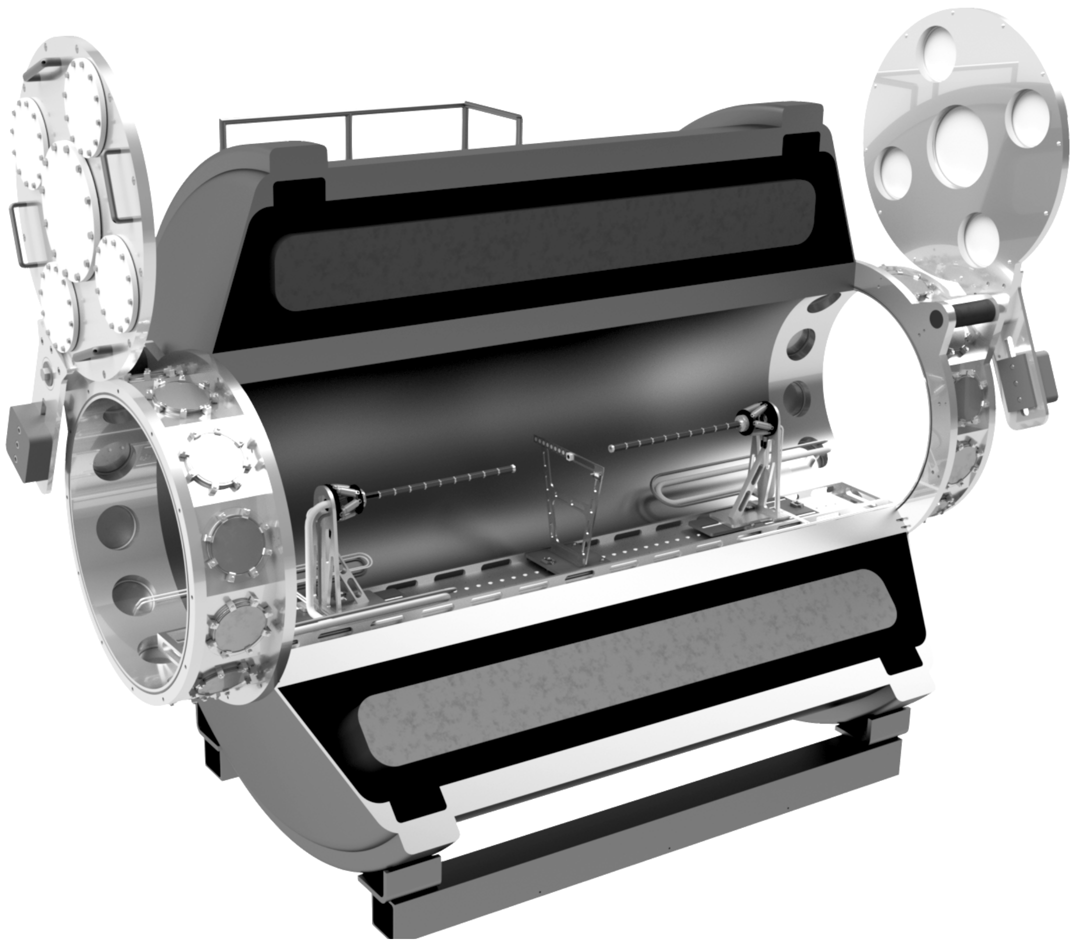
# SOLARIS White Paper



# SOLARIS

# A Solenoidal Spectrometer Apparatus for Reaction Studies

## White Paper

March, 2018

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www.anl.gov/phy/group/solaris

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# 1. Executive Summary

The SOLARIS (SOLenoid spectrometer Apparatus for ReactIon Studies) project is to develop and implement a multi-mode charged-particle spectrometer to realize the full potential of the re-accelerated (ReA) beams [1] at the National Superconducting Cyclotron Laboratory (NSCL), and subsequently, at the Facility for Rare Isotope Beams (FRIB). SOLARIS will comprise a high-resolution charged-particle spectrometer similar to the HELIOS spectrometer [2, 3] at Argonne National Laboratory (ANL), and the active-target time-projection chamber (AT-TPC) [4, 5, 6] which has been developed at the NSCL.

