Major Nuclear Physics Facilities for the Next Decade

Report of the NSAC Subcommittee on Scientific Facilities

March 14, 2013

Summary

In December 2012 the Nuclear Science Advisory Committee was charged by Dr. William Brinkman, Director of the Office of Science at the Department of Energy, to help with the task of assessing proposed major scientific user facilities. In this case "major" is defined as new facilities or upgrades with a total cost of at least $100M. Dr. Brinkman asked that current user facilities and major proposed facilities and upgrades be assessed for their "ability to contribute to world-leading science in the next decade (2014-2024)." In addition, proposed facilities and upgrades were to be assessed for the "readiness of the facility for construction." Such advice was requested of all Federal Advisory Committees reporting to the Office of Science; the collective input will ultimately be used by the Office to produce a prioritized list of major facilities for this timeframe. Dr. Brinkman's charge letter is included as Appendix A.

The field of nuclear science has a long tradition of prioritizing and planning scientific projects. Long Range Plans have been produced about every 6-7 years (the last one, in 2007, can be found here), and the agencies (DOE and NSF) have taken them very seriously in making decisions on funding. Recently an *ad hoc* Subcommittee of NSAC was charged with recommending how the latest Long Range Plan could best be implemented in different funding scenarios that are more constrained than those anticipated in 2007. The report of this Subcommittee (*Implementing the 2007 Long Range Plan*) can be found here.

In addition the National Research Council recently completed a report that surveyed the past decade of accomplishments and the future prospects for nuclear science. This report, *Nuclear Physics: Exploring the Heart of Matter*, discussed at length the scientific advances that will be enabled by enhanced facilities in nuclear science; the report is available here. These reports provide guidance to the DOE NP Office and to the community for strategic planning.

In preparation for NSAC to address the charge, the NP Program Office at DOE was asked to provide the Office of Science (and NSAC) with its assessment of the importance and readiness of facilities and upgrades that it believes are anticipated by the community. The NP Program Office was also asked to provide its assessment of the scientific importance of current user facilities funded by DOE NP. The charge invited NSAC to add or subtract facilities to the list provided by the Program Office as appropriate.

To accomplish the task set out in the charge in the short time available, NSAC established an *ad hoc* Subcommittee on Scientific Facilities. Members of the Subcommittee were chosen for their expertise and for their representation of the different areas of nuclear physics, following consultation with NSAC members. The membership of the Subcommittee is included as Appendix B. This Subcommittee met in Bethesda, MD on February 15 and 16, 2013 to hear presentations from groups representing current and proposed major facilities and projects and to decide on its advice to NSAC concerning the charge from the Office of Science. The agenda for the meeting is included as Appendix C.

The NRC report used four very broad questions to frame the field:

1. How did visible matter come into being and how does it evolve?

2. How does subatomic matter organize itself and what phenomena emerge?

3. Are the fundamental interactions that are basic to the structure of matter fully understood?

4. How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

These questions served to frame the scientific reach of each facility or project considered by the Subcommittee.

The list of current scientific user facilities from the Program Office includes the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory, the Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility, and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Each of these facilities, in addition to being world-leading in the science performed, is in the process of upgrading its capabilities.

The list of proposed facilities or projects from the NP Program Office includes: an Electron-Ion Collider (EIC), which is being developed by two major laboratories; the Facility for Rare Isotope Beams (FRIB), which is well-along in planning and pre-construction activities at Michigan State University; and a Neutrino-less Double Beta Decay Experiment (NLDBD) with about a ton of decay isotope, which is under consideration by a number of groups currently working in both the NP and HEP communities. Both an EIC and FRIB would build on existing major facilities, while an NLDBD experiment would take advantage of US leadership and expertise in this area.

The Subcommittee invited input broadly from the community concerning the question of whether these are the correct and complete lists of current and proposed major facilities. The Subcommittee also discussed this question early in its deliberations and decided that these are indeed the facilities to consider in answering the charge. This does not preclude intriguing ideas for possible important new capabilities for the field. But such ideas have not yet been sufficiently developed or vetted by the field such that the Subcommittee was comfortable considering them in answering this charge. These other capabilities should be considered at future Long Range Plan discussions and similar exercises.

The Subcommittee had available a lot of thoughtful input on the scientific importance of different capabilities. Our recommendations are fully consistent with the recent reports referred to above; the projects under consideration will allow nuclear scientists to make progress in answering all of the four core questions set out in the NRC study. The nuclear science community has recently gone through processes of evaluation and prioritization, and the major projects that have been endorsed are all of high scientific importance. The list of major facilities in nuclear science is not long, but it is a powerful list.

The charge from the Office of Science asked NSAC, in answering the question about the ability of current or proposed facilities "to contribute to world-leading science in the next decade", to place each facility in one of four categories: (a) absolutely central; (b) important; (c) lower priority; and (d) don't know enough yet. Concerning the "readiness of the facility for construction" question for proposed facilities, NSAC was asked to place each facility or project in one of three categories: (a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; and (c) mission and technical requirements not yet fully defined.

Considering the existing three user facilities, the Subcommittee ranked all three in the category "absolutely central" in terms of their ability to contribute to world-leading science in the next decade. The fact that each of the facilities is in the process of completing significant upgrades that bring new capabilities played an important role in our reaching these rankings. The Subcommittee was unanimous in its decisions on these rankings.

Considering the three proposed facilities or projects, the Subcommittee ranked all three in the category "absolutely central" in terms of their ability to contribute to world-leading science in the next decade. These projects have been well reviewed and vetted by the community and it is clear that they will bring outstanding scientific opportunities. In the area of readiness of the facility for construction, the Subcommittee ranked FRIB as "ready to initiate construction" and EIC and NLDBD as "significant scientific /engineering challenges to resolve before initiating construction". The Subcommittee was unanimous in its decisions on the rankings for proposed facilities or projects.

The Subcommittee recommendations are summarized in the tables below.

Current Facility	**Science**
ATLAS	**a**
CEBAF	**a**
RHIC	**a**

Proposed Facility or Project	**Science**	**Readiness**
EIC	**a**	**b**
FRIB	**a**	**a**
NLDBD	**a**	**b**

In the sections that follow, more details about the capabilities and roles of each facility and the arguments that support these recommendations are provided.

