayan,ND)
- Benjamin Heacock (Young,NCSU)
- Josh Hooker (Rogachev,TAMU)
- Sean Hunt (Iliadis,UNC)
- Shahid Iqbal (Kayani,WMU)
- Heshani Jayatissa (Rogachev,TAMU)
- James Kelly (Brodeur,ND)
- David La Mantia (Tanis,WMU)
- Rebeka Lubna (Tabor,FSU)
- Samuel Meijer (Wilkerson,UNC)
- Rachel Osofsky (Garcia,UW)
- Jamin Rager (Henning,UNC)
- Adrian Valverde (Brodeur,ND)
- Kalisa Villafana (Riley,FSU)
- Merinda Viola (Folden,TAMU)
- Zhidong Yang (Fries,TAMU)
- Bryan Zeck (Young,NCSU)

2020

- Hasna Abdullah M Alali (Kayani,WMU)
- Tyler Anderson (Collon,ND)
- Eames Bennett (Christian,TAMU)
- Lori Downen (Iliadis,UNC)
- Kevin Glennon (Folden,TAMU)
- Kevin Howard (Garg,ND)
- Patricia Huestis (LaVerne,ND)
- Andrea Jedele (Yennello,TAMU)
- Xiaqing Li (Gao,Duke)
- David Little (Janssens,UNC)
- Qian Liu (Wiescher,ND)
- Jacob Long (Brodeur,ND)
- Ronald Malone (Howell,Duke)
- Prashanta Mani Niraula (Kayani,WMU)
- Caleb Marshall (Longland,NCSU)
- Som Paneru (Brune,OU)
- Craig Reingold (Simon-Robertson,ND)
- Elizabeth Rubino (Tabor,FSU)
- Kevin Siegl (Aprahamian,ND)
- Michael Skulski (Collon,ND)
- Sabrina Strauss (Aprahamian,ND)
- Sriteja Upadhyayula (Rogachev,TAMU)
- Weizhi Xiong (Gao,Duke)

2021

- Eric Aboud (Rogachev,TAMU)
- Ben Asher (Almaraz-Calderon,FSU)
- Nathan Gerken (Almaraz-Calderon,FSU)
- Gula Hamad (Meisel,OU)
- Samuel Hedges (Barbeau,Duke)
- Samuel Henderson (Ahn,ND)
- Curtis Hunt (Rogachev,TAMU)
- Sean McGuinness (Peaslee,ND)
- Luis Morales (Couder,ND)
- Gulden Othman (Henning,UNC)
- Jesus Perello (Almaraz-Calderon,FSU)
- Nirupama Sensharma (Garg,ND)
- Doug Soltesz (Meisel,OU)
- Shiv Subedi (Meisel,OU)
- Bryant Vande Kolk (Wiescher,ND)
- Taylor Whitehead (Holt,TAMU)

2022

- Derek Anderson (Mioduszewski,TAMU)
- Joseph Atchison (Rapp,TAMU)
- Connor Awe (Barbeau,Duke)
- Om Bhadra Khanal (Chajecki,WMU)
- Daniel Burdette (Brodeur,ND)
- Bryce Frentz (Wiescher,ND)
- August Gula (Wiescher,ND)
- Khushi Jayeshbhai Bhatt (Famiano,WMU)
- Long Li (Barbeau,Duke)
- Collin Malone (Howell,Duke)
- Orlando Olivas-Gomez (Simon-Robertson,ND)
- Federico Portillo Chaves (Longland,NCSU)
- Chris Seymour (Couder,ND)
- John Wilkinson (Peaslee,ND)
- Vera Zakusilova (Folden,TAMU)

Table 1: Ph.D. graduates 2015 – 2022 in experimental nuclear science from ARUNA institutions.

The ARUNA facilities

ARUNA facilities provide a unique set of nuclear probes that are often not available at national facilities. They offer flexibility and quick response to new research developments and challenges.

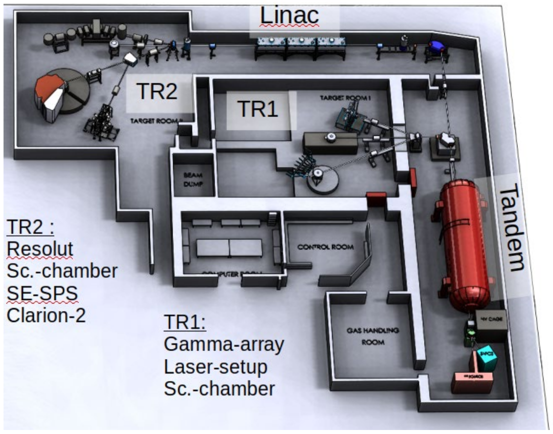
The connection of research goals at the ARUNA facilities to the goals of the national community allows for a synergy of scales, where new detector and methodological developments can be pursued at ARUNA facilities, which in turn lead to new opportunities at the national user facilities. ARUNA facilities have a history of developing new techniques, from the first in-flight radioactive beam facility, Twinsol at Notre Dame, to the currently highest sensitivity cross section measurements for astrophysics at LENA (TUNL). In many other examples, ARUNA labs have been used to push the boundaries of scientific inquiry and have great opportunities to continue to do so in the future.

