The ATLAS Facility at Argonne National Laboratory

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Some Historical Remarks

The Argonne Tandem Linac Accelerator System (ATLAS) is a superconducting low-energy heavy-ion accelerator [1]. Its primary purpose is to provide beams for research in nuclear structure physics. It therefore seems quite fitting that ATLAS is located in Building 203 at Argonne National Laboratory, the same building where Marie Goeppert-Mayer worked on her Nobel-prize winning contributions to the nuclear shell model.

ATLAS grew out of the nuclear physics program with the tandems purchased by the Argonne Physics Division from High Voltage Engineering Corporation in the 1960s: the EN Tandem which was installed in 1960/1961, and the present FN tandem which replaced the EN tandem in 1967. During the 1960s the tandem was primarily used with light ion beams. During that period, reaction spectroscopy at

Argonne helped lay many of the corner stones in our understanding of the structure of the nucleus. This included single-particle levels, nucleon-nucleon two body effective interactions, and other microscopic aspects of nuclear structure and dynamics. In the early 1970s light heavy-ion beams became available and a program of nuclear reactions and structure studies with heavy ions started. It soon became obvious that it would be desirable to upgrade the facility to a higher voltage, in order to allow acceleration of heavier nuclei to energies above the Coulomb barrier.

In the early 1970s development work started at Argonne on a superconducting post-accelerator [2]. The effort initially focused on niobium helix structures, but soon was redirected towards the mechanically more stable split-ring resonator [3] based on the early developments at Caltech. The superconducting res-

onator development at Argonne resulted in major advances. Since niobium metal possesses excellent superconducting properties but is a poor heat conductor, resonators were developed from explosively bonded niobium-copper composite metals, with copper providing the cooling path. Control of the high-Q resonators was achieved with a voltage controlled reactance (VCX). Adequate cooling was established with a robust liquid-helium continuous flow system. Many other innovative solutions to technical problems in superconducting RF acceleration, cryogenics, and accelerator beam optics were developed. In 1978, the first superconducting accelerator for ions was brought into operation at Argonne. The concept of independently phased resonators, made feasible through the low power levels in the high-Q superconducting cavities, provided for new aspects of accelerator design

and operation. The independent phasing allows matching sequential resonators to a broad velocity profile thus permitting flexible acceleration of a broad range of ion species. It also allowed incremental use of sections of resonators for experiments when completed. This was crucial for the ability to construct a useful post-accelerator (the 'booster') since funding was provided as R&D funds in incremental steps on a yearly basis.

Figure 1. Layout of the ATLAS Facility.

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Figure 2. Energies and intensities for various beam species at ATLAS.

Major milestones in the history of the ATLAS Facility were: the on-line operation of the first resonator and booster section for research in 1978; the completion of the booster linac with 24 splitting resonators in 1982 (at that time already about 10,000 hours of beam on target had been logged with a constantly changing (and growing) post-accelerator), completion and first acceleration of beams through the full ATLAS system in 1985; and completion of the positive ion injector PII in 1992 [4]. The last step concluded the creation of the state-of-the-art low-energy heavy ion accelerator for nuclear structure research.

The Present Facility

ATLAS now provides ion beams with energies above the Coulomb barrier for all stable isotopes and elements up to uranium, and with excellent beam quality: 100% duty cycle, small transverse and longitudinal emittances, sub-nanosecond timing, easy energy variability, and rather intense beams even for low-abundance isotopes.

stripping from the FN tandem), all ions up to uranium can be accelerated to energies well above the Coulomb barrier. Intensities and energies for various beam species are shown in Figure 2. Figure 3 illustrates the impact of the ECR ion source and PII injector linac on the distribution of ion beams used in experiments: in 1991, before this upgrade, beam species concentrated below mass 60 while two years later, with PII operational, a large fraction of beams used in experiments have mass 100 to 238.

