# Summary of the
# April 8 ATLAS Users Workshop

In developing the Strategic Plan for ATLAS four main scientific goals were identified. These are: (a) understanding the stability and structure of nuclei as many-body systems built of protons and neutrons bound by the strong force, (b) exploring the origin of the chemical elements and their role in shaping the reactions that occur in the cataclysmic events of the cosmos, (c) understanding the dynamics governing interactions between nuclei at energies in the vicinity of the Coulomb barrier, and (d) testing with high accuracy the fundamental symmetries of nature by taking advantage of nuclei with specific properties.

These goals led in turn to four major research topics. These summarize a number of important contemporary physics issues identified and prioritized, most recently in a Users workshop held in April 2006.

It is the purpose of the present document to (1) briefly present the science supporting the four research topics, to (2) show their relation to the objectives of the nuclear science community at large, as expressed in the 2002 Long Range Plan and the Office of Science 2004 Strategic Plan, by mapping them onto the DOE-OMB Performance Measures, and to (3) show how they translate in the priorities expressed in the Strategic Plan for ATLAS.

**A. <u>The Science Supporting the Four Research Topics:</u>**

<u>Topic 1</u>: the development of beams of short-lived isotopes and their subsequent use for measurements of astrophysics interest and for nuclear structure and reaction studies.

A large number of the nuclear reactions responsible for nucleo-synthesis involve radioactive nuclei. Among the main processes to be investigated at ATLAS figure the CNO cycle, the reactions responsible for the break-out of the CNO cycle into the rp-process, reactions strengths along the rp-process path, as well as some key reactions in the s- and r-processes. Major efforts will concentrate on high-precision data for the $^{12}C(\alpha,\gamma)^{16}O$ reaction, on the determination of cross sections at stellar energies responsible for the break-out of the hot CNO cycle and for the first stages of the rp-process (such as those producing and destroying F, Ne, Na, Mg, Al and Si nuclei), on the competition between $(\alpha,p)$ and $(p,\gamma)$ reactions for the break-out of the CNO cycle and along the rp-process path and on measurements of s-process reactions above the iron peak by using (d,p) reactions to infer $(n,\gamma)$ yields. The latter technique will also be instrumental in quantifying $(n,\gamma)$ rates for important nuclei close to the r-process path such as $^{84}Ge$ or $^{138}Te$ once they become accessible with CARIBU.

At ATLAS, the single nucleon transfer reactions (d,p), ($\alpha$,$^3$He), ($^3$He,d) and pick-up reactions (d,t) and (d,$^3$He) in inverse kinematics offer the opportunity to determine single particle strengths in an optimal way since they can be carried out in the energy regime of 8-12 MeV/A, where the velocities of nucleons in the target and the projectile are well matched and reaction theories are well calibrated. In the short term, a main focus of research at ATLAS will be the testing of ab-initio calculations (Greene's function Monte Carlo and/or no-core shell model) and shell model calculations with effective interactions in neutron-rich, light nuclei ($^{6,7}$He, $^8$Li, $^{13}$B,..). With the advent of CARIBU, the research program will shift towards the delineation of single-particle strengths in the direct vicinity of doubly-magic, neutron-rich $^{132}$Sn. Predicted changes in shell structure will be probed in other neutron-rich nuclei as well such as in the Sr-Zr region where, for example, the melting of the Z=40 and N=64 sub-shell closures can be quantified. Possible changes in the pairing strength in neutron-rich nuclei will be studied with two-particle transfer ((p,t), and (t,p)) reactions in inverse kinematics. In addition, with the ($^3$He,p) reaction, the possible presence of a new form of pairing in the neutron-proton channel (S=1, T=0) can be explored in N=Z nuclei such as $^{44}$Ti, $^{48}$Cr and $^{56}$Ni.

The availability of exotic nuclei from CARIBU also impacts the study of reaction dynamics in the vicinity of the Coulomb barrier. There is great interest in the formation of the heaviest nuclei and the possible roles deformation, shell structure and diffuseness may have. Another point of emphasis is the proton-neutron asymmetry dependence of the surface and volume terms in the Fermi gas expressions of the level density.