SOLARIS will be a unique system of instrumentation for charged-particle spectroscopy that is ideally suited for probing nuclei through direct single- and multi-nucleon transfer, elastic, and inelastic scattering reactions in inverse kinematics. With SOLARIS, measurements with radioactive ion beams of intensities as low as 100s of particles per second will be possible. The marrying of the exceptional reach of rare-isotope beams envisioned at ReA, SOLARIS, and the reaction techniques mentioned above will allow us to probe hitherto inaccessible aspects of nuclear structure, nuclear astrophysics, fundamental symmetries and nuclear applications. Several of these key areas are highlighted below.

SOLARIS will enable the nuclear physics community to gain significant insight into the following:

- modifications in the nuclear shells and changes in the single-particle structure of nuclei,
- pairing modes and strengths in nuclei,
- describing emerging collective features in complex nuclei,
- nuclear reactions integral to modeling explosive nucleosynthesis,
- the structure of nuclei used in testing fundamental symmetries,
- and stockpile stewardship.

These are behind the fundamental questions put forward by the Nuclear Science Advisory Committee (NSAC) in their recent Long Range Plans for Nuclear Science [7, 8] and they are closely aligned with the four fundamental science drivers for FRIB as laid out by the National Research Council Rare Isotope Science Assessment Committee (RISAC) review [9]. These key FRIB science drivers can be characterized by 17 benchmarks which fall out naturally from the overarching questions put forth in the NSAC 2007 Long Range Plan [7], as shown in Figure 1.1. To ensure that these benchmark programs can be realized, SOLARIS proves to be a critical instrument for FRIB.

SOLARIS unites two demonstrated technologies into a common infrastructure: a large-bore superconducting solenoid that operates in vacuum mode with an on-axis Si array, and in a gas-filled mode that acts as an active-target time-projection chamber (AT-TPC). Both instruments have been developed over the last decade with the intention of best exploiting next generation radioactive ion beam facilities, such as FRIB. The techniques are discussed in detail in Section 3, with reference to their prototype or demonstrator versions; HELIOS [3] at ANL and the AT-TPC [5, 6] at the NSCL. The following sections lay out the scientific motivation for SOLARIS focusing on the benchmarks highlighted in red in Figure 1.1. SOLARIS enables new research in each of the four science drivers for FRIB.

**Science drivers from NRC RISAC**

| Nuclear Structure | Nuclear Astrophysics | Tests of Fundamental Symmetries | Applications of Isotopes |
|---|---|---|---|

**Overarching questions to be answered by rare-isotope research**

| Nuclear Structure | Nuclear Astrophysics | Tests of Fundamental Symmetries | Applications of Isotopes |
|---|---|---|---|
| - What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?<br>- What is the origin of simple patterns in complex nuclei? | - What is the nature of neutron star and dense nuclear matter?<br>- What is the origin of the elements in the cosmos?<br>- What are the nuclear reactions that drive stars and stellar explosions? | - Why is there now more matter than antimatter in the universe? | - What are new applications of isotopes to meet the needs of society? |

**17 benchmarks programs to answer overarching questions**

| Nuclear Structure | Nuclear Astrophysics | Tests of Fundamental Symmetries | Applications of Isotopes |
|---|---|---|---|
| **1. Shell structure**<br>2. Super heavy elements<br>3. Skins<br>**4. Pairing**<br>**5. Symmetries**<br>**13. Limits of stability**<br>**14. Weakly bound nuclei**<br>15. Mass surface | **6. Equation of state**<br>**7. r-Process**<br>8. $^{15}O(\alpha,\gamma)$<br>9. $^{59}Fe$ s-process<br>15. Mass surface<br>**16. rp-Process**<br>**17. Weak interactions** | **12. Atomic electric dipole moment**<br>15. Mass surface<br>**17. Weak interactions** | 10. Medical<br>**11. Stewardship** |

Figure 1.1: Highlighting the benchmark capabilities SOLARIS will provide, behind the four core science drivers of FRIB. Figure is modified from FRIB Scientific and Technical Merit documentation [10].

# 2. Science Opportunities

The two modes of operation of SOLARIS, a Si-array mode and an AT-TPC mode, lend themselves to a broad range of science opportunities, covering all key areas of inquiry that FRIB was designed to address. SOLARIS will be able to operate in AT-TPC mode with beams as weak as a few hundred ions per second, allowing for the study of nuclear reactions at the limits of stability. In the Si-array mode, high-resolution studies can be carried out with more intense beams, nominally greater than about $10^4$ ions per second.

