Equipment Initiatives at ATLAS

Birger B. Back

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HELIOS

Description: The Helical Orbit Spectrometer (HELIOS) is a novel spectrometer that will enable us to carry out detailed nuclear structure studies via inverse kinematics reactions using re-accelerated, neutron-rich beams from the new CARIBU injector as well as radioactive beams produced by the in-flight method at ATLAS. The spectrometer design has several advantages over conventional techniques using large-area Si detectors. These are: 1) avoidance of kinematical compression of states, 2) simple particle identification without ΔE measurements and the associated detection thresholds, 3) large acceptance achieved with relatively few Si detector channels. The superior performance of HELIOS was demonstrated in August 2008 using the d(^{28}Si,p)^{29}Si reaction to study excited states in ^{29}Si. A Q-value resolution of ~75 keV was achieved (without planned cooling of Si detectors), about 4 times better than can be achieved in conventional Si detector arrangements.

Physics justification: The main focus of the HELIOS research program is the study of light-ion transfer and inelastic reactions using radioactive beams from the ATLAS in-flight facility and neutron-rich CARIBU beams. Such studies will provide detailed information on the single-particle/hole strength, pair-correlations and inelastic excitations in exotic nuclei that are accessible only as radioactive beams. Such detailed studies were used extensively for nuclei near the line of stability to develop and refine theories on nuclear single particle structure. The prospect of extending such studies to very neutron-rich nuclei provided by CARIBU holds promise for extending the validity of such theories into this region, which is also a crucial interest for the stellar processes including the r-process. This research addresses Nuclear Structure milestones NS3, NS9 and Nuclear Astrophysics milestones NA4, NA5 and NA6, NA9 and NA10.

Funding justification: This demonstration version of the HELIOS uses only a rather rudimentary Si-detector array at backward angles that is comprised of 24 position-sensitive Si detectors that were salvaged from another project. Although this array was adequate for validating the potential of the spectrometer, it will not allow for full utilization of the spectrometer concept. Two arrays of custom-designed Si detectors are needed – one mounted at backward angles increasing the azimuthal angle coverage from ~π to ~2π, and another, more complex array for the forward angles, which will allow for the coincident detection of heavy recoils. It is anticipated that this technique will be a central component of the study of exotic nuclei at FRIB. It is therefore of central importance that this technique be developed and refined before the FRIB facility is realized.

Helios is a collaborative effort between scientists at Western Michigan University, the University of Manchester and Argonne National Laboratory.

X-Array

Description: This is a γ-ray array optimized for radioactive decay studies, where high efficiency and good energy resolution are paramount. The system consists of large, closely-packed, unshielded, HpGe clover detectors integrated into a self-contained mobile unit that can conveniently be utilized at various locations at ATLAS, *e.g.* the FMA focal plane, the Beta Paul Ion Trap (BPT), and at a planned CARIBU tape transport station on the Low Energy Beam Line (LEBT). It will be self contained, with its own electronics and LN_2 autofill system. The addition of a set of BaF_2 scintillators for Compton suppression and total-energy calorimetry, and a plastic scintillator box for β detection are planned upgrades to widen the scope of science opportunities.

Physics justification: Spectroscopy following the decay of nuclear ground states and isomers remains a key to understanding nuclear structure far from stability. Fast and clean separation of the nuclides of interest, and very efficient experiments, have allowed decay spectroscopy to be pushed beyond the proton dripline, and into the heaviest nuclei. This has had major impact on our understanding of the limits of stability. Isotopes produced at the 10's nb level have now been studied. In future, with the CARIBU upgrade, exploration of very neutron-rich species will be pursued. For all these exotic decay experiments, the X-Array offers an excellent and flexible solution with photopeak efficiency for low energy radiation as high as 70%. Studies will provide fundamental information about the decay properties, like branching ratios, half-lives, angular correlations, *etc.*, which are valuable to further test and refine nuclear theories and extend their reach into the neutron-rich region. This research addresses Nuclear Structure milestones NS3, NS8, NS9 and NA6

Funding Justification: The X-array has been built up over several years and consists now of four large HpGe clover detectors mounted in an integrated frame together with the associated read-out electronics, bias supplies *etc.* The remaining funding will allow for the completion of this system, the main component being the addition of a fifth HpGe "Superclover" detector, such that five of the six faces of a cube will be covered. When used at the FMA with large silicon DSSDs the zero degree position has special significance, so a larger detector is optimum. The addition of existing BaF_2 detectors and a plastic scintillator box will allow for calorimety of the decay (Total Absorption Calorimetry), some Compton Suppression, and efficient coincident detection of the β-decay branches. These improvements are valuable for decay studies of the most exotic, and interesting nuclei produced at ATLAS, which are invariably only in low cross-section channels. The improvements also open R&D paths for a "Super Decay Station (SDS) for FRIB in the future. This will consist of a full box of "SuperClovers" will triggerless operation and full digital readout to preserve time correlations.