Topic 2: the production and characterization of nuclear structure away from the valley of stability including nuclei at the very limits of stability, i.e.; nuclei at and beyond the proton drip-line, on the neutron-rich side of the valley of stability, and in the region with Z > 100.

While the exact location of the proton drip line has essentially been established experimentally from tin up to bismuth, a number of important physics issues continue to require attention such as the impact of deformation – and especially triaxiality – on the properties of proton radioactivity, the delineation of shell structure at the drip line, and the impact of weak binding on high-spin properties such as alignment gains and crossing frequencies. Of special interest also are the nuclei with the same number of protons and neutrons for which tin (Z=50) forms the approximate upper boundary of the region where such nuclei lie inside the proton drip line. With stable beams and present day experimental techniques, the study of $^{100}$Sn, is within reach, hereby providing, together with investigations of its direct neighbors, a new important benchmark for shell structure. As already mentioned above, since protons and neutrons in N=Z nuclei can occupy the same orbitals, special symmetries may play a significant role and a unique new type of proton-neutron pairing interaction (S=1, T=0), i.e., a new type of superconducting phase, can be present. Search for manifestations of this type of pairing field in the properties of N=Z nuclei is a matter of considerable theoretical debate to which, in addition to the pair transfer reactions discussed above, experiments exploring the low- and high-spin properties of N=Z nuclei will contribute. Finally, it is also in mirror nuclei near the proton drip line that the role of isospin breaking interactions can be quantified.

The physics of the heaviest elements (Z > 100) is that of the delicate balance between the large Coulomb repulsion and the nuclear interaction which gives rises to characteristic shell energies. The gaps in the single-particle spectrum yield a stabilizing shell-correction energy which creates a fission barrier where none would otherwise exist. Rather than focusing on the synthesis of new elements, the experimental program at ATLAS will contribute to the investigation of the properties of heavy nuclei by establishing the nature of the states located at the Fermi surface in 100<Z<110 nuclei (these are the states which dictate the size of the fission barrier), the overall nuclear shape and the magnitude of the shell gaps, and by documenting structural evolution with excitation energy and angular momentum. They are best studied by (1) investigating the level structure of odd-A nuclei, (2) identifying isomers and studying their decay pathways, (3) delineating alignments and crossing frequencies along the yrast lines of the even nuclei, and (4) providing information on fission barrier from calorimetry measurements (a technique pioneered with Gammasphere at ATLAS).

The properties of neutron-rich nuclei remain largely unexplored, but represent an ever increasing focus of nuclear structure research. This is the domain where new shell structure is anticipated, decoupling between neutron and proton motions may occur, weak binding leads to neutron halos and, possibly, skins and new types of collectivity are proposed. Research at ATLAS will increasingly contribute in this area by continuing to exploit deep inelastic reactions and fission as sources of the neutron-rich nuclei for which detailed spectroscopy can be obtained. Coulomb excitation of long-lived radioactive targets and fusion-evaporation reactions with the most neutron-rich beams ($^{36}$S, $^{48}$Ca, $^{64}$Ni) on long-lived radioactive targets ($^{14}$C, for example) represent another important venue in the exploration of this new territory. With the development of the CARIBU project, however, new opportunities to penetrate barely explored regions of neutron-rich nuclei will arise. Besides the studies of single-particle strengths already identified under topic 1 above, and the opportunities for research with stopped beams addressed under topic 4 below, reaccelerated neutron-rich beams from CARIBU will be ideally suited for multi-Coulomb excitation experiments and measurements of magnetic moments with hyperfine fields. This will enable searches for experimental signatures of modified pairing in neutron-rich matter, collective excitations of protons versus neutrons, modifications in shell structures, new nuclear shapes etc.