Current User Facilities

ATLAS

Assessment of the ability of the facility to contribute to world-leading science in the next decade

A description of all bound nuclear systems that has real predictive power and is based on models that use realistic nucleon-nucleon forces is a key goal for nuclear physics in the next decade. To challenge these new approaches many new experimental data are needed, including precise measurements from near stability and results from both near the drip lines and in heavy nuclei. The ATLAS superconducting linac facility is evolving to provide capabilities to address all of these issues in the next decade. The developments are in three directions: more intense stable beams; light radioactive beams produced by "in-flight" methods; and neutron-rich beams of fission fragments. These developments will both enable excellent science in the coming decade and provide a testing ground for instrumentation that will be used at FRIB. For the most part, these upgrades have either received full funding or can be completed with normal operations funding.

The stable beam upgrade will boost the intensity of beams of all ions at energies 2-3 times the Coulomb barrier. Beam currents at the >1 particle μA level for all species will ensure that ATLAS remains a world-leading facility for low-energy research for the next decade. The intense beams enable new physics along the proton drip line and in the very heaviest elements. The gas-filled AGFA spectrometer is a good match for this new capability. Gammasphere will be upgraded with digital electronics, another technical advance that is essential to leverage the physics potential of the more intense beams. Exploring excited states in ^{100}Sn and in nuclei beyond Z=104 are key goals.

The intense stable beams also greatly increase the scope for producing secondary radioactive beams through inverse-kinematic "in-flight" production techniques. During the last ten years this approach has been used successfully for measuring reaction rates of astrophysical importance, especially those relevant to breaking out of the CNO cycle and into sd-shell nuclei. With more intense beams, improved production targets, and a dedicated "in-flight" spectrometer, beams of light radioactive species can be enhanced by several orders of magnitude. In addition, the intense stable beams can be used in "deep-inelastic" transfer reactions to produce nuclei "south-east" of ^{208}Pb. Combining intense stable beams with a specially configured "gas stopper" can provide world-unique isotopes in this region, at intensities suitable for mass and moment measurements and for decay studies.

The third approach is to produce beams of fission fragments in the spontaneous fission of californium. The core physics interest is related to those nuclei lying close to the r-process nucleosynthesis path. The enabling technology, developed at

Argonne for FRIB, is a large volume gas stopper with RF fields that can produce low-emittance beams in less than 50ms. This is the core technology of the CARIBU ion source. With sources up to 1 Ci, a wide range of opportunities is available in mid-mass neutron-rich nuclei that are not available elsewhere until FRIB is operational. This includes stopped beam experiments measuring masses, β-decay, electromagnetic moments and radii, and reaccelerated beam experiments using the full ATLAS accelerator for nuclear structure and reaction measurements.

All of these science opportunities are world-class; some are world-unique. The ATLAS facility is in great demand and currently has more than 700 registered users, of whom nearly 400 are actively involved in experiments this year. A significant fraction of the users are international collaborators.

The Subcommittee ranks ATLAS as **Absolutely Central** in its ability to contribute to world-leading science in the next decade.

CEBAF

Assessment of the ability of the facility to contribute to world-leading science in the next decade

Jefferson Lab with its Continuous Electron Beam Accelerator Facility (CEBAF) is making ground-breaking discoveries in the structure of hadrons (strongly interacting particles, such as protons and neutrons), quark confinement, quark hadronization, nuclear structure, fundamental forces and symmetries, theory and computation, superconducting accelerator science and technology, and related subjects such as medical imaging. The lab has a large user-base, including significant international collaboration. The 12 GeV upgrade was ranked at highest priority in the 2007 NSAC Long Range Plan; construction is 73% complete, with 85% of funds obligated. The lab is expected to deliver beams to Hall A in the 2nd quarter of FY14 and then to Hall D in the 1st quarter of FY15.

The upgraded facility will operate with 4 experimental halls. Hall A is suited for form factor measurements and precision electroweak experiments. Hall B with its large acceptance spectrometer will explore nucleon structure via generalized and momentum-dependent parton distributions. Hall C will be used for precise determinations of the distributions of valence quarks in nucleons and nuclei. Hall D will explore the origins of quark confinement and gluon excitations by studying exotic mesons.

The 12 GeV CEBAF Upgrade funds baseline equipment in Halls B, C, and D and modest beamline upgrades in Hall A. Additional detector systems that are needed to fully exploit the precision electroweak physics potential of Hall A include MOLLER and SoLID , as well as resources for smaller detector upgrade projects in the other Halls.

A $73M Science Lab Infrastructure project is almost complete. This provides a new building plus the renovation and expansion of the test lab. This space will be used primarily for superconducting RF activities and some general engineering. The lab continues to look beyond its borders and offers its expertise for FRIB cryogenics, crab cavity research, the next-generation light source, the European spallation source, and polarized target technology.

Demand for CEBAF 12 GeV beam time is extremely high. Already more than 50 experiments requiring 7 years' worth of high-priority physics running have been approved. The CEBAF User Group numbers more than 1200 scientists, including many international collaborators

The questions these experiments will address are:

What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Where is the missing spin of the nucleon, and how much of it might come from orbital angular momentum of the valence quarks?

What is the three-dimensional landscape of nucleon substructure?

What are the relationships among nucleon short-range interactions in nuclei, the partonic structure of nuclei, and the origins of the nuclear force?

What physics lies beyond the Standard Model of particle physics?

These are fundamental questions about the nature of atomic nuclei and the forces and symmetries that govern them. Answering these questions will lead to much deeper understanding of Quantum Chromodynamics (QCD) and the Standard Model.

Nuclear physicists have been able to understand the change of parton distributions over many orders of magnitude in energy scale, but the parton distributions themselves remain empirical. Significant theoretical progress has been made in the last decade in understanding the 3-dimensional structure of the nucleon. Consequently, the resulting new generalized and transverse-momentum-dependent parton distributions are starting to be empirically constrained. Without CEBAF the field of nuclear physics will fail to get much closer to answering the question of how QCD works in nucleons and nuclei, which account for almost all of the mass of the visible universe.

No other facility around the world is competitive with CEBAF in addressing many of these questions. Experiments using hadron beams at the CERN SPS and the Fermilab main injector offer complementary measurements of quark dynamics, but scattering experiments using electron beams at CEBAF have much greater precision, which is essential to rigorously sort out the multi-dimensional kinematics of these complex next-generational observables of the structure of the proton and of the nucleus. Experiments such as COMPASS at CERN utilize a higher-energy muon beam, but with much lower intensity. The capabilities of CEBAF at 12 GeV are therefore crucial for making significant progress in understanding the internal structure of nucleons and nuclei.

The reach of CEBAF's physics program is broad and includes understanding QCD from quarks to nucleons to nuclei, putting the Standard Model to the test in precise electroweak interactions, and promoting accelerator and superconducting technology.