The PII Injector

As mentioned above, completion of the positive ion injector (PII) was crucial for the creation of what is probably the state-of-the-art accelerator for low-

energy heavy-ion research. Because of the significance of PII we discuss here some relevant details (Figure 4). It consists of an electron cyclotron-resonance ion source (ECR) on a 300-kV platform coupled to a 12-MV superconducting drift-tube-type linac. This system represents the first use of an ECR source at high voltage and the first application of superconducting resonators for the acceleration of very low velocity ($\beta \geq 0.008$) ions. The injector linac is formed by an array of 18 superconducting niobium 4-gap structures that are independently phased. Four different types (sizes) of structures are needed to accelerate the heaviest particles ($q/A \approx 0.10$) from $\beta \approx 0.008$ to $\beta \geq 0.043$. These structures, of which three classes operate at an RF frequency of 48.5

The cutaway in Figure 1 shows the layout of the present facility with the two injectors (the FN tandem and the positive ion injector PII), the booster linac, and the ATLAS linac additions. The target areas house a variety of experimental equipment. This accelerator system provides an acceleration voltage of about 50 MV. With the high charge state ions from the ECR ion source (or after

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Figure 3. Distribution of ion beams at ATLAS in 1991 and 1993 (before and after completion of the positive ion injector PII)

Figure 4. Layout and resonator structures of the positive ion injector PII at ATLAS (above). Photograph of a PII resonator section (below).

M Hz, make use of technology developed for the main part of the ATLAS linac, including housings made of a composite material consisting of niobium explosively bonded to copper.

The main technical challenges for PII were (a) to bunch the very slow-moving ions from the source into pulses < 0.3 ns wide at the first accelerating structure, (b) to accelerate these ions without much degradation of beam quality, (c) to avoid loss of beam because of defocusing caused by RF acceleration at low velocity, and (d) to achieve phase control of the resonators. It turned out that all of these

problems were solvable. About 60% of the initial beam is bunched into 12.125-MHz pulses 0.3 ns wide by a 2-stage system consisting of a 4-harmonic buncher on the voltage platform ($\beta \approx 0.0015$) followed by a 24.25-MHz buncher at the entrance to the linac ($\beta \approx 0.008$). The effects of transverse defocusing are controlled in the difficult low-velocity end of the linac by a superconducting solenoid after each accelerating structure, by alternating-phase focusing in the first structure, and by velocity focusing caused by the extremely rapid increase in velocity in the first few structures. The result is $\sim 100\%$ beam transmission. Similarly, the compact geometry employed leads naturally to the preservation of longitudinal beam quality if the linac is properly tuned; indeed, the longitudinal emittance for the beam from PII is only about 20π keV-nm even for the heaviest ions, a new standard of excellence.

Superconducting RF and Linac Development

There is an ongoing program at ATLAS in basic research and development of the accelerator physics of superconducting linacs and related technologies. Much of this effort is related directly to upgrading or improving technology of ATLAS, with a continuing goal of enhancing its capabilities. This includes R&D related to the topics of superconducting accelerator structures, electron cyclotron resonance ion sources, accelerator controls, beam diagnostics, and fast timing technology.

Some of these activities are generic research in the basic technology of RF superconductivity with emphasis on low-frequency structures used for heavy-ions and low velocities. Subjects investigated include field limiting phenomena and multipacting. These investigations, along with the continued evolution of

Figure 5. Target area IV at ATLAS with the Fragment Mass Analyzer (FMA) on the left, and the ATLAS Positron Experiment (APEX) on the right.

fabrication methods, should lead to more cost-effective structures with increased performance. Some progress was made recently towards observing and controlling the Q-degradation effect from hydride formation in niobium resonator structures.

A prototype cylindrically symmetric quarter-wave coupled linac structure was constructed as part of the joint project with the Nuclear Science Centre in Delhi, India. The construction of a niobium superconducting radio-frequency quadrupole (RFQ) structure is nearing completion in collaboration with Acc Sys Technology Inc. Production of superconducting cavities for the University of Sao Paulo, Brazil, is also nearly complete. Altogether resonators of the ATLAS type have been fabricated at Argonne and provided for accelerator upgrades at Florida State University, Kansas State University, the University of Sao Paulo in Brazil, and currently the Nuclear Science Centre, India.

Detailed studies of the dynamics of the front-end of the PII linac are in progress with emphasis to possibly extending the technology to even lower velocities. This work aims toward developing an optimal solution for the front-end of an ISOL type radioactive accelerator facility.

Some effort is also directed towards improving ECR ion source performance as well as developing techniques which will apply to increasing charge states for future radioactive beam accelerators. A sputter method to generate beams from solids in an ECR ion source was developed.

Construction of an advanced ECR ion

source with a stronger magnetic field and higher operating frequency is underway in collaboration with the ECR group at LBL Berkeley, and completion of this second ECR source at ATLAS is scheduled for the spring of 1996.