<u>Topic 3</u>: the study of the nature of nuclear excitations as a function of mass, proton or neutron excess, spin and temperature: characteristics such as nuclear shapes, the interplay between degrees of freedom, and changes in shell structure;

There is substantial overlap between this topic and the issues addressed under topic 2. However, it is important to emphasize that stressing nuclei by rotation continues to provide stringent tests of our understanding and modeling of nuclear properties. Rotation reveals the microscopic structure and limits to collective motion. In recent years, new collective modes (wobbling and chirality) have been uncovered which have been associated with triaxial shapes. However, these modes are far from ubiquitous. Understanding which nuclei exhibit them, and in what spin range(s) they occur remain open questions. The often subtle interplay of aligned single-particle angular momentum and collective motion appears to persist to the very highest spins, in fact beyond the angular momentum range where collectivity is predicted to terminate. This behavior is at present not understood. Hints of structures associated with extreme elongation continue to emerge, though direct evidence for nuclear hyperdeformation remains elusive. At high excitation energy, in the continuum beyond the regime of discrete bands, significant progress has been made in understanding the nature of collectivity, the mixing between states and the onset of a chaotic regime, but a quantitative understanding awaits further experiments exploiting recently developed techniques.

Topic 4: the use of traps for high precision mass measurements for astrophysics and for searches of physics beyond the standard description of the weak interaction.

The mass is a fundamental property of every nucleus, a first finger print of its quantal nature. Hence, high accuracy measurements of this quantity provide a direct means to highlight regions of the nuclear chart where unexpected shell effects, new correlations or new deformations can occur. Moreover, such measurements represent an essential input for the delineation of astrophysical processes (rp- and r-process) and for the study of fundamental interactions.

High precision mass determination with traps, following fusion-evaporation reactions with high intensity beams from ATLAS, provide direct input to the astrophysical rp-process by contributing to both the identification of waiting point nuclei and the delineation of the process path from the iron peak to the end point of the process in the A~100 region. High intensity ATLAS beams also provide the opportunity to carry out high-precision mass determinations for very heavy nuclei, a complement to the structure studies of Z>100 nuclei discussed under topic 2. The availability of the neutron-rich beams from CARIBU opens up the opportunity to measure masses of nuclei close to the r-process path, and will provide first indications of possible effects due to weak binding. Furthermore, Penning traps also represent the ultimate performance in terms of isotopic separation. Hence, beta decay studies of neutron-rich, trap-selected isotopes will reach nuclei whose properties are important from both the nuclear structure and nucleo-synthesis points of view. Finally, the availability of unique beams from CARIBU provides another opportunity to explore the ground state properties of neutron-rich nuclei that had not been considered earlier: by collinear laser spectroscopy, spins, nuclear moments and charge radii will be determined.

Superallowed $0^+ \rightarrow 0^+$ decays, with their inherent simplicity, are an invaluable probe of possible extensions of the electroweak sector of the standard model. Q values of such decays, from high precision mass measurements, are required to determine the value of $G_V$, the weak vector coupling constant with high precision. This quantity in turn is essential input to tests of the conserved vector current (CVC) hypothesis and the unitarity of the first row of the Cabibbo-Kobayashi-Maskawa (CKM) matrix to which it contributes the up-down quark mixing matrix element $V_{ud}$. A number of important new cases have been identified. They address issues related to the reliability of earlier mass measurements with other techniques and to new checks of a number of corrections of nuclear structure origin to the nuclear matrix element for these Fermi transitions. Furthermore, traps provide the ideal environment to improve one order of magnitude or more searches for possible scalar, tensor and right-handed components to electro-weak interactions from the measurement of beta-neutrino correlations.

## B. Relation to the DOE-OMB Performance Measures:

The topics of research at ATLAS outlined above are in line with the priorities of the nuclear physics community and of the DOE's Office of Science as expressed in their most recent plans. This is shown here by confronting them with the DOE-OMB performance measures.

*(1) Nuclear Structure & Reactions milestones*:

The 2006 milestone on changes in shell structure and collective modes as a function of neutron and proton number from the proton drip line to moderately neutron-rich nuclei is discussed primarily under topics 2 (structure at the proton drip line and ATLAS reach for neutron–rich nuclei) and 3 (structure as investigated through high spin excitations).