The science case for SOLARIS builds on similar themes that have motivated, for example, HELIOS [11], the AT-TPC [5], ISLA [12], the ReA facility, and ReA Energy Upgrade [1] among others. Below, we highlight examples across a number of different themes addressing the structural properties of nuclei, their role in astrophysical environments, as tools for probing fundamental symmetries, and broader contributions to society. It is natural that in some instances these overlap with examples from other FRIB and ReA writings. For each science opportunity, a connection is made to ReA and the AT-TPC or Si-array mode of operation of SOLARIS.

## 2.1 Evolution of Single-Particle Energies

Tracking single-particle excitations as a function of nucleon number has been instrumental in elucidating the role of nucleon-nucleon interactions and the interplay between single-particle behavior and collective phenomena in nuclei [13]. Nucleon-adding and -removing reactions allow the properties of excited states to be determined, including their excitation energies, quantum numbers, and spectroscopic overlaps. Together, these data allow for a quantitative description of the evolution of single-particle energies.

It has proven extremely challenging to access information on single-particle excitations at the extremes of isospin in all but the lightest systems. For example, while there is now limited information on collective excitations in the neutron-rich Ca isotopes [14], the underlying single-neutron and single-proton properties have yet to be explored. The same could be said for almost any chain of singly magic systems above oxygen.

With SOLARIS and the flexibility to switch between different operating modes, it will be possible to obtain detailed spectroscopic information on key nuclei in isotopic chains of Ca, Ni, Sn, and Pb isotopes, as well as along isotonic chains, such as the $N = 50$ isotones. For the latter, it is possible that single-neutron excitations at $N = 51$ could be tracked from the proximity of $^{101}$Sn to $^{79}$Ni via the use of the neutron-adding $(d,p)$ reaction. Figure 2.1 gives a sense of the degree to which knowledge could be extended in these key systems.

The interplay between collectivity and single-particle structure has recently been explored theoretically leading to a so-called Type II shell-evolution model [15]. The neutron-rich nuclei around $A = 100$, such as the Zr and Mo isotopes, have been highlighted as an ideal region to explore this experimentally. For these nuclei, a well-known sudden transition from spherical to deformed ground states with isospin occurs at around $N = 60$, which can be described as a quantum phase transition. With SOLARIS, the microscopic arrangement of protons and neutrons in those systems close to the phase transition could be probed through combinations of nucleon transfer reactions.

Proton-adding reactions prove challenging in inverse kinematics, where the natural choices are the ($d$,$n$), ($^3$He,$d$), and ($\alpha$,$t$) reactions. In one case, the outgoing nucleon is a neutron, and in the other two a He gas target is required. In the case of ($\alpha$,$t$) reactions, which typically have large negative $Q$ values, beam energies of around 15 MeV/u would be required. While the use of a gas target has been demonstrated in a solenoidal spectrometer (see Ref. [16] and Section 3.4), it is challenging to obtain a $Q$-value resolution of less than a few hundred keV. An alternative to using proton-adding reactions is to use proton elastic resonance scattering with SOLARIS in the AT-TPC mode. The same spectroscopic information, excitation energies and spectroscopic factors, can be extracted using this technique and it could prove invaluable in tracking, for example, proton excitations in the Sb isotopes above neutron-deficient and neutron-rich Sn isotopes. Proton elastic scattering can also be used to probe isobaric analog states, yielding spectroscopic information on neutron excitations. One can envisage probing the single-particle structures of both $^{133}$Sb and $^{133}$Sn, or other similarly interesting systems, in a single measurement.