Summary of unique capabilities provided by ARUNA facilities

- Mono-energetic Gamma-beam (TUNL)
- Mono-energetic Neutron-beams (UK, OU, UM)
- Long-base line (30 m) neutron time-of-flight spectroscopy (OU)
- High-intensity light-ion beams for Nuclear Astrophysics (TUNL-LENA, ND-Caspar)
- High-Intensity heavy-Ion beams for Nuclear Astrophysics (ND-St.Ana)
- High-resolution magnetic spectrographs (FSU, TUNL-Tandem, ND-Tandem)
- High-intensity activities of ^{6}He,^{19}Ne for precision measurements (UW)
- Bremsstrahlung photon beam and mono-energetic electron beam (JMU-MAL)
- X-ray digital imager with 2-D and 3-D imaging capabilities (JMU-MAL)
- World's only triple-solenoid separator (ND-TriSol)

Florida State University, John D. Fox Accelerator Laboratory

- 9-MV FN tandem accelerator, Pelletron charged
- 8-MV Superconducting Linear Accelerator as booster, using 14 split-ring niobium on copper cavities (ATLAS design)
- Ion beam mass range and maximum energy: A≤7: 10 MeV/u, A≤16: 8 MeV/u, A≤40: 5 MeV/u
- In-flight radioactive beam facility RESOLUT; exotic beams between mass 6 and 30
- Clarion-2 Gamma-detector array
- Super-Enge Split-Pole spectrograph with SABRE silicon-array
- Planned linac and cryogenics upgrade to 14 MV, extending RIB reach to mass 50



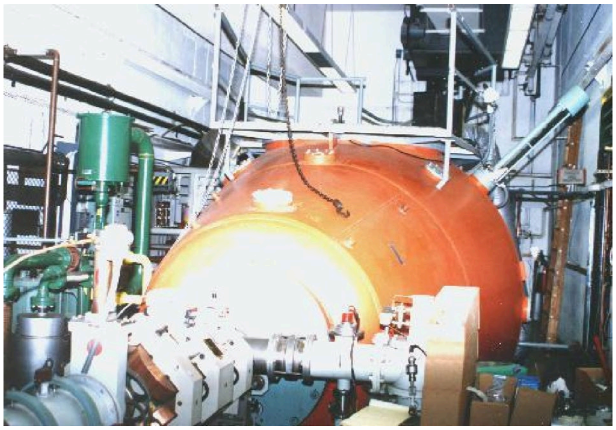
Hope College, Ion Beam Analysis Laboratory

- 1.7-MV tandem accelerator for ion beam analysis
- Programs in materials analysis

James Madison University, Madison Accelerator Laboratory

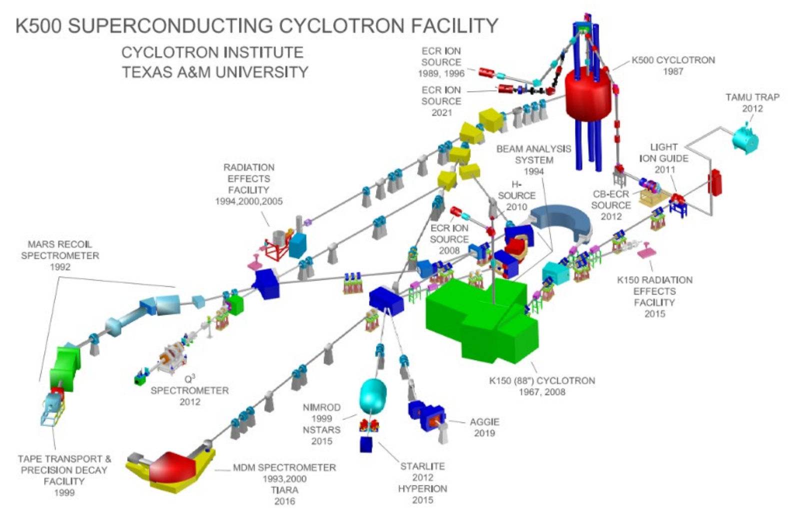
- Medical electron linear accelerator that can provide both bremsstrahlung photon beam and electron beam
- Pulsed electron beam with default electron energies of 5, 7, 8, 10, 12, 14 MeV and default bremsstrahlung endpoint energies of 6 and 15 MeV
- X-ray digital imager with both 2-D and 3-D imaging capabilities
- Developing programs in materials analysis, nuclear astrophysics and nuclear structure physics.