The 2007 milestone on the properties of the heaviest elements above Z ~ 100 is addressed squarely by a dedicated paragraph under topic 2 describing the four prong approach to be used at ATLAS (level structure of odd-A nuclei, isomers studies, structure evolution with frequency and fission barriers from calorimetry).

Contributions by the ATLAS research program toward the 2009 milestone on spectroscopic information of crucial doubly-magic nuclei far from stability will be coming from the studies of neutron-rich nuclei with CARIBU described in topics 1 (single particle strength in the vicinity of $^{132}$Sn), 2 (structure of neutron-rich nuclei) and 4 (high precision mass measurements).

Research at ATLAS is unlikely to contribute to the second 2009 milestone on the determination of the neutron drip line up to Z=11. This milestone is likely to require the production of the exotic beams of interest through fragmentation, a process requiring beam energies outside the facility's energy range.

The 2010 milestone on the completion of GRETINA is outside the range of the ATLAS strategic plan. Nevertheless, it should be noted that the scientific issues described in topics 2 and 3 match with the sensitive studies of structural evolution and collective modes mentioned in this milestone. Thus, the ATLAS research program could contribute to the 2010 milestone, if the instrument was to be based at the facility within the appropriate time frame.

The 2013 milestone on microscopic calculations, density functionals, many-body symmetries, collective modes and effective forces is primarily theoretical in nature. However, it is clear that the ATLAS research program as expressed in topics 1 (single particle strength and studies of pairing), 2 (shell structure at the proton drip line, in the heaviest elements and in neutron-rich nuclei), 3 (nuclear response under the stress of collective excitation) and 4 (ground state properties through trap measurements and collinear laser spectroscopy) will provide essential experimental input which will help define the interactions and correlations required for the successful descriptions implied by the milestone.

*(2) Nuclear Astrophysics milestones:*

The 2007 milestone on transfer reactions on r-process nuclei near the N=50 and N=82 closed shells cannot be addressed directly at ATLAS until beams from CARIBU become available (as discussed under topic 1, in the paragraph on transfer reactions). However, the ATLAS research program continues to contribute structure information for neutron-rich nuclei in the two regions (around $^{82}$Ge and $^{132}$Sn) as outlined under topic 2 (neutron-rich nuclei via deep inelastic reactions and fission).

The 2009 milestone on the measurement of properties of and reactions on selected proton-rich nuclei in the rp-process is addressed squarely under the first paragraph of topic 1 (production and destruction of F, Ne, Na, Mg, Al and Si nuclei, competition between ($\alpha$,p) and (p,$\gamma$) reactions on the rp-process path) and topic 4 (high precision mass measurements).

The second 2009 milestone is theoretical in nature (flame propagation in type 1a supernovae) and is not addressed directly at ATLAS.

The 2010 milestone on the reduction by a factor of two of uncertainties of the most crucial stellar evolution nuclear reactions is also addressed explicitly under topic 1. Indeed, the $^{12}$C($\alpha$,$\gamma$)$^{16}$O reaction is mentioned explicitly, as are reactions associated with the MgAl cycle.

The ATLAS research program contributes to the 2011 milestone on neutron capture reactions to constrain s-process isotopic abundances under topic 1 (s-process cross sections above the iron peak and (d,p) reactions as surrogate reactions for (n,$\gamma$) reactions).

The availability of neutron-rich beams from CARIBU will allow the ATLAS research program to contribute significantly to the 2012 milestone on measuring masses, lifetimes, spectroscopic strengths and decay properties of neutron-rich nuclei in the supernova r-process. These physical quantities are mentioned explicitly under topic 4. Moreover, as outlined under topic 1, re-accelerated beams will also provide some of the cross sections data required as input to calculations of radionuclide production in supernovae, the second part of this milestone.

The two 2013 milestones are concerned with simulations of core collapse supernovae and neutron star structure and evolution that are not addressed directly by the ATLAS research program.

*(3) Contributions to milestones in other sub-fields*

The ATLAS program contributes (directly or indirectly) to some of the milestones in Neutrinos, Astrophysics and Fundamental Interactions. For example, experiments at ATLAS on the determination of the $^{8}B$ neutrino spectrum, covered under topic 1 (production of short-lived nuclei for astrophysics measurements) contribute to the 2007 milestone on solar $^{8}B$ neutrinos.