Relocating CPT to CARIBU

Description: The Canadian Penning Trap (CPT) mass spectrometer is a high precision ($\Delta m/m \sim 10^{-7}$-10^{-9}) instrument for measuring nuclear masses. It has been used extensively for mass measurements on species produced either by heavy-ion fusion reaction at ATLAS or from fission decays of ^{252}Cf in the form of a 100µCi source. This instrument is presently located in the triangle room next to the Area II production station, but it is planned to be re-located to the CARIBU low-energy beam line to take advantage of the unique opportunities available there to extend the measurements on neutron-rich isotopes far into the unknown neutron-rich region. This project encompasses the site preparation at CARIBU as well as the partial dismantling and re-assembly associated with the move itself.

Physics justification: Precise mass measurements of very neutron-rich nuclei approaching or on the *r-process* path are of central importance for understanding the synthesis of heavy nuclei, to which this reaction path is believed to be a strong contributor. As a basic property of nuclei, the mass plays a central role in determining the path of the *r-process* and the decay properties of exotic nuclei. The move of the world-class CPT setup to CARIBU allows for precise measurements of the mass of a large number of very neutron-rich nuclei, for which this property is either completely unknown experimentally or measured with inadequate precision by other methods. The physics pay-off of this project is very significant: the measurements that it will enable will yield the largest bounty of nuclear mass information in the neutron-rich region until FRIB comes on-line. This research addresses Nuclear Structure milestones NS3, NS9 and Nuclear Astrophysics milestone NA6, NA9

Funding justification: The project involves, in addition to site preparation and the actual move of the CPT, funding to build an RFQ cooler needed to capture and accumulate the mass separated CARIBU beams coming at 50 kV, cool the ions and bring them to ground potential so that they can be injected into the CPT tower for precise mass measurement.

Tape Station at CARIBU

Description: A modern, fast tape station system will be required to fully utilize the unique possibilities for fundamental nuclear structure studies, astrophysics, and reactor related applications that will be carried out at the CARIBU low-energy beam line. This system will be a compact design that can also be used at other experimental locations in the facility. For most flexible use, the design parameters call for very fast (<100ms) advancement of the tape from the collection point to the detection station, which will be designed to be compatible with β,γ detection of decay products using the X-array. This fast, advanced, system will also be ideal for studying the shorter-lived activities that will be produced at FRIB, and at ATLAS as one seeks short-lived nuclear isomers in the neutron-rich regime.

Physics justification: Unique opportunities arise for studies of ground-state decay properties and spectroscopy of the low-lying states in very neutron-rich, mass separated beams that will be available in the low-energy area of CARIBU. The use of a fast-acting tape station in this location is important for the removal of the longer-living products in order to reach the most interesting and least abundant neutron-rich isotopes produced at CARIBU. The control system for the tape advancement will be computer controlled in order to achieve maximum flexibility and possible integration with the data acquisition system. This fast tape system will complement a more conventional slow (>1s) tape transport system which will be the work-horse for "Advanced Fuel Cycle" research on longer-lived isotopes which was recently funded by an ANL/LDRD. This research addresses Nuclear Structure milestones NS3, NS9, and Nuclear Astrophysics milestones NA6 and NA9

Funding justification: The requested funding is required for the design, fabrication and integration of the fast tape station including vacuum systems, fast acting motors for tape advancement, control systems, as well as the integration of these components into a compact mobile system.

Laser Laboratory at CARIBU

Description: We propose to setup a laser spectroscopy apparatus at the CARIBU low-energy beam line for the study of nuclear ground state properties of neutron-rich fission isotopes. This work will initially concentrate on a compact setup for laser spectroscopy of selected short-lived species confined in an ion trap and is envisioned in the future to include a setup for collinear laser spectroscopy. This work will take full advantage of the high resolution mass spectrometer and RFQ cooler and buncher located on the CARIBU high voltage platform and a stable beam ion source off the platform. It will include design studies and off-line experiments to optimize ion trap performance and the setup of a respective laser system.