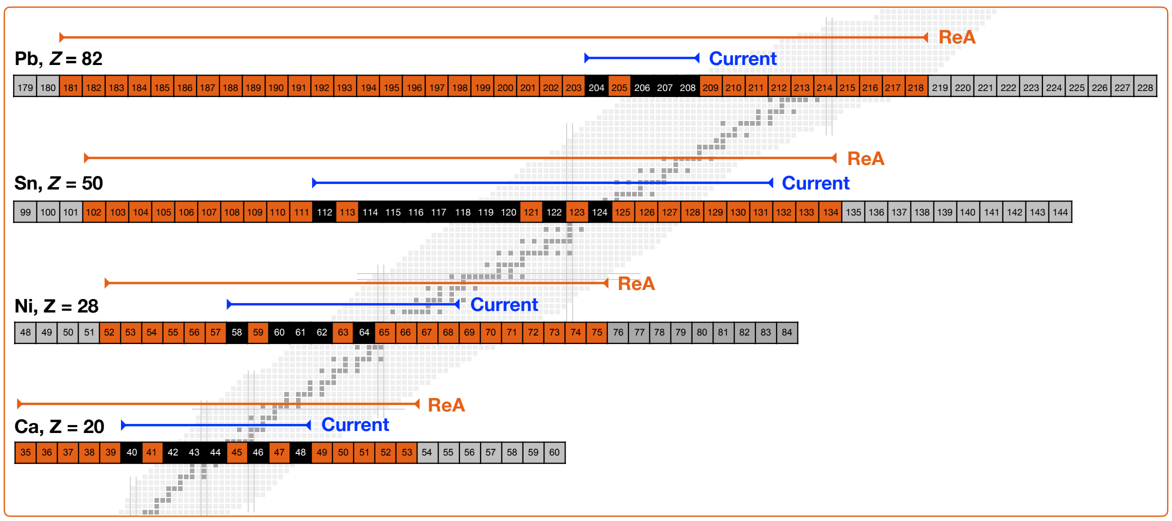


Figure 2.1: An example of the extended reach that comes with the coupling of ReA and SOLARIS. Isotopes at $Z = 20$, 28, 50, and 126 are shown. In this example a nominal beam rate of $10^4$ ions per second was assumed, using estimates from Ref. [17].

## 2.2 Weak-Binding Phenomena

Much of the science of FRIB will be focused on understanding the behavior of weakly-bound systems, which are inherent at the limits of stability. In these systems, the challenge will be to understand the interplay between the bound and unbound states, coupling to the continuum, and the underlying collective structures. Charged-particle spectroscopy will play an important role in characterizing both weakly-bound and unbound states, where it is not possible to use other approaches such as gamma-ray spectroscopy.

Weak-binding effects are somewhat ubiquitous across the nuclear chart. In light nuclei, the reordering of the commonly accepted shell-model levels is evident in nuclei in the proximity of $N = 8$, and can be easily understood as being dominantly a geometric effect related to the weak binding of $s$

states [18].This effect can be dramatic, resulting in shifts of single-particle energies by many MeV. It is the same qualitative effect that results in the formation of halo nuclei in neutron-rich systems [19], where they have been identified in systems from He to Mg.

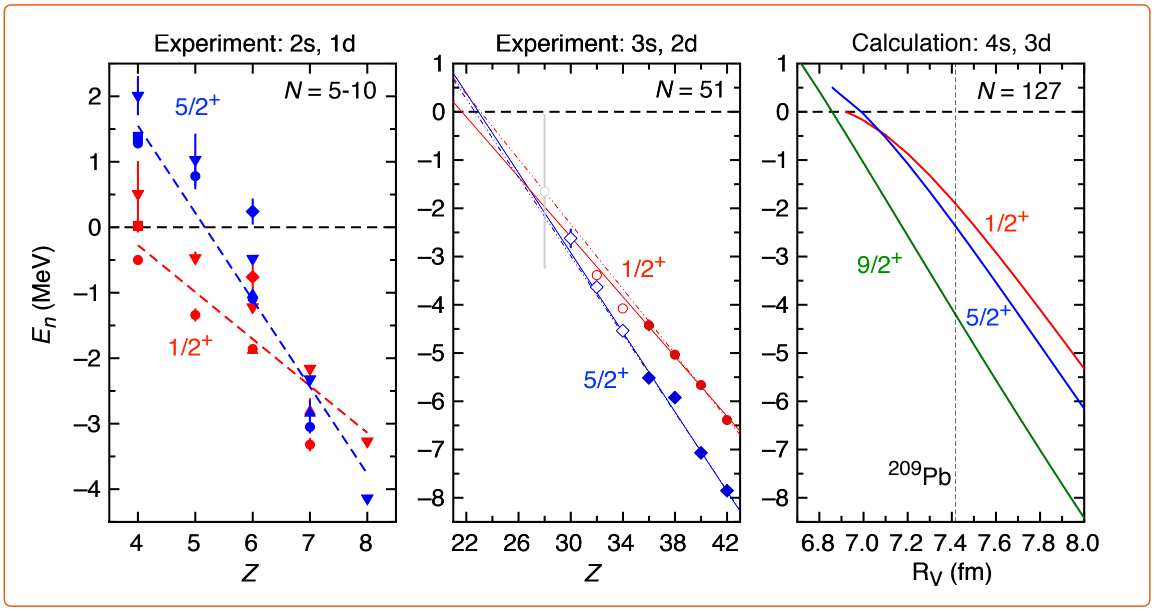


Figure 2.2: Systems where weak-binding effects could play a significant role in the low-lying structure of nuclei. With data from ReA and SOLARIS, significant constraints can be put on theoretical calculations of various phenomena. Figure modified from Ref. [20], which also includes references for the experimental data and descriptions of the calculations.