The trap program described under topic 4 (unitarity of CKM matrix, search for scalar, tensor and right-handed components to electro-weak interactions) addresses directly the 2010 milestone on neutron and nuclear β-decay and physics beyond the standard model. The ATLAS program also contributes indirectly to a new lifetime measurement of the neutron by determining the purity of the $^{4}He$ gas used in the NIST experiment through an AMS measurement.

## C. <u>Relation Between the Research Program and the Priorities of the Strategic Plan</u>:

In order to meet its scientific goals, the ATLAS facility must balance four primary elements: the effective operation of the ATLAS facility, the development of new accelerator capabilities, the effective support for experimental installation and operations, and the continued development and operation of experimental capabilities. As a result of the 2006 User workshop and previous discussions with the user community, the following set of priorities have been developed to guide the ATLAS facility for the future.

(1) <u>*Secure reliable 5.3 days/week ATLAS operations:*</u>

Funding at the FY2006 level places severe limitations on the effective operation of ATLAS and its experimental systems both in terms of manpower and of funds for maintenance and repair. This is reflected in the fact that ATLAS operations are curtailed to only 4400 h and in the postponement of various upgrades and repairs. Effective operation of the facility, including experiment support, at a minimum of 5500 hours/year while new upgrades are carried out is essential to address the large demand for low cross section experiments and for detection of rare events, as well as the need of a large user community for flexibility in scheduling and operations. In addition, operations at this level are also required to address the need to develop new beams, especially exotic beams, and novel instrumentation.

(2) <u>*Timely completion of CARIBU and other upgrades linked to research with exotic beams at ATLAS:*</u>

The scientific potential of CARIBU in the areas of nuclear structure and nuclear astrophysics is considerable as it will give access to neutron-rich nuclei that, at present, either cannot be extracted or cannot be accelerated to the appropriate energy regime of ~10 MeV/u at any other facility worldwide. This energy of 10 MeV/u, will be reached for nuclei in the A=100-200 range only with the completion of the ATLAS energy upgrade. Finally, the production of short-lived isotopes with the inflight technique remains a unique asset of the ATLAS program. The installation of an RF chopper to improve the purity of the beam is urgently needed as it will enable to measure lower cross sections relevant for nucleosynthesis.

(3) *<u>Timely construction of the solenoid for studies of transfer reactions in inverse kinematics and other instrument upgrades</u>*:

The superconducting solenoid (HELIOS) will take full advantage of the CARIBU upgrade. By providing close to 4π solid angle coverage, with energy and angle resolutions in the center of mass superior to what can be achieved in inverse kinematics with conventional instrumentation, ATLAS Users will, for example, be able to map single-particle strengths in neutron-rich nuclei of the $^{132}Sn$ region as well as study the evolution of pairing with neutron excess.

Spectroscopy at the very limits of stability and in the heaviest nuclei also requires the timely completion of the X-array at the focal plane of the FMA. Until the end of the decade, Gammasphere will remain the world's most powerful γ-ray spectrometer. The instrument will remain an important spectrometer when Gretina comes on-line. In fact, its capabilities will remain unsurpassed for a number of important applications, especially those involving high-multiplicity events. The timely upgrade of the instrument is imperative if the community is to continue to take full advantage of this world-class instrument.

The GRETINA detector will be completed in 2010 and become available for use at the nation's user facilities for unique experiments involving gamma-ray tracking. ATLAS should and will be prepared to use this powerful new detector.

(4) *<u>Return to 7 days/week operations</u>*:

As stated in (1) above, the timely completion of the outlined scientific program, and in particular, the successful exploitation of the unique capabilities provided by the CARIBU upgrade requires the facility to be operated at its full potential. It, however, remains the view of the User community and of the management of the Physics Division that 7 days/week operation of ATLAS at all cost is the wrong approach, and that a return to this desired level of operations is warranted only if investments in the maintenance and upgrade of the accelerator and the associated instrumentation can be made.