The Subcommittee ranks CEBAF as **Absolutely Central** in its ability to contribute to world-leading science in the next decade.

RHIC

Assessment of the ability of the facility to contribute to world-leading science in the next decade

The Relativistic Heavy Ion Collider (RHIC) facility has unique capabilities that allow the study of the QCD phase transition in nuclear collisions over a wide range of initial temperature and baryon densities. RHIC is capable of colliding a wide variety of ions from protons up to ^{238}U over a range of nucleon-nucleon center of mass energies from 7 to 200 GeV. As the only polarized hadron collider in the world, RHIC also provides unique capabilities for studying the spin content of the proton. RHIC has a user community of more than 1000 physicists, including significant international representation. Japan has made over $130M in investments in the RHIC program and scientific community, including the funding of the RIKEN-BNL Research Center (RBRC). For all of these reasons, RHIC was identified as an essential component of the US nuclear science program in the 2007 Long Range Plan. The essential nature of RHIC was reiterated in the recent (January 2013) NSAC report on *Implementing the 2007 Long Range Plan*.

The early universe is believed to have been filled with a plasma of quarks and gluons (QGP). As it expanded and cooled, protons and neutrons were formed. Measurements at RHIC have provided the first conclusive evidence for the creation of this primordial plasma in the laboratory. At the very low baryon densities achieved at top RHIC energies and at the LHC, the QCD transition from the QGP to hadrons is thought to be a cross-over transition. At higher baryon densities a first-order phase transition is expected, with the transition line terminating at a critical point. RHIC can study the QCD transition at higher baryon density by reducing the collision energy. In a first phase of a beam energy scan, RHIC studied Au-Au collisions with energies down to 7.7 GeV. Resulting measurements suggest that QGP formation “turns off” at the lowest collision energies, indicating that RHIC is uniquely positioned to study the onset of deconfinement. Future measurements with an order-of-magnitude increase in statistics and with improved detectors will examine the high baryon density region in detail with the goal of locating the critical point and finding clear evidence for first-order phase transitions.

Measurements at RHIC of the collective expansion of the QGP have probed the long wavelength behavior of the QGP. The long-wavelength response of the QGP can be characterized by the shear viscosity to entropy ratio, η/s. Estimates of η/s obtained by comparing experimental measurements to results of viscous hydrodynamic calculations indicate that the QGP is strongly coupled with η/s lying within a factor of two of a strong-coupling lower bound suggested by Anti-deSitter/Conformal Field Theory calculations. These calculations invoke a duality between string theories near a black hole and gauge field theories to calculate properties of the gauge theories at strong coupling. The small values of η/s extracted from RHIC data motivated the conclusion that the QGP is a nearly “perfect liquid”. Recent results from the LHC suggest that η/s may be larger in Pb-Pb collisions at the LHC than at RHIC, which would indicate that the plasma is more weakly coupled at higher temperature. As part of the energy scan program, RHIC will carry out precise studies of elliptic and higher order flow at different initial temperatures and baryon densities to determine the temperature and baryon density dependence of η/s near the transition. Recently, RHIC has used its flexibility in colliding species to perform exploratory measurements in U-U collisions and in Cu-Au collisions. The static deformation of the U nucleus and the asymmetry of the Cu-Au collisions provide valuable tests of our understanding of the collective dynamics of the QGP, and additional measurements in the future will help improve the determination of η/s.

Parity violating domains may result from quantum fluctuations in the QGP. Similar quantum fluctuations, occurring in the early universe when it was 1000 times hotter than the matter studied at RHIC, have been proposed as the reason the universe today consists almost solely of matter. Theoretical studies suggest that the intense transient magnetic fields created in heavy-ion collisions exert forces on the particles in the parity-violating domains producing experimentally observable signals. An initial search at RHIC has found results consistent with the theoretical predictions but, because the observable is parity even, the measurement is not yet considered definitive. The parity violation effect can be enhanced or suppressed relative to the parity-allowed backgrounds by changing the colliding ions and the beam energies, and RHIC is uniquely positioned to be able to perform such measurements in the future.

Observations of "jet quenching" in nuclear collisions at RHIC, and more recently the LHC, have demonstrated that the QGP is opaque to the passage of high-momentum quarks and gluons. The jet measurements probe the coupling of the QGP at higher momentum scales than the flow measurements and potentially provide insight on the nature of the quasi-particles in the QGP – if such quasi-particles exist. Charm and bottom quarks provide additional insight on the physics of jet quenching due to suppressed radiative energy loss for heavy quarks and the relatively low velocities of the quarks in the medium. Detector upgrades designed to separate charm and bottom quarks are underway at RHIC. A proposed major upgrade of the PHENIX detector will allow calorimetric jet measurements similar to those carried out by ATLAS and CMS. These upgrades will provide a "second generation" of jet quenching measurements at RHIC that will characterize the transport and diffusion properties of the perfect liquid near the phase transition.

RHIC is the world's first, and only, polarized hadron collider. This gives it unique abilities to contribute to our understanding of the spin structure of the proton. Measurements from RHIC have provided the first indication that gluons in the proton with momenta accessible to RHIC are polarized and, in fact, might contribute as much to the proton spin as the quarks do. RHIC has begun to delineate the polarization of the sea quarks in the proton through measurements of spin asymmetries for $W^{+/-}$ production. RHIC has also demonstrated that large transverse single-spin asymmetries, which had been observed previously for forward hadron production at p+p center-of-mass energies up to 20 GeV, persist to the highest RHIC energies. Substantial progress on all of these fronts is expected during the coming years. Also, late in this decade, measurements of spin asymmetries for Drell-Yan production will provide a crucial test of our current understanding of transverse-momentum-dependent effects in high-energy *p+p* and *e+p* collisions.

Measurements at RHIC have provided intriguing hints of “parton saturation” or non-linear evolution of parton distributions in nuclei. Such non-linear evolution is expected to result from recombination of gluons at high parton densities and is thus uniquely characteristic of the non-Abelian nature of QCD. Confirmed observation of saturation would represent a major advance in the exploration of QCD at high gluon density. Future high-luminosity measurements in proton-nucleus (p-A) collisions at RHIC, combined with forward detector upgrades of the STAR and PHENIX experiments, will extend the studies of QCD at high parton density at RHIC. Measurements of p-A collisions at the LHC using data from the 2013 p-Pb run will probe substantially lower x values than those accessible at RHIC and should make possible a definitive conclusion regarding the effects of saturation. However, if the LHC results confirm the role of saturation in p-A collisions, the measurements at RHIC will be essential for determining how the saturation effects “turn on” with increasing collision energy.