The Experimental Equipment

ATLAS delivers beam to 12 beam lines and target stations which are equipped with a variety of experimental equipment (see Figures 1 and 15). In addition to general purpose beamlines and scattering chamber facilities, there are several pieces of major, in some cases unique, equipment. These include: Two Enge split-pole magnetic spectrographs. Originally built in the 1960s for experiments with light ions ($p, d, {}^3\text{He}$, etc.), these spectrometers have intrinsic properties well-matched to reaction studies with heavy ions: good resolution ($\sim 1:2000$) and solid angle ($\leq 5\text{msr}$); large momentum acceptance (60%), of importance because of heavy-ion charge-state distributions; and momentum dispersion well-matched to state-of-

Figure 6. Gamma-ray spectra for ${}^{187}\text{Tl}$ and ${}^{186}\text{Pb}$, selected by mass gates on evaporation residues analyzed by the FMA.

Figure 7. Schematic layout of FMA and its associated detector systems: a) for coincidences between gamma rays near the target and recoils, b) for delayed particle spectroscopy at the focal plane correlated with recoil implants.

the-art position detector resolution. The spectrometers are equipped with focal plane detectors for heavy ions providing good momentum resolution and excellent particle identification. One of the split-pole spectrographs is also equipped with devices for use as a gas-filled magnetic spectrometer for fusion reactions, AMS, and other applications which need very good isobar separation.

The Argonne/Notre Dame CSS/BGO gamma-ray facility: This facility consists of 12 Compton suppressed high-resolution germanium detectors and an energy-sum/multiplicity inner array, with 80% solid angle coverage, consisting of 50 hexagonal BGO

crystals. The system is used in stand-alone mode for high spin studies, in particular superdeformation, but also in recoil tagging mode in front or near the focal plane of the FMA.

The Fragment Mass Analyzer (FMA): The FMA (Figure 5) is a recoil mass spectrometer that came into operation in 1991. It consists of electric and magnetic ion optical elements that provide excellent mass resolution for heavy fragments (> 500 has been achieved for heavy nuclei) [5]. The FMA is normally positioned at 0 degrees but it can be moved out to scattering angles of 30 degrees. With its excellent properties,

including large solid-angle and momentum acceptances, the FMA is currently used in about 40% of all ATLAS experiments.

The Lepton-Spectrometer APEX (Figure 5): A large solid-angle (nearly 4π) two arm electron-positron spectrometer with solenoidal magnetic guide field and two arrays of about 200 high-resolution Si-detectors each was recently constructed by a collaboration involving 7 universities and Argonne for detection of leptons and lepton pairs in the range 150 keV to 1 MeV. In addition, this spectrometer is equipped with large solid-angle heavy ion detectors covering most of the forward hemisphere. High resolution germanium detectors can be positioned near the target to observe gamma rays.

The superconducting electron spectrometer: A large solid-angle spectrometer exists to efficiently collect conversion electrons on a high-resolution Si detector. This device can also be used successfully in measurements of β decay spectra (e.g. the 17 keV neutrino experiment).

Figure 8. Chart of nuclides near the proton drip line and the heavy proton emitters recently discovered at the FMA.

Figure 9. Schematic of the APEX electron-positron coincidence set-up at ATLAS.

The Research Program

The current research program is largely focused on aspects of nuclear structure and dynamics and on the interplay between the two. In addition, programs exist in atomic physics with highly-stripped ions, in material sciences, and in some applied research. In the following we discuss some recent examples.

Gamma-ray spectroscopy of high-spin states has been a major program over the last decade at ATLAS. The program has focused on superdeformation, in particular in the mass 190 region where its occurrence was first observed at Argonne. These studies were mostly carried out at the Argonne/Notre Dame CSS/BGO setup described above. Recently, the FMA has been employed to tag weak reaction channels in coincidence with gamma rays. Especially for heavy nuclei, fission is the dominant decay channel, and clean gamma-ray spectra from compound nucleus-like recoils are difficult to measure. Tagging with the FMA substantially cleans up the gamma-ray spectra and provides mass identification of the heavy residue. This

is illustrated in Figure 6 with the example of ^{186}Pb [6]. The very neutron-deficient Pb isotopes are of much current interest because they exhibit shape coexistence between a spherical groundstate and a deformed prolate excited configuration located very low in excitation energy. The results of this work confirm and extend a band of levels tentatively proposed earlier and provide a definitive mass assignment for the nucleus emitting the observed gamma rays. The band observed in ^{186}Pb bears a very close resemblance to the yrast band in the isotone ^{184}Hg , supporting the view that the ^{186}Pb band is built upon a prolate structure.