Ohio University, John E. Edwards Laboratory



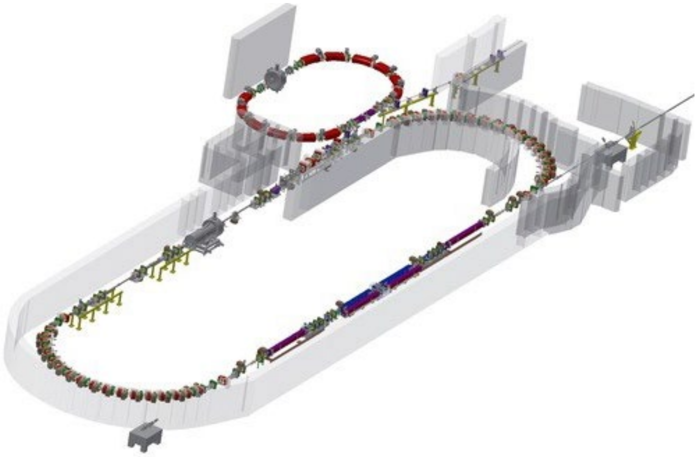
- 4.5-MV T-type tandem accelerator, Pelletron charged
- Beams of p,d, ^{3}He, ^{4}He, heavy ion beams
- 2 target rooms
- 30-m long, time-of-flight tunnel for neutron spectroscopy
- Particularly well equipped for time-of-flight experiments and neutron detection

Texas A&M Cyclotron



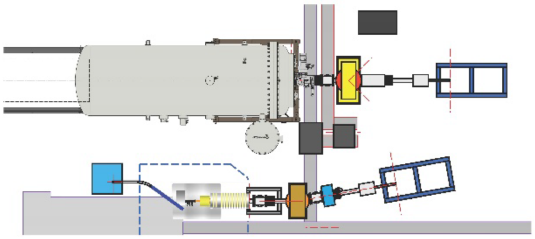
- K-150 cyclotron
- K-500 superconducting cyclotron
- ECR ion sources
- Negative ion source
- MARS recoil spectrometer, production and separation of radioactive beams
- Nimrod high-efficiency multi-particle detector
- Precision on-line β-decay γ-detector system
- MDM spectrometer
- FAUST-QTS
- HYPERION Germanium-detector array
- DAPPER
- TAMU-trap
- Radiation effects facility

TUNL-HIγS, High Intensity γ-ray Source



- World’s most intense accelerator-driven γ–ray source
- 1.2-GeV e^- -storage ring Free Electron Laser (FEL)
- γ-ray beam through Compton-backscattering of FEL photons
- Linearly and circularly polarized quasi-monoenergetic γ-ray beams
- Program for γ-ray induced astrophysical reaction rates
- Program in nuclear structure (high-resolution nuclear resonance fluorescence, photofission and Compton scattering)
- Upgrade-project: Increase capacity of FEL wigglers, increase photon energy to 150 MeV
- Upgrade-project: HIγS2, x100 increase in γ-ray beam intensity with optical cavity pumped with external laser

TUNL-LENA, Laboratory for Experimental Nuclear Astrophysics



Two high-intensity low-energy accelerator systems

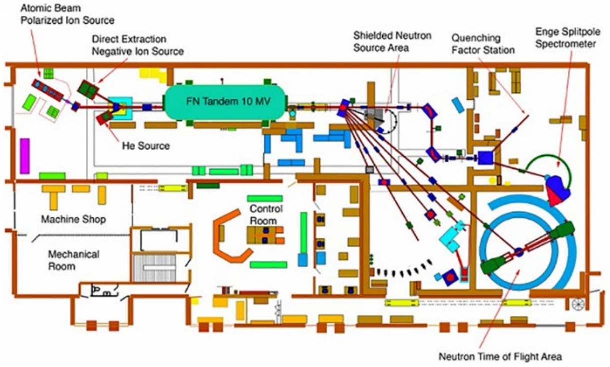
Accelerator I: Singletron, 2 MV, 2 mA beam current, beam pulses of 4 MHz frequency and 2 ns pulse width

Accelerator II: upgraded 200-kV platform with RF-Pulsing ECR source, ≤ 20 mA beam current