In addition to the important role that RHIC plays in exploring questions in basic nuclear science, RHIC operation also supports nuclear science applications in the form of isotopes produced for commercial and research stakeholder communities.

The Subcommittee ranks RHIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade.

Proposed Facilities

EIC

Assessment of the ability of the facility to contribute to world-leading science in the next decade

For the past fifty years physicists in particle and nuclear science have striven to comprehend how, from the primordial soup of elementary particles, the core of the hydrogen atom (the proton) emerged with its distinct properties. Most of the mass of the visible universe is contained in atomic nuclei, comprising protons and neutrons, which are collectively termed nucleons.

Nucleons owe their existence to the strong interaction of the basic constituents known as quarks and gluons. Gluons, the quanta of strong (color) interactions, play the paramount role in generating the mass of the nucleon. The defining property of the strong interaction is that gluons carry "color charge", causing them to interact among themselves. This property results in the "confinement", or binding, of gluons and their quark partners inside the proton and other hadrons. It also causes the proliferation and eventual saturation of the gluon density, forming a novel kind of matter deep inside atomic nuclei. Confinement played an important role in the early evolution of the universe, and an Electron-Ion Collider (EIC) will allow us to study and understand this fundamental process in completely new ways.

To date experiment has shown that, although quarks determine the charge of the nucleon, they contribute only about half of its total momentum, a third of its spin, and a few percent of its mass. In contrast, gluons are believed to be responsible for much of the nucleon mass, contribute the rest of its momentum, and may make a substantial contribution to its spin. But the way these contributions come about is not understood. CEBAF, even with the 12 GeV upgrade, does not have sufficiently high energy to study the gluons in detail. However, this limitation can be overcome by colliding a beam of electrons directly with a beam of protons or heavier nuclei, thereby achieving much higher center-of-mass energy collisions. The EIC will have this capability.

What is the distribution of the gluons and their spin, in space and in momentum, inside the nucleon? How is this distribution modified by the nuclear environment? Where is the onset of the saturation of gluon density? These are key questions that can only be answered by a modern EIC with very high luminosity and highly polarized beams. Answers to these questions will revolutionize the understanding of hadronic matter and of the role of gluons in the formation of the building blocks of visible matter.

The EIC would be a unique and powerful microscope to provide a dynamical mapping of gluons in the nucleon and in nuclei. It is an ideal tool to investigate the mechanism of how quarks and gluons propagate in nuclear matter and join together to form hadrons. The EIC is our portal to an in-depth and fundamental understanding of gluonic matter and of QCD.

As stated in the 2007 Long Range Plan, "An EIC with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier."

The Subcommittee ranks an EIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade.

Assessment of the readiness of the facility for construction

It would be very expensive to build an EIC on a green-field site. However, the Subcommittee heard two presentations related to the realization of an EIC in the US, building on existing investments: one from Brookhaven National Laboratory (BNL) and one from Jefferson Laboratory (JLab). The labs are working together and have made progress in exploring pre-conceptual design options and in defining the technical challenges. They have refined their designs and have identified the performance of the designs with respect to EIC expectations of luminosity and energy, as articulated in an EIC white paper. Both laboratories have also considered staged implementations of the EIC. Cost projections of increasing maturity and thoroughness are being made by both teams.

The BNL concept utilizes the infrastructure of RHIC for tunnels, cryosystems, and the hadron portion of the collider. The added capability needed for electron-ion collisions is an electron accelerator, and BNL addresses this by proposing an energy recovery linac (ERL) which means that electrons are only used for collisions in one pass; their energy is then recovered and transferred to new bunches of electrons, thereby preserving the highest beam quality and enabling a much higher rate of interactions (higher “luminosity”) than a more conventional design. Present R&D is directed at the development of a Gatling polarized electron gun, which would allow much higher polarized electron beam currents, and at the commissioning of the demonstration ERL. Cooling of the hadron beam is needed and BNL has chosen to pursue the technique of Coherent Electron Cooling (CeC). R&D is proceeding on this as well with the intent to do a proof-of-principle experiment, using RHIC, by about 2015.

The JLab concept utilizes electrons from the CEBAF facility at energies up to 12 GeV. They will be injected into a ring where they circulate and are topped up from CEBAF to maintain a constant current. The hadron source and ring(s) are new construction. New conventional construction is needed for both the ion accelerator systems and the detector/interaction region. The design utilizes a figure-8 configuration for polarization. The hadron source is being designed to match this. Several R&D issues are under study: interaction region design addressing chromatic compensation and dynamic aperture; polarization; low energy ion beam dynamics; and electron cooling of the hadron beam. Here, as in the BNL case, a demonstration of the cooling technique is expected by about 2015.

Subsequent comments apply to the state of the designs in general and are not laboratory specific. Both designs are in very early stages relative to the Office of Science project review process. There are outstanding R&D issues that remain to be addressed in order to achieve performance metrics. Staging approaches to the EIC are also being explored by the laboratories. Both laboratories are actively addressing R&D issues and are making good progress. Project costs have been estimated by the laboratories, but they have not been externally reviewed. The Subcommittee believes that further work and consistent reviews of costing need to be done before concluding that construction costs are fully understood.

Concerning readiness of the facility for construction, we rank this facility in the category **(b) significant scientific/engineering challenges to resolve before initiating construction**.

FRIB

Assessment of the ability of the facility to contribute to world-leading science in the next decade

The Facility for Rare Isotope Beams (FRIB) will be transformational for nuclear science. FRIB will be world-unique in the power of its driver accelerator, leading to production of a broad array of new isotopes at rates that are orders of magnitude higher than any other existing or planned facility. In these thousands of new nuclei lies the discovery potential: for example, the physics of nuclei with huge neutron excesses which are not found on earth, but only in the crusts of neutron stars and in the transient environment of supernovae. Here the weak binding and skins of neutron matter are expected to result in structures and phenomena not yet well understood, but important for models of nuclear structure. Thousands of new isotopes will become accessible at a level of intensity sufficient for spectroscopy. In nuclear structure, building on and supported by research at ATLAS, FRIB will provide data for developing, testing, and refining a new generation of nuclear models, based on realistic nucleon-nucleon forces, and with the predictive power needed to describe properties of all nuclei, including exotic nuclei. In astrophysics FRIB data will enable quantification of r-process nucleosynthesis, the mechanism responsible for producing most heavy nuclei. Improved understanding of the r-process will help to identify the astrophysical environments where this synthesis takes place. In studies of fundamental symmetries the enhanced production of certain key isotopes, along with new opportunities that may arise when using currently unknown nuclei, can open the way for exquisitely sensitive measurements that probe physics beyond the standard model. Finally, a copious yield of exotic isotopes can be harvested parasitically for use in a variety of applications that will provide benefits to society. Applications have already been identified in the key areas of stockpile stewardship, materials science, biomedical science, and energy production.