A broad spectrum of experiments are being performed at the FMA. Figure 7 shows the schematic layout of the detector systems

used, either for prompt gamma-ray spectroscopy in front of the FMA or for delayed, correlated particle spectroscopy after the FMA. The recent results on new spontaneous proton emitters are particularly intriguing [7]. With excellent mass resolution to identify and tag the recoiling compound nucleus (after particle evaporation), superior beam suppression (often better than 1 in 10^{12}), and large acceptances in solid angle and momentum, clean proton-decay spectra have been recorded for five new proton emitters discovered at the FMA (Figure 8), the heaviest yet observed.

APEX is an experiment to study lepton production in collisions of very heavy ions. In these collisions electrons rapidly rearrange around the di-nuclear system and for a short time experience a combined nuclear charge so large that the inner electron shells dive into the negative energy continuum. The Coulomb field has enough energy for spontaneous electron-positron production. A K-shell vacancy could be filled by a produced electron and a positron emitted.

Figure 10. Electron-positron sum energy spectra measured with APEX for the two collision systems $^{238}\text{U} + ^{181}\text{Ta}$ and $^{238}\text{U} + ^{232}\text{Th}$.

Figure 11. One- to six-neutron transfer cross sections measured for the $^{58}\text{Ni} + ^{100}\text{Mo}$ system at sub-barrier energies

Realistic calculations set a time scale for the collision that produces a broad positron spectrum hundreds of keV wide. The observation of positron lines and of sharp electron-positron pair lines at GSI was thus completely unexpected. This prompted the APEX experiment. The setup is shown schematically in Figure 9. The first results from the collision systems $^{238}\text{U} + ^{181}\text{Ta}$ and $^{238}\text{U} + ^{232}\text{Th}$ are shown in Figure 10. With cross section limits well below the values reported by GSI, no sharp electron-positron pair lines have yet been observed. [8]

The range of ion beam species at ATLAS has allowed a broad range of reaction studies. An example is shown in Figure 11. Multiple-neutron transfers were studied with the Enge split-pole spectrograph. It was suggested in the past that in grazing collisions of heavy systems the transfer of several

correlated neutron pairs could occur. However, the data for one- to six-neutron transfer all lie on an exponential curve, revealing no enhancement for 2, 4 and 6 neutron transfers over the transfer of 1, 2 and 3 neutrons. [9]

The excellent performance characteristics of ATLAS have allowed the use of the accelerator for rather unusual studies, i.e. as a very sensitive spectrometer for accelerator mass spectrometry (AMS). This requires extreme stability and reproducibility of an accelerator system and excellent beam qualities. AMS with small accelerators is now routinely used for dating and tracing of lighter radioisotopes, in particular ^{14}C . There are many possible applications for AMS involving heavier radioactive nuclei; in general, however, this requires a larger accelerator. The excellent machine characteristics have allowed the use of ATLAS for AMS. Measurements were successfully performed for a number of heavy radioisotopes, including ^{60}Fe and ^{59}Ni in meteorites

and in moon rock [10], among others. Recent applications, involving the positive ion injector PII, have concentrated on noble gases which cannot be studied at the tandems widely used in AMS. Figure 12 shows as an example measurements of ^{39}Ar [11], potentially of importance for environmental studies, to concentrations as low as 8×10^{-16} for natural samples.

A program in atomic physics takes

advantage of the highly-stripped ions at ATLAS for various spectroscopic studies: Lamb-shifts in two-electron ions, two-photon transitions, precise lifetime measurements for atomic states etc. Other studies at ATLAS are directed towards material sciences and applications: columnar pinning of high T_c superconductors for which the heavy beams at ATLAS provide maximum pinning density; wear studies with implanted radioactive ^{18}F ; breakup studies of C_{60} molecules and other fullerenes.

We discuss the latter as an example. The discovery of the highly stable and symmetric quasispherical molecule C_{60} and related fullerenes has led to intense studies on a wide variety of the properties of this newly found form of carbon that can now be produced in macroscopic quantities. Atomic collision techniques offer a powerful tool for investigating fullerene structures and dynamics and several such studies have already been reported. In the experiments at ATLAS the center-of-mass energies

Figure 12. Accelerator mass spectrometry of ^{39}Ar with ATLAS.

Figure 13. Measured mass distribution (solid points) and predictions of a bond-percolation model for multifragmentation of C_{60} molecules by 625 MeV $^{136}\text{Xe}^{35+}$.

exceeded those used in previous work by several orders of magnitude. The high values of projectile velocity and charge state result in excitation and decay processes differing significantly from those seen in

We have developed a concept for extension of ATLAS to a major ISOL type radioactive beam facility (discussed in the last section). In preparation for the research program

first experiments were carried out at ATLAS with a radioactive ^{18}F beam [23].