High-resolution HPGe–detector inside NaI(Tl) annulus, surrounded by muon veto shield

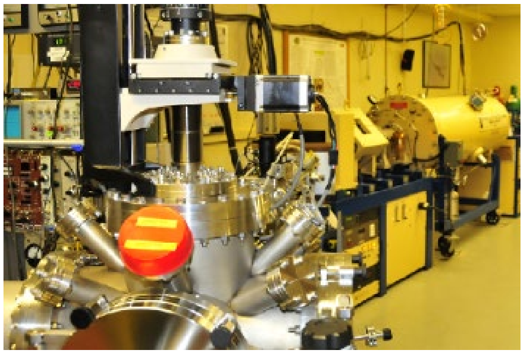
Program to measure proton and α-particle induced reactions important for stellar evolution and explosions

TUNL-Tandem Laboratory



- 10-MV FN tandem accelerator, Pelletron-charged
- p, d, ^{3}He, ^{4}He, and heavy-ion beams
- Secondary neutron beams
- Splitpole high-resolution magnetic spectrograph
- Versatile implantation facility for fabricating targets of noble gases and refractory elements
- Program to measure the nuclear structure of levels important for globular cluster nucleosynthesis and galactic radioactivity

Union College, Ion Beam Analysis Laboratory



- 1.1-MV tandem accelerator for ion beam analysis
- PIXE, PIGE, Rutherford back-scattering facilities

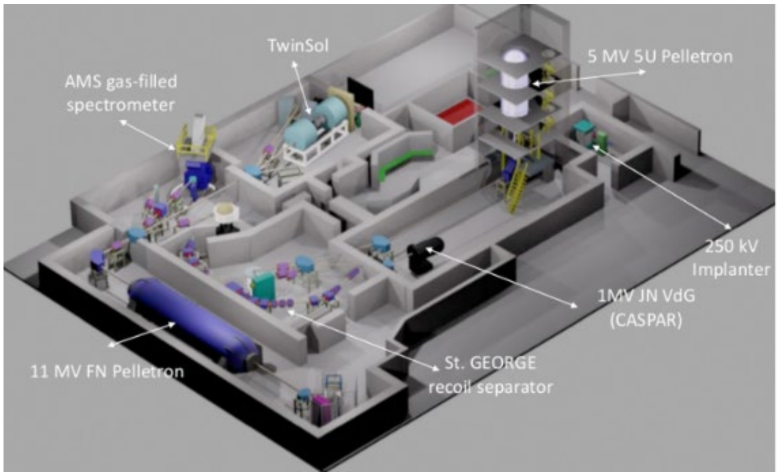
University of Kentucky, Accelerator Laboratory

- 7-MV single-ended Van de Graaff accelerator
- p,d, ^{3}He, ^{4}He beams
- Terminal and post-acceleration bunching system, sub-ns resolution
- In-flight production of mono-energetic neutrons
- Shielded setup for high-resolution γ–ray spectroscopy after inelastic neutron scattering; neutron time-of-flight capabilities

University of Massachusetts Lowell, Radiation Laboratory

- 5.5-MV single-ended Van de Graaff accelerator
- 100μA DC beam
- Terminal bunching system, sub-ns resolution
- In-flight production of mono-energetic, pulsed neutron-beam
- Programs in neutron detector development
- 1-MW research reactor, hot-cell with remote manipulators
- 100-kCi ^{60}Co source for γ irradiation
- Programs in neutron and segmented-Ge detector development

University of Notre Dame, ISNAP, Institute for Structure and Nuclear Astrophysics



- 11-MV FN tandem accelerator, Pelletron charged
- TriSol in-flight radioactive beam facilty
- Accelerator mass spectrometry with ion source and gas-filled spectrometer
- 250 kV accelerator for implantation and low energy studies.
- 5-MV single-ended Pelletron with ECR source (St. Ana)
- St. George recoil seperator for Astrophysical reaction rate measurements
- CASPAR accelerator at Sanford Underground Research Facility

**University of Washington, CENPA,
Center for Experimental Nuclear Physics and Astrophysics**

- 10-MV FN tandem accelerator, Pelletron-charged
- World-record production of ^{6}He,^{19}Ne isotope, used for β–decay measurement in Laser-trap

Western Michigan University, Van de Graaff Tandem Accelerator

- 6.0 MV tandem accelerator
- Three ion sources: NEC RF charge exchange ion source (used primarily for He beams), NEC SINCS II negative ion source and Duoplasmatron source positive ion source
- RBS, NRA, channeling, ion irradiation
- Development and testing of the detectors for the low energy nuclear physics community

Acknowledgement

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