Physics justification: The CARIBU upgrade at ATLAS will provide a source for neutron-rich fission isotopes independent of their chemical properties. In particular, short lived isotopes of certain refractory elements will be accessible for the first time. The proposed laser spectroscopic setup would provide precision measurements of ground state properties like spin, moments and charge radii of these isotopes. Some regions of interest accessible with CARIBU beams lie in the strongly deformed isotopes beyond N = 60 around yttrium and zirconium, in the very neutron-rich barium isotopes and around the double magic ^{132}Sn. For this work, a novel ion trap system in combination with buffer gas cooling will be developed with sufficient sensitivity and spectroscopic resolution to cope with isotopic yields down to a few ions per second. This capability is important to take full advantage of the rare isotope beams at CARIBU and – in the future – of low energy beams delivered at FRIB. This research addresses Nuclear Structure milestones NS3 and NS9.

Funding justification: The requested funding includes initial development work for the ion trap and laser system as well as the fabrication of the low energy ion beam-line and trap system including instrumentation and vacuum components. Major funding in FY2010 will be required to purchase a versatile laser system consisting of a tunable continuous-wave titanium-sapphire laser, a solid state pump laser and a frequency doubling unit for a wide coverage of the visible wavelength range. In addition, funding is requested for laser infrastructure and its installation at ATLAS as well as auxiliary diode lasers systems, optical components, photon detectors and general instrumentation.

Digital Gammasphere

Description: Gammasphere is the premier γ-spectroscopy instrument in the world, but it is using 1980ies vintage read-out electronics based on analog signal readout at a fixed shaping time of 10 μs, which severely limits the data taking rate of the device to about 10kHz. The proposed upgrade, which will be implemented in two phases to minimize the disruptions to the Gammasphere research, will incorporate a modern, flexible digital read-out and triggering system that will increase the data taking rate to over 50kHz to allow for the study of species produced with small cross sections embedded in large backgrounds.

Physics justification: As the frontier of nuclear structure physics is shifting towards the study of exotic nuclei that can be produced only at low rates and often along with strong background reactions, upgraded instrumentation that is able to deal with these challenges is needed. A specific example is the study of the structure of nuclei near the doubly magic ^{100}Sn, which is produced in heavy ion fusion *xn* reactions in the face of strong competition from charged particle (proton and alpha) emission. Also the study of heavy nuclei is faced with a large background of fission fragments, the γ-emission from which limits the rate at which the weakly populated evaporation residues can be studied. The combination of the Gammasphere and the Fragment Mass Analyzer is quite unique and powerful for studying the structure of exotic nuclei and the proposed upgrade will enable a substantial increase in the range of nuclei for which these studies can be carried out. This research addresses Nuclear Structure milestones NS3, NS8, and NS9. Gammasphere has also been contributing to nuclear astrophysics studies and is anticipated to contribute to milestones NA6, NA9 and NA10.

Funding justification: The proposed upgrade is separated into two phases. Phase I will be implemented in FY2009 and FY2010 and includes a digitized readout of the 110 HPGe detectors implemented in parallel with the analog system. Eleven 11 ten-channel GRETINA digitizers will be used and a VME readout of these modules will be implemented. Phase II includes the replacement of the VXI analog electronics with VME-based digitizers for all detectors. One GRETINA digitizer can handle one Gammasphere detector module which consists of 1 Ge central contact, 2 Ge outer contacts, and 7 BGO signals. All signal processing leading to energy and time outputs as well as the Compton suppression will be done in the FPGA. Signals corresponding to clean Ge and modular hit will be sent to the main trigger module to generate clean and modular multiplicities used for trigger decisions. To implement this option, an additional 100 digitizer modules are needed. Additional funds are needed to develop the new FPGA-based trigger system and the data acquisition system.

FMA Upgrades

Description: The Fragment Mass Analyzer is a workhorse in the ATLAS experimental program, which needs several upgrades in order to allow the most difficult, but most interesting, experiments to proceed. These upgrades are: 1) A modification to the first electric dipole tank is planned to allow the beam to be stopped outside the tank – away from the anode. In the present setup the beam stop is inside the tank just behind the first anode. This causes problems with current loading of the anode by back-scattered electrons and limits the beam intensity in some experiments using high beam currents. 2) In experiments with high recoil rates at the FMA focal plane, a channel plate detector capable of accommodating recoil rates in excess of 100 kHz is used. The present detector has limited coverage and its position resolution does not match the FMA mass dispersion. A replacement with a bigger detector equipped with magnets to guide electrons for better image quality is planned. 3) The first quadrupole doublet is a bottleneck in the system. Its replacement with a new doublet with a shorter and smaller diameter first quadrupole with higher tip field, and the second quadrupole with 50% larger diameter and length will enhance the angular acceptance of the device by more than 50%. The new quadrupole doublet will also allow GAMASPHERE to be placed closer to the FMA with increased solid angle for in-beam experiments. 4) Finally, digital electronics for the DSSD system is required to allow studies of fast activities and reduce the decay background from overlapping implant events. Combined with a trigger-less data acquisition system, the dead time at high implantation rates will be significantly reduced.