Major questions remain as to how weak binding plays a role in heavy nuclei and whether neutron skins and neutron halos might exist in these systems. While $2s_{1/2}$ neutrons play a role in halo nuclei like $^{11}$Li and $^{15}$C, could the $3s_{1/2}$ neutron play a role in halo formation in, for example, the neutron-rich Ca isotopes [21] or nuclei in the proximity of $^{78}$Ni [22]? Experimental data [23] and theoretical calculations [24, 25] suggest the $s$ and $d$ states outside of $N = 50$ are weakly bound and degenerate around $^{78}$Ni. The $s$ states are known to 'linger' below threshold, showing a reluctance to become unbound when compared to other states and, thus, the ordering of states is modified. What about the level sequences for nuclei around $N = 126$? These are open questions. With SOLARIS, neutron-adding reactions can be carried out to determine the character of these weakly-bound states and to constrain calculations that could reveal the onset of neutron halos or skins.

Figure 2.2 shows experimental data and simple theoretical calculations for the trends of neutron $s$ states in different oscillator shells at $N = 5$–$10$ and $N = 51$, constrained by some limited experimental data, and $N = 127$, where there are essentially no data. In all cases, ReA and data from reactions in SOLARIS, will provide invaluable insights and constraints.

Weak-binding effects are likely to play a significant role in the interpretation of other data. Effects such as the weakening of the spin-orbit interaction have often been postulated [26, 27] when unexpected trends in single-particle energies have been observed. For example, trends in the separation of the $2p$ states outside $N = 21$ have led to the postulation of a proton bubble and an effective weakening of the spin-orbit interaction. A closer examination reveals that the trends are likely a consequence of weak-binding effects [28], however, improved data are needed for these exotic nuclei and high resolution measurements with SOLARIS will reveal the complete picture.

## 2.3 Effective Interactions Deduced from Nuclear Spectra

Access to new regions of the nuclear chart will allow for improved effective interactions from single-particle spectra. Such data can be derived from single-nucleon transfer and inelastic scattering. Historically, nuclei one and two nucleons away from stable doubly-magic nuclei have been well studied and used to derive effective interactions which have led to highly refined shell-model calculations. Transfer reactions provide the necessary information, including excitation energies (binding energies) and cross sections, allowing for the extraction of spectroscopic factors and the determination of single-particle energies. For particle unbound systems, it is expected that modifications to effective interactions will arise due to coupling to the continuum [29].

Past studies have been limited to $^{16}$O, $^{40,48}$Ca, and $^{208}$Pb for the stable nuclei and, to a lesser extent, $^{90}$Zn. No such studies have been done with unstable doubly-magic nuclei. With ReA, detailed studies around $^{24}$O, $^{56}$Ni, $^{68}$Ni, and $^{132}$Sn become possible.

Taking $^{132}$Sn as an example, determining the location of each member of the multiplets in the particle-particle, particle-hole, and hole-hole systems ($^{134}$Te, $^{134}$Sb, $^{134}$Sn, $^{130}$Sn, $^{130}$In, $^{130}$Cd, $^{132}$Sb, and $^{132}$In) allows one to extract effective interactions [30]. The states could be probed through neutron/proton adding and removing reactions on beams of $^{133}$Sb, $^{133}$Sn, $^{131}$Sn, and $^{131}$In. The high resolution of SOLARIS in the Si-array mode is necessary for such measurements. A plot of the nuclei involved in such a study is shown in Figure 2.3. It is intended that SOLARIS can operate with two arrays in the Si-array mode (see Sections 4.2 and 4.4), such that reactions with outgoing ions moving in both the upstream and downstream directions can be measured simultaneously. For example, the $^{133}$Sb($d$,$p$) and $^{133}$Sb($d$,$t$) reactions can be measured at the same time, maximizing the outcome from a given amount of beam time.