Optimizing science goals and reach for FRIB has transpired over more than a decade. This activity has spanned at least two NSAC Long Range Plans and involved several National Research Council panels and a large number of technical workshops. The most recent NSAC LRP made the FRIB project its highest priority for new construction because it determined that "Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, produce an understanding of matter in the crust of neutron stars, and establish the foundation for innovative applications of nuclear science to society". Two recent National Research Council (NRC) reports, "Scientific Opportunities with a Rare-Isotope Facility in the United States", NRC RISAC report (2007), and "Nuclear Physics: Exploring the Heart of Matter", NRC Decadal Study (2012), have documented the scientific importance of FRIB and helped to sharpen the key challenges and opportunities of FRIB science. The RISAC report strongly supported the FRIB concept and laid out the drivers for FRIB science. The 2012 NRC Decadal Study concurred with the RISAC report: "Data to date on exotic nuclei are already beginning to revolutionize our understanding of atomic nuclei. FRIB will enable experiments in uncharted territory at the limits of nuclear stability. FRIB will provide new isotopes for research related to societal applications, address longstanding questions about the astrophysical origin of the elements and the fundamental symmetries of nature." A vibrant community of more than 1300 users has been involved in technical workshops to further refine science goals and push forward novel detector designs needed to efficiently exploit the power of FRIB. Rare isotope beams will be available over a range of energies, from isotopically separated stopped beams through beams near the Coulomb barrier (5-15 MeV/u) up to full fragmentation energies (~200 MeV/u). This broad suite of beam energies, combined with the vast range of isotopes, will allow the full range of experimental techniques and innovative detector systems to be applied to extract new science.

The Subcommittee ranks FRIB as **Absolutely Central** in its ability to contribute to world-leading science in the next decade.

Assessment of the readiness of the facility for construction

The FRIB project has progressed through the DOE Office of Science (SC) project review process. The FRIB project underwent a readiness for CD-2/3A review in April of 2012. The result of the review was that this project is ready for baselining (the specific question asked at a CD-2 review), and therefore the technical feasibility and robustness of cost to build the project have been thoroughly reviewed, with concurrence in the review process. Furthermore the review found that the project is well managed and has sufficient cost and schedule contingency. The project has requested and received authority to begin some long-lead-time procurements. The proposed baseline leverages significant existing infrastructure and new investments at MSU by the State of Michigan. The project is preparing for CD2/3A approval in FY2013 and pursuing authority to start construction.

The operating requirements and costs of FRIB have been analyzed by the facility and have been presented and considered at various reviews. The formal development of an operational budget is required for CD-3B, which is anticipated in FY14.

Concerning readiness of the facility for construction, we rank this facility in the category **(a) ready to initiate construction**.

Neutrino-less Double Beta Decay

Assessment of the ability of the facility to contribute to world-leading science in the next decade

The matter asymmetry of the universe remains one of the deepest mysteries in physics. The absence of significant amounts of antimatter requires, as Sakharov explained, a time when the universe was not in equilibrium, the non-conservation of baryon number, and violation of CP invariance. Non-conservation of baryon number has not been experimentally discovered, despite heroic efforts to observe proton decay. The observation of neutrino-less double beta decay (NLDBD) would demonstrate the non-conservation of lepton number and, by inference, the non-conservation of baryon number.

Over the past half century the neutrino sector of the Standard Model has proven to be fertile ground for understanding the universe. The fact that neutrinos have small, but non-zero, masses is a critical signal of physics beyond the Standard Model. Furthermore their masses are a million or more times smaller than those of the next lightest fundamental particle, suggesting a non-Higgs mechanism for generating mass.

In contrast to all other fundamental building blocks of matter, neutrinos, which carry no electric charge, can be their own antiparticles if no conserved quantum number forbids it. Therefore, if lepton number is not conserved, neutrino-less double beta decay can occur. No other method is known to access this physics. Nuclear physics, specifically the nuclear pairing force, provides a unique window into this second-order weak interaction and thus can provide insight into a symmetry of matter, independent of and complementary to experiments at the LHC. In the nuclear beta decay of certain medium and heavy elements where, because of the pairing force a single decay is not energetically possible, it is possible instead that a 'simultaneous' decay of two neutrons occurs. This rare event normally results in the emission of two electrons and two neutrinos. If neutrinos are their own antiparticles, they can be both emitted and absorbed during such a process resulting in a decay with no neutrinos and a total electron energy equal to the mass difference of the parent and daughter nuclei, "neutrino-less double beta decay."

Experiments to search for neutrino-less double beta decay can also be used to study other important physics issues, such as searches for light dark matter.

Approximately 200 US scientists, from both the NP and HEP communities, are currently participating in NLDBD experiments.

The 2007 Nuclear Science Long Range Plan recognized this scientific opportunity and called experimental searches for this effect a "highlight". The 2013 NSAC

Report on the Implementation of the 2007 Long Range Plan reaffirmed the importance of this work even in times of severe budget stringency.

The Subcommittee ranks experiments addressing neutrino-less double beta decay as **Absolutely Central** in their ability to contribute to world-leading science in the next decade.