The $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction was studied at energies which are of interest to explosive nucleosynthesis, i.e. in the laboratory energy range around 600 keV per nucleon. Good transmission of these low-energy beams was achieved through the full

ATLAS system. The gas-filled magnet technique was used with the Enge split-pole spectrograph to achieve clean identification of the reaction products.

The results are shown in Figure 14. Cross sections were measured at three energies at an angle of $\theta_{\text{cm}} = 110 \pm 5^\circ$. The solid line corresponds to a resonance at an excitation energy of 7.066 MeV in ^{19}Ne with a total width of 40 keV, taken from the literature. The point at 660 keV represents the average of three measurements. The horizontal bars reflect the energy interval covered by the target thickness. The results are consistent with an s-wave resonance in the $^{18}\text{F}(p,\alpha)$ reaction that is likely to play an important role at energies of astrophysical interest.

Proposal for a Radioactive Beam Facility

The acceleration of beams of unstable nuclei has opened up new research frontiers. Experiments at existing accelerators, and particularly at the first generation of radioactive ion beam facilities, have convincingly demonstrated that unique new information becomes accessible. Critical cross sections for astrophysical processes that were impossible to obtain previously, qualitatively new and unexpected nuclear structure effects in nuclei far from stability, completely new approaches to studies of nuclear decays, reactions and structure, all have triggered much excitement for this new dimension in nuclear research. To explore this new dimension an extension of present technical capabilities and facilities is needed.

We have developed a proposal for a two-accelerator ISOL-type facility based on ATLAS [14] to provide intense beams of highest quality at the energies required for nuclear structure research and for reactions of astrophysical interest (Figure 15). Our base design uses a

Figure 14. Cross sections for the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction at energies of astrophysical interest.

Figure 15. Layout of the proposed ISOL-type radioactive beam facility based on ATLAS.

flexible approach for the primary accelerator and builds on the availability of the state-of-the-art heavy-ion accelerator ATLAS as the post accelerator. This is particularly important in view of the stringent beam quality requirements for nuclear structure and astrophysics experiments.

The core idea of our concept is the use of about 0.1 pA of 100 MeV neutrons from the breakup of 0.5 pA of 200-MeV deuterons [15]. Spatial separation between the breakup target and the radioisotope production target solves some of the ion source problems encountered at high beam powers with charged-particle beams that undergo predominantly electronic (heat and radiation damage generating) energy loss. The purely nuclear energy loss and the long range of neutrons allow rather large target thicknesses to be used for more effective isotope production. To retain flexibility for

optimizing secondary production yields by using a variety of radionuclide production mechanisms, the choice for the primary accelerator is a 215 MV linear accelerator which can deliver a range of ions at a beam power of 100 kW (beam currents of 1 pA for protons, 0.5 pA for deuterons, 0.25 pA for alphas, 0.08 pA for ^{12}C , and 0.06 pA of ^{18}O). Figure 16 shows predicted production yields in thick targets per particle μC (or production yields per second for beams of 1 pA). These yields need to be multiplied with the beam intensities ($\sim$ factor 100 for the neutron 'beam') and the ion source extraction efficiency (based on results

from ISOLDE). This leads to predicted radioactive beam currents on target of, for example, 9.6×10^9 ^{132}Sn with a uranium production target.

The predicted production yields for energetic neutrons in uranium have recently been verified in an experiment [16] with 200 MeV deuterons at the MSU National Superconducting Cyclotron

Laboratory (Figure 17). Ion source configurations for the proposed facility are based on the concepts and extensive experiences gained at ISOL-type facilities (in particular at ISOLDE at CERN). In addition, the facility includes a high-resolution isobaric-mass separator, followed by a new low q/m ,

Cs Isotope production

Figure 16. Production-yield predictions (per μC) for various primary beams of an ISOL-type radioactive beam facility.

Figure 17. Setup and gamma-ray spectra measured for a determination of ^{132}Sn production with 200-MeV deuterons incident on a uranium target.

low velocity accelerator section, 90% of which is directly based on existing ATLAS superconducting technology. The beams are then either used directly after the ion source (for research with ion traps), after low-energy acceleration up to ~ 1 MeV/u (for experiments in nuclear astrophysics), or injected into the existing ATLAS facility for acceleration to energies above the Coulomb barrier (for studying nuclear reactions and structure).

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