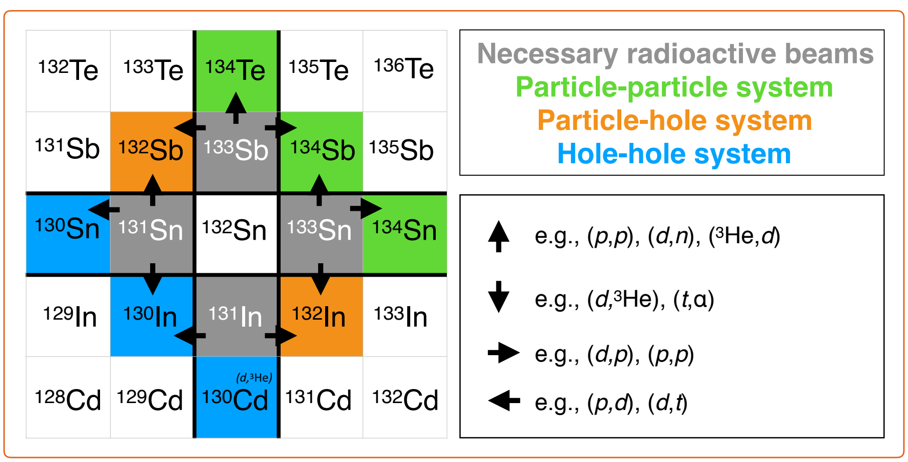


Figure 2.3: A plot of nuclei used to map out one- and two-nucleon effective interactions. A similar plot could be drawn for other doubly-magic systems, like $^{24}$O and $^{56}$Ni.

Alternatives to the use of transfer reactions include inelastic scattering. Such measurements would be ideal for the AT-TPC mode of operation. While in some cases charged-particle spectroscopy should be sufficient, simultaneous or complementary gamma-ray spectroscopy may be required as the level density in these systems could be high. For example, the coupling of the $g_{7/2}$ proton to the $h_{11/2}$ neutron hole results in eight states alone, often over a small excitation-energy range. The above examples imply a range of probes, from transfer reactions that populate low and high angular momentum states to inelastic scattering, are necessary to extract the required information. Options to run experiments with beams at energies of up to 10 MeV/u allows all of these reactions to be carried out.

## 2.4 Pairing in Nuclei

The transfer of a pair of nucleons to or from a nucleus can yield insights into both the underlying single-particle and collective aspects of the its structure [31]. The spectroscopic amplitude derived from pair-transfer cross sections such as $(t,p)$ and $(^3\mathrm{He},p)$ are sensitive probes of the ground state wave functions and provide complementary information to single-nucleon transfer and inelastic scattering measurements. Pair transfer will likely be an essential probe for revealing nuclear-structure properties across the nuclear chart at ReA.

There are many open questions that can be addressed with ReA beams and SOLARIS where pair-transfer reactions are the ideal approach. Some examples include: what is the role of neutron pairing correlations in more diffuse neutron-rich nuclei and in halo nuclei? Does isoscalar *np*-pairing occur in nuclei? In what region of the chart are there pairing vibrations, the interplay of shape coexistence, deformation, and single-particle properties? Many of these questions have been discussed for a long time, but there has yet to be appropriate beams, beam energies, and instrumentation to pursue the relevant measurements. ReA and SOLARIS will be the ideal combination to answer these questions. Some examples are given below.

Light neutron-rich isotopes are a region of key interest in the study of halo systems and neutron correlations. Pair-transfer reactions, such as the $(p,t)$ reaction, have already been carried out on the quintessential halo nucleus $^{11}$Li [32]. A reaction such as $^{12}$Be$(t,p)$ would be an ideal probe of $s$-wave amplitudes in $^{14}$Be. There has been discussion of potential excited halo states in $^{12}$Be. In addition, the $(p,t)$ reaction on these light neutron-rich systems becomes an attractive option as the $Q$ values are amenable to measurements in a solenoidal spectrometer such as SOLARIS. $^{12}$Be$(p,t)$ could be used as a probe of correlated $0^+$ states in $^{10}$Be, as it cannot be accessed through the $(t,p)$ reaction from $^8$Be. One could anticipate high-precision two-nucleon transfer studies on halo systems, such as $^{15}$B, $^{17}$C, and possibly $^{20}$C, $^{20,21}$N, $^{21}$O, neutron-rich Ne and Mg isotopes, and so on.