Assessment of the readiness of the facility for construction

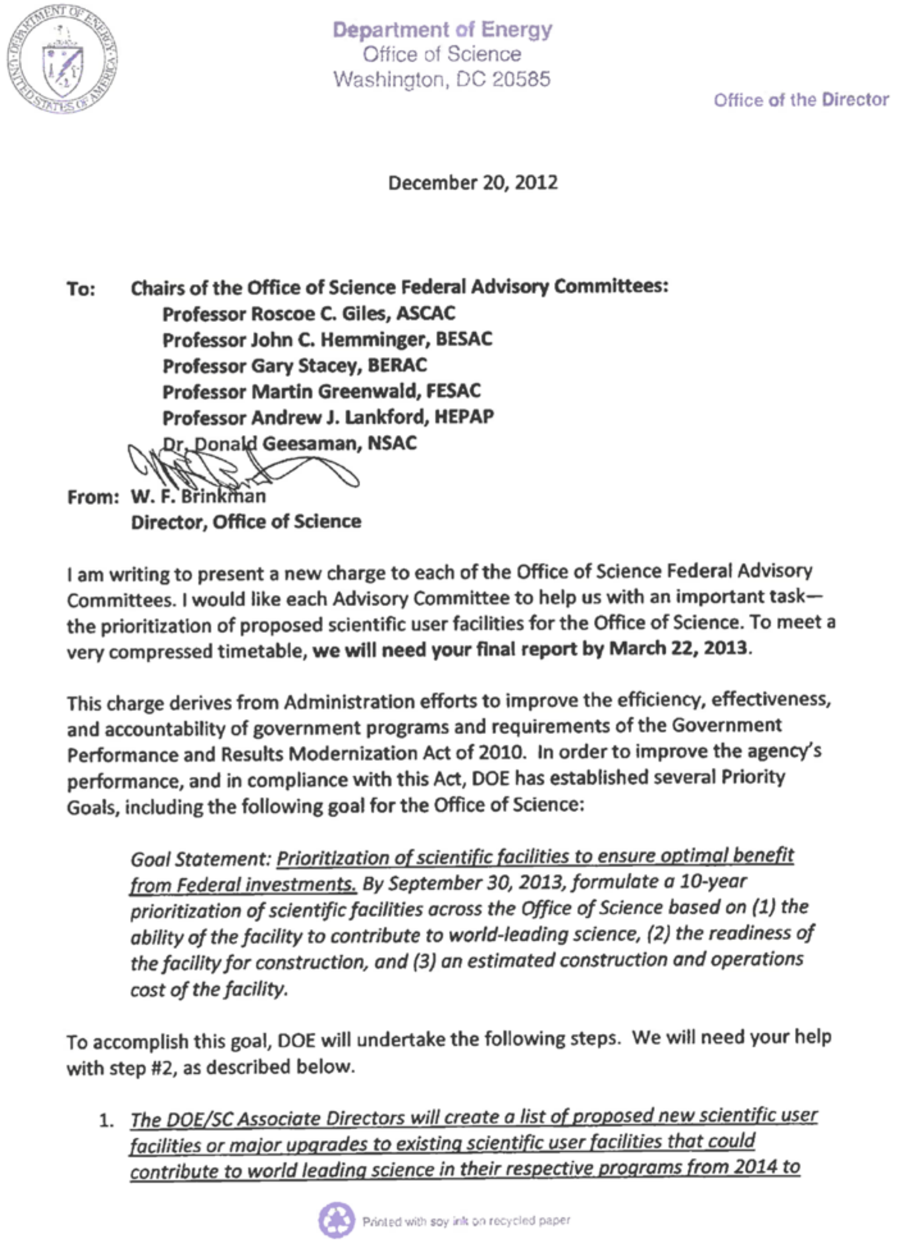
Present knowledge of the neutrino mass scale suggests that detectors containing on the order of one ton of a specific isotope will have a good chance of measuring neutrino-less double beta decay, especially if nature has arranged neutrino masses in the "inverted hierarchy." Vigorous R&D efforts have led to experiments at the 100-kg scale in, or nearing, operation and based on the isotopes ^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe, and ^{150}Nd. Our Subcommittee heard updates from six of these groups and received written information from a seventh. This remarkable set of experiments, some already providing lower limits of $T_{1/2} \sim$ few x 10^{25} years (10^{15} times the age of the universe), are the candidates to be scaled up from the current 100-kg scale to the ton scale. The concepts are well defined. Technical challenges still exist, but many have been successfully resolved. However, R&D is still needed in most cases with respect to achievable backgrounds.

Projected costs for ton-scale experiments cover a wide range, scattered about the $100M level. In some cases the cost estimates provided were schematic. In a few cases project-management principles were applied and the costs included contingency and risk.

With such an important physics objective at stake, a judicious balance between continued technical development and timeliness will be required. A careful technical judgment, including readiness, of each candidate technology is planned. In drawing conclusions of the highest significance to physics, incontrovertible experimental evidence is called for. Measures that build confidence in a result include good signal-to-background levels, statistical accuracy, redundant identification of signal events, and reproducibility of the result either in the same isotope or in a different isotope.

Concerning readiness of the facility for construction, we rank this facility in the category **(b) significant scientific/engineering challenges to resolve before initiating construction**.

Appendix A



Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

December 20, 2012

To: Chairs of the Office of Science Federal Advisory Committees:
Professor Roscoe C. Giles, ASCAC
Professor John C. Hemminger, BESAC
Professor Gary Stacey, BERAC
Professor Martin Greenwald, FESAC
Professor Andrew J. Lankford, HEPAP
Dr. Donald Geesaman, NSAC

From: W. F. Brinkman
Director, Office of Science

I am writing to present a new charge to each of the Office of Science Federal Advisory Committees. I would like each Advisory Committee to help us with an important task—the prioritization of proposed scientific user facilities for the Office of Science. To meet a very compressed timetable, **we will need your final report by March 22, 2013**.

This charge derives from Administration efforts to improve the efficiency, effectiveness, and accountability of government programs and requirements of the Government Performance and Results Modernization Act of 2010. In order to improve the agency's performance, and in compliance with this Act, DOE has established several Priority Goals, including the following goal for the Office of Science:

> *Goal Statement: Prioritization of scientific facilities to ensure optimal benefit from Federal investments. By September 30, 2013, formulate a 10-year prioritization of scientific facilities across the Office of Science based on (1) the ability of the facility to contribute to world-leading science, (2) the readiness of the facility for construction, and (3) an estimated construction and operations cost of the facility.*

To accomplish this goal, DOE will undertake the following steps. We will need your help with step #2, as described below.