Physics justification: The FMA equipped with the new beam dump will be able to handle symmetric reactions up to 100 pnA which will be the upper limit for the digital GAMMASPHERE. This will allow for studies of core excited states in ^{101}Sn or excited states in ^{100}Sn. The new quadrupole will improve the FMA transmission depending on the specific reaction used. For example, when a target is placed at the nominal 30 cm distance from the FMA, the efficiency will be increased by a factor of about 2 for ^{58}Ni+^{58}Ni type symmetric reactions followed by α evaporation. Significant gains are also expected for reactions with light beams and heavy targets such as ^{208}Pb(^{20}Ne,4n)^{224}U, where high-Z slow recoils suffer straggling in the target, and for transfer reactions with light beams in inverse kinematics. Digital electronics will allow disentangling pileup events in the DSSD. This will facilitate detection of fast proton or alpha decays (such as the isomeric states in ^{256}Rf) or fast sequences of alpha decays (such as the ^{108}Xe-^{104}Te-^{100}Sn alpha decay chain). Also, digital electronics will decrease the decay background due to pileup implant events which is the limiting factor in studies of beta-delayed proton emitters such as ^{100}In (neutron-proton interactions near ^{100}Sn) or ^{99}In (proton single-particle states at ^{100}Sn). Taken together, these upgrades are all aimed at being able to study exotic nuclei that are produced only with small cross sections. This research addresses Nuclear Structure milestones NS3, NS8, and NS9 as well as nuclear astrophysics milestones NA4, NA9 and NA10.

Funding justification: The external beam-dump upgrade is a rather simple mechanical project that involves modifying the vacuum tank. The fast focal-plane detector upgrade involves an updated design of system using magnetic guide fields and larger channel plates. The new first quadrupole doublet will be designed and build in collaboration with commercial vendors, although the basic design specifications have already been worked out. Digital electronics required for the DSSD readout will be based on the Gretina digitizer modules and a trigger-less DAQ adapted for this application.

Gas-filled Spectrometer

Description: The Fragment Mass Analyzer, which was taken into operation about 16 years ago, has proven to be an exceptionally versatile and productive instrument for both nuclear reaction and structure studies. The excellent mass resolution of the instrument is, however, achieved by sacrificing some acceptance, which sets limits on how small a cross section can be measured. Especially in experiments where the selectivity is augmented by ancillary detectors operated in coincidence, prompt or delayed, a larger acceptance would in many cases be desirable and allow for the exploration of new regions of interesting physics. In order to be able to explore these physics opportunities, we propose to start designing a new large acceptance spectrometer, probably of the gas-filled variety. The aim of the design will be to optimize the angular acceptance to a level where fusion products, which have undergone charged particle emission, will be efficiently transported to the focal plane. The spectrometer will also be designed such as to take optimal advantage of the many detectors that are presently being employed at the FMA, including Gammasphere, Chico, etc.

Physics justification: The main physics justification for a large acceptance spectrometer is its synergy with existing and planned instrumentation (*e.g.* Gammasphere, X-array, *etc.*) and beam-intensity upgrades at ATLAS. One example is the study of the single-particle structure of heavy actinide nuclei, for which the production cross sections are very small. There is much interest in the nuclear structure of the heaviest elements and to explore nuclear spectroscopy at the limits of Z and A. Other laboratories (GSI, RIKEN, Dubna) are engaged in the discovery of new heavy elements and isotopes. The Argonne program is complementing this research by concentrating on the underlying single particle structure that gives rise to the stability of the super-heavy nuclei. This and numerous other areas of physics would benefit greatly from a spectrometer with larger acceptance operated in conjunction with the excellent γ-ray detection of Gammasphere.