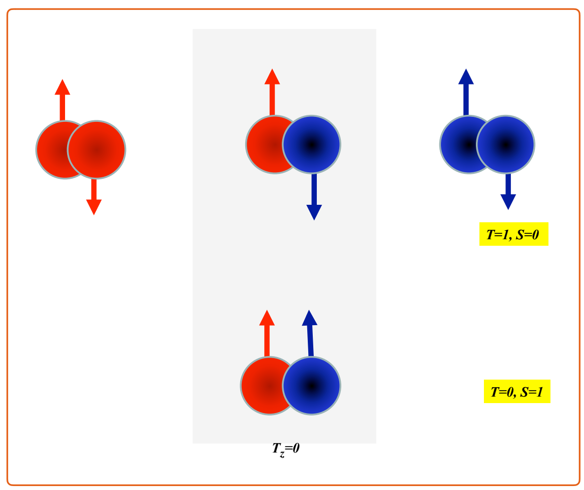


Figure 2.4: Nucleon pairing schemes in $N = Z$ nuclei. Figure taken from Ref. [36]

Given the complementarity of single-nucleon and pair-transfer reactions, it is not surprising that the other key regions of interest here mirror those of interest in single-particle structure studies. The use of neutron-pair adding reactions around the island of inversion has already created significant discussion, with the interpretation of the $^{30}$Mg$(t,p)$ reaction data still being debated [33, 34]. Key reactions that would resolve any ambiguities involve $^{32}$Mg$(t,p)$ and the reverse reactions, $^{34}$Mg$(p,t)$ and $^{32}$Mg$(p,t)$. Again, mirroring regions of interest in single-nucleon transfer, studies such as $^{32,34}$Si$(t,p)$ would be valuable in understanding the proposed ‘bubble’ nuclei [35], nuclear structure at $N = 20$, and pair transfer on the neutron-rich Ca isotopes.

The tritium-induced reactions will most likely be carried out with SOLARIS in the Si-array mode, where a solid tritium target can be used. Proton-induced reactions and those induced by He species, as discussed below, would benefit from the AT-TPC mode of operation.

Reactions such as ($^3$He,$p$) and ($^4$He,$d$) can be used to probe deuteron-like pair condensates in the final nucleus [36]. Speculation still remains as to whether this deuteron-like $T = 0$, $J = 1^+$ pairing exists in heavier nuclei, though there is a tentative claim of evidence for this [37]. The possible nucleon pairing schemes in nuclei are shown in Figure 2.4. Systems most likely to exhibit such behavior are those with $N = Z$, where protons and neutrons fill the same orbitals close to the Fermi surface. At present, studies of $T = 0$, $J = 1^+$ states via deuteron transfer have typically been limited to systems lighter than Ni. While normal isovector pairing dominates at low excitation energies in lighter ($A = 40$–$60$) nuclei, evidence for isoscalar pairing may be seen at higher excitation energy. With ReA it is possible that reaction studies can be pursued on these heavier systems. SOLARIS in the AT-TPC mode would offer a high resolution approach to studying such reactions.

Other regions where pair-transfer reactions will be of key interest are those near phase changes, where the sudden onset of deformation is approached. The quintessential example which requires exotic beams is around $A = 100$, for example moving from $^{98}$Zr to $^{100}$Zr. ($t$,$p$) and ($p$,$t$) reactions in this region will be a perfect probe for exploring the pairing properties of these systems. Regions of shape coexistence, such as $^{44}$S and $^{186}$Pb, also become available for study with pair-transfer reactions.

## 2.5 Charged-Particle Probes of Collective Properties in Nuclei

Collectivity is another key nuclear-structure property that has yet to be understood as nuclei evolve to large proton-neutron asymmetries. While techniques such as Coulomb excitation are available, and have been somewhat of a mainstay over recent years, they can be limited in terms of interpreting the complex gamma-ray spectra and fitting the experimental data with Coulomb-excitation models.

Nuclear inelastic scattering, such as ($p$,$p'$), ($d$,$d'$), and ($\alpha$,$\alpha'$) reactions, is an attractive alternative. The magnitude of the cross section scales with deformation length of a given excitation. It directly probes low-lying collective modes with moderate cross sections, comparable to those in transfer reactions. One such example is the isoscalar ($d$,$d'$) reaction, which can be used to probe quadrupole and octupole collectivity allowing the $B(E2)$ and $B(E3)$ reduced transition probabilities to be extracted. Key studies at ReA would be on those systems around $A = 140$, where octupole correlations are strong as indicated by current, but limited, data from Coulomb excitation studies [38, 39], and on nuclei in regions of the chart where shape changes/coexistence occur [40]. Elucidating regions of the chart where nuclei might exhibit octupole deformations is of major interest in studies of fundamental interactions as discussed in Section 2.7.