1. *The DOE/SC Associate Directors will create a list of proposed new scientific user facilities or major upgrades to existing scientific user facilities that could contribute to world leading science in their respective programs from 2014 to*

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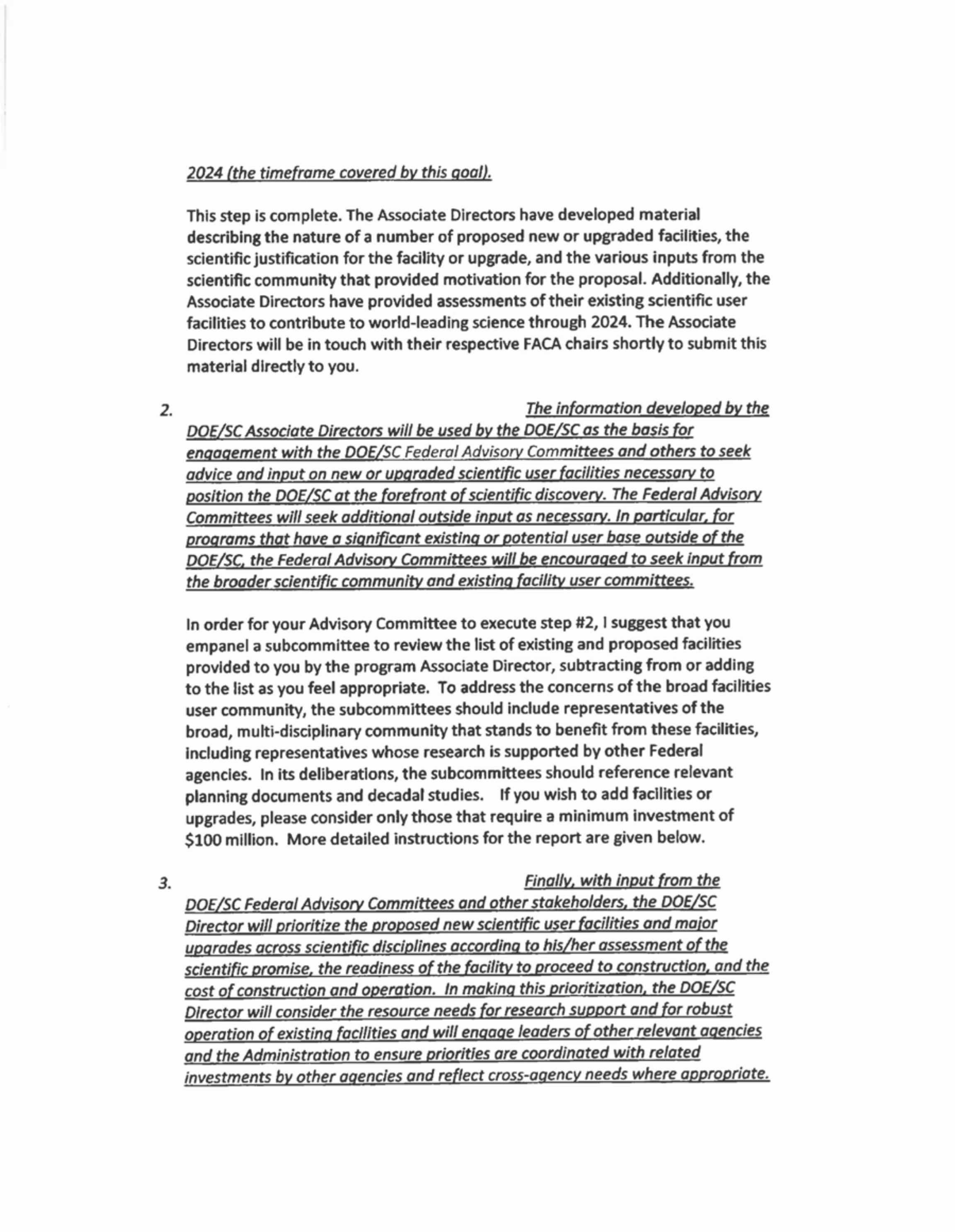


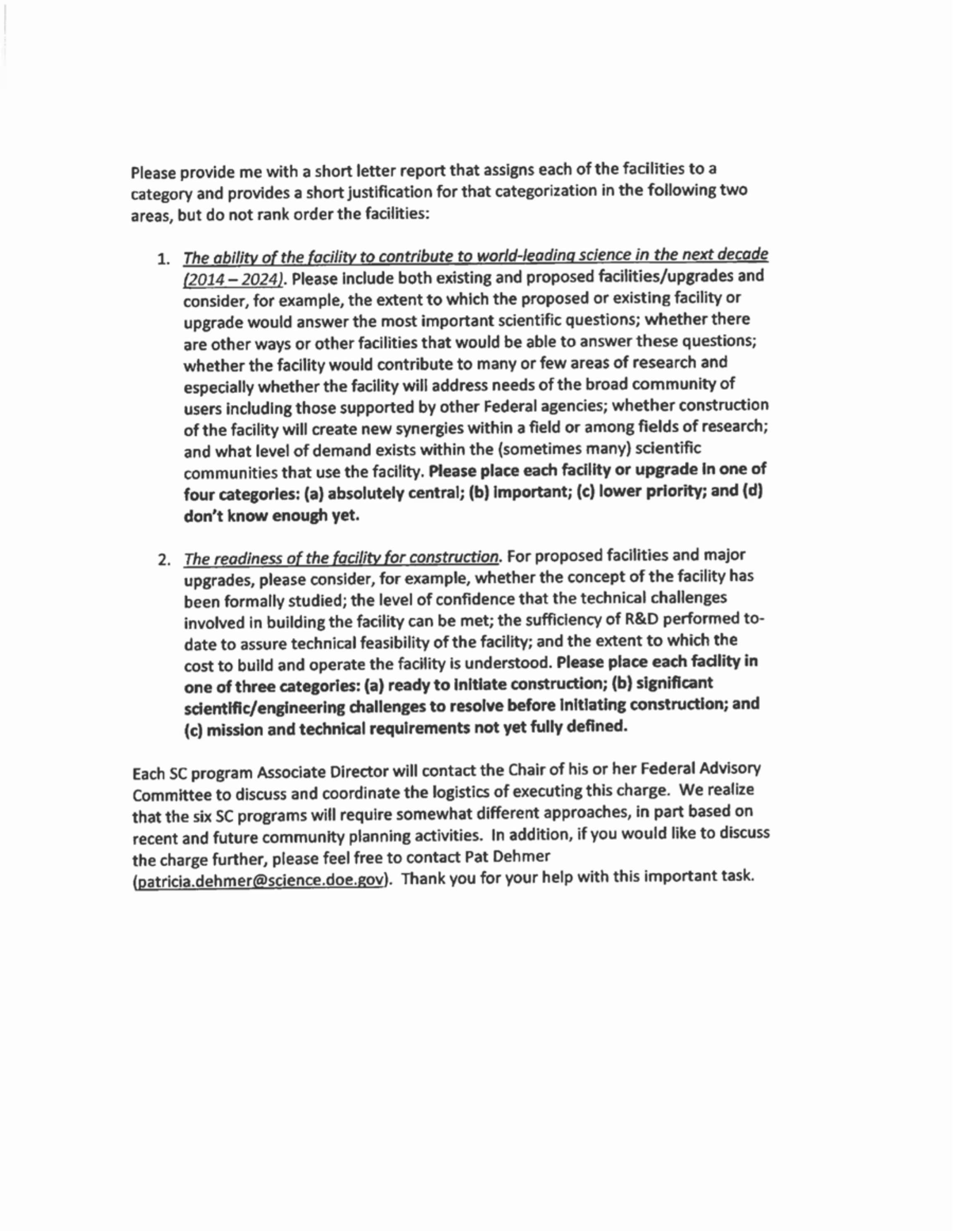
2024 (the timeframe covered by this goal).