Funding justification: We propose to start exploring various designs of a new high-acceptance spectrometer in FY2009/FY2010 with the aim of starting the construction in FY2011. A main cost component is clearly the magnet and power-supply. Here we will explore the possibility of acquiring a surplus, but suitable, magnet from other laboratories. However, even if this endeavor is successful, funding is needed for vacuum chambers, pumping, target station, focal plane detectors, read-out electronics and data acquisition.

<u>Gretina at ATLAS</u>

Background: The GRETINA/GRETA Physics Working Group workshop entitled "Optimizing GRETINA Science: A workshop dedicated to planning the first rounds of operation" was held at University of Richmond, October 14-15, 2007. The discussions centered on how to best optimize the discovery potential and physics impact of GRETINA with unstable and stable beams upon the expected completion in early CY2011. The prospective host institutions presented the physics justification for temporarily hosting the device by emphasizing the uniqueness and impact of research at each institution. At the workshop, the user community reached unanimous agreement that the following sequence is optimal for the utilization of Gretina. The assembly, testing and commissioning will be carried out at LBNL followed by campaigns at MSU, ORNL, and Argonne. The scientific case for bringing Gretina to Argonne was presented at the workshop and accepted by the user community as reflected in the recommended rotation sequence. This physics justification is re-iterated below, and it continues to be valid in our view.

Physics justification: The justification for Gretina at ATLAS is a little different from that of the other laboratories, in that Argonne already is the host for the National Gamma Facility, Gammasphere, so a major relative gain in science reach needs to be demonstrated. The most clear-cut case for such a gain is in the spectroscopy of very heavy nuclei. Here, the Gammasphere community has led the world into a new field and caused a paradigm shift in understanding the shell-stabilization of the very heaviest systems. The Argonne Fragment Mass Analyzer (FMA) has been crucial for selecting exotic superheavy nuclei and triggering Gammasphere in order to suppress the radiation from the dominant reaction process, fission. However, Gammasphere@FMA has severe limitations:

- Gammasphere is physically large, and requires that the FMA be operated at 900 mm from the target position, instead of the optimum 300 mm position. This causes a loss of recoil-gamma coincidences of a factor of 2-3 for very heavy nuclei, and >10 for light systems. Gretina can fit in the "upstream" hemisphere, allowing the FMA to be operated most efficiently.

- Gammasphere has conventional analog signal processing, which is optimized for good energy resolution, but is count-rate limited to ~10 kHz/counter. Gretina has digital electronics, and can be optimized for fast counting, beyond 50 kHz, with only modest loss of resolution.

- Gammasphere is a 4-π counter, so some downstream counters are near the beam-dump, causing further count rate limitation, often by more than a factor of 2. Gretina is compact and can be shielded from the beamdump.

- Heavy element production involves intense beams, with Gretina probably up to 100pnA. This requires operation of a large target wheel to dissipate the beam heating. With Gretina there is space for a large wheel, with Gammasphere, only a small wheel can be used.

Thus, altogether, a factor of 30-50 in efficiency for recoil-gamma experiments on heavy elements can be gained. This corresponds to compressing a week experiment into a couple of hours. Compared to the RMS setup at the Holifield facility at ORNL, ATLAS can deliver reliable beams of >100 pnA of heavy ions and an established target wheel technology for using them. Compared to the BGS at the 88” cyclotron facility, the FMA accepts only the two most intense charge states at a cost of up to a factor of ~5 in efficiency, but a gain in cleanliness is realized as the data are mass-selected, such that there is no ambiguity in the origin of newly observed gamma rays (priceless). Many of these issues also apply to other physics opportunities. We are well positioned to study the ^{100}Sn region, where most of the gains mentioned above can also be realized. The near symmetric reactions required to reach the ^{100}Sn cannot be pursued with a gas-filled separator, due to excessive reactions in the gas.

There are also some gains with Gretina to be exploited in Coulomb Excitation of CARIBU beams (superior Doppler corrections), and in deep-inelastic spectroscopy of neutron-rich nuclei. CARIBU provides access to regions of the nuclear chart that remain unique until FRIB beams become available, For example, spectroscopy of neutron-rich nuclei in the Zr - Pd region will explore collective excitations, possibly associated with triaxiality. The impact of octupole correlations will be investigated in the Kr and Ba regions. Spectroscopy following deep inelastic reactions has become an important component of the ATLAS program providing access to the structure of neutron-rich nuclei at medium spin. Here, it is the high count rate capability and the Doppler reconstruction that provide opportunities to reach reactions with smaller cross sections, i.e., offer the means to reach more neutron-rich species.