This step is complete. The Associate Directors have developed material describing the nature of a number of proposed new or upgraded facilities, the scientific justification for the facility or upgrade, and the various inputs from the scientific community that provided motivation for the proposal. Additionally, the Associate Directors have provided assessments of their existing scientific user facilities to contribute to world-leading science through 2024. The Associate Directors will be in touch with their respective FACA chairs shortly to submit this material directly to you.

2. *The information developed by the DOE/SC Associate Directors will be used by the DOE/SC as the basis for engagement with the DOE/SC Federal Advisory Committees and others to seek advice and input on new or upgraded scientific user facilities necessary to position the DOE/SC at the forefront of scientific discovery. The Federal Advisory Committees will seek additional outside input as necessary. In particular, for programs that have a significant existing or potential user base outside of the DOE/SC, the Federal Advisory Committees will be encouraged to seek input from the broader scientific community and existing facility user committees.*

In order for your Advisory Committee to execute step #2, I suggest that you empanel a subcommittee to review the list of existing and proposed facilities provided to you by the program Associate Director, subtracting from or adding to the list as you feel appropriate. To address the concerns of the broad facilities user community, the subcommittees should include representatives of the broad, multi-disciplinary community that stands to benefit from these facilities, including representatives whose research is supported by other Federal agencies. In its deliberations, the subcommittees should reference relevant planning documents and decadal studies. If you wish to add facilities or upgrades, please consider only those that require a minimum investment of $100 million. More detailed instructions for the report are given below.

3. *Finally, with input from the DOE/SC Federal Advisory Committees and other stakeholders, the DOE/SC Director will prioritize the proposed new scientific user facilities and major upgrades across scientific disciplines according to his/her assessment of the scientific promise, the readiness of the facility to proceed to construction, and the cost of construction and operation. In making this prioritization, the DOE/SC Director will consider the resource needs for research support and for robust operation of existing facilities and will engage leaders of other relevant agencies and the Administration to ensure priorities are coordinated with related investments by other agencies and reflect cross-agency needs where appropriate.*



Please provide me with a short letter report that assigns each of the facilities to a category and provides a short justification for that categorization in the following two areas, but do not rank order the facilities:

1. *The ability of the facility to contribute to world-leading science in the next decade (2014 – 2024)*. Please include both existing and proposed facilities/upgrades and consider, for example, the extent to which the proposed or existing facility or upgrade would answer the most important scientific questions; whether there are other ways or other facilities that would be able to answer these questions; whether the facility would contribute to many or few areas of research and especially whether the facility will address needs of the broad community of users including those supported by other Federal agencies; whether construction of the facility will create new synergies within a field or among fields of research; and what level of demand exists within the (sometimes many) scientific communities that use the facility. **Please place each facility or upgrade in one of four categories: (a) absolutely central; (b) important; (c) lower priority; and (d) don't know enough yet.**

2. *The readiness of the facility for construction*. For proposed facilities and major upgrades, please consider, for example, whether the concept of the facility has been formally studied; the level of confidence that the technical challenges involved in building the facility can be met; the sufficiency of R&D performed to-date to assure technical feasibility of the facility; and the extent to which the cost to build and operate the facility is understood. **Please place each facility in one of three categories: (a) ready to initiate construction; (b) significant scientific/engineering challenges to resolve before initiating construction; and (c) mission and technical requirements not yet fully defined.**

Each SC program Associate Director will contact the Chair of his or her Federal Advisory Committee to discuss and coordinate the logistics of executing this charge. We realize that the six SC programs will require somewhat different approaches, in part based on recent and future community planning activities. In addition, if you would like to discuss the charge further, please feel free to contact Pat Dehmer (patricia.dehmer@science.doe.gov). Thank you for your help with this important task.

Appendix B

2013 NSAC Subcommittee on Scientific Facilities

Doug Beck, U. Illinois
Jim Beene, ORNL
Brian Cole, Columbia U.
Carl Gagliardi, TAMU
Don Geesaman, ANL (ex officio)
Rod Gerig, ANL
Keith Griffioen, William and Mary
Kim Lister, U. Mass. Lowell
Zein-Eddine Meziani, Temple U.
Bob Redwine, MIT (Chair)
Don Rej, LANL
Hamish Robertson, U. Washington
James Symons, LBNL

Appendix C

AGENDA

Meeting of the NSAC Subcommittee on Scientific Facilities

Bethesda North Marriott Hotel and Conference Center
Forest Glen Conference Room
(Note: All sessions not designated Executive Sessions will be open to interested parties.)

Friday, February 15

9:00 AM	Executive Session: Discussion of Charge and Process
9:30 AM	CEBAF Presentation (Bob McKeown)
10:30 AM	Break
10:45 AM	RHIC Presentation (Berndt Mueller)
11:45 AM	ATLAS Presentation (Guy Savard)
12:45 PM	Working lunch/Executive Session
1:45 PM	FRIB Science (Brad Sherrill)
2:45 PM	FRIB Readiness and Cost (Thomas Glasmacher)
3:45 PM	Break
4:00 PM	EIC Science (Jianwei Qiu)
5:00 PM	eRHIC Project (Thomas Roser)
5:45 PM	MEIC Project (Rolf Ent)
6:30 PM	Executive Session
7:00 PM	Dinner

Saturday, February 16

9:00 AM Neutrino-less Double Beta Decay Science (Wick Haxton)

10:00AM Discussion of Neutrino-less Double Beta Decay Projects
(with participation by project spokespersons:

CUORE	Yury Kolomensky
KamLAND Zen	Lindley Winslow
Majorana Tonne Ge	John Wilkerson
nEXO	Andreas Piepke
NEXT	Azriel Goldschmidt
SNO+	Josh Klein)

11:00 AM (Held for other presentations as needed)

12:30 PM Working Lunch/Executive Session

5:00 PM Adjourn