Coulomb excitation is a purely electromagnetic probe depending on the charge (proton) motion for both electric and (to first order) magnetic transitions. Neutron motion could contribute to large collective matrix elements, either coupled with or decoupled from the proton motion. Those neutrons decoupled from the proton motion would not be evident in Coulomb excitation measurements, but would be apparent in inelastic scattering. Access to extremely neutron-rich and deficient beams will allow such possible effects to be explored in more depth and likely form an essential alternative and complementary probe to Coulomb excitation. Such studies, albeit at very high beam energies, have already begun with the neutron-deficient Sn isotopes [41].

Inelastic scattering can also be used as a probe of other modes, such as soft-dipole resonances. Interesting results have been obtained from using both isoscalar ($d$,$d$') [42] and isovector probes in light neutron-rich nuclei to characterize soft-dipole resonances, a mode which is shown schematically

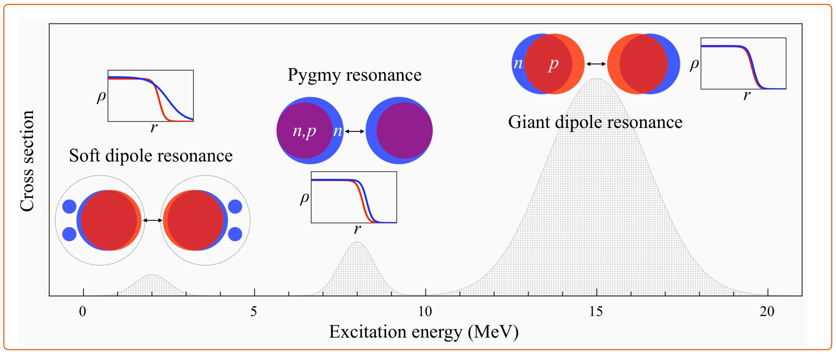


Figure 2.5: Various collective dipole resonance modes that could be probed via charged particles.

in Figure 2.5. It is likely to be a fascinating technique for neutron-rich systems. SOLARIS offers major benefits over recent approaches in that, regardless of the mode of operation, it can measure yields at relatively forward center-of-mass angles. In the AT-TPC mode, it will allow for studies of inelastic scattering induced by $^{3,4}$He species, being the target medium. Using different probes will allow for the isovector and isoscalar collective matrix elements to be separated, e.g., by using $(p,p')$ and $(\alpha,\alpha')$ reactions. Other recent studies have looked at extremely neutron-deficient systems and elastic scattering to provide insights into the nuclear force [43].

Finally, inelastic scattering can be used as a probe of unbound states and determine their widths and branching ratios. A recent example [44] of this approach is the precision study of the $E2$ transition matrix elements in the $A = 10$ isospin triplet $^{10}$C, $^{10}$B, and $^{10}$Be. In $^{10}$B, the relevant $2^+$ state is particle unbound. Using inelastic scattering, and a solenoidal spectrometer allows recoils from different decay channels to be measured and, for example, the $\alpha$-decay branch to be determined. This technique is likely to become an essential tool for probing collective structures in weakly-bound nuclei, where given excitations are above the separation energy. Both modes of operating SOLARIS will flourish here.

## 2.6 Nuclear Astrophysics

A main thrust of radioactive beam programs world-wide, and a key component of the future FRIB science opportunities, is the study of reactions that address fundamental questions in science, such as: What are the origins of the heavy elements? What are the driving mechanisms of stellar explosions? Various processes have been identified in which nuclei are synthesized under certain extreme temperature and density conditions. However, there is still significant debate concerning the specific astrophysical sites in which many of these processes occur [45]. Figure 2.6 illustrates possible paths for just two of these processes on the chart of nuclides. Nearly all the known elements heavier than iron are synthesized either by slow neutron-capture reactions ($s$-process) or rapid neutron-capture reactions ($r$-process).

Reaction network calculations for the $r$-process require many crucial inputs such as nuclear masses, $\beta$-decay lifetimes, and neutron-capture reaction rates [46, 47, 48]. However, direct measurements of neutron-induced reactions on low-intensity, short-lived exotic nuclei are not yet feasible. Therefore, indirect methods must be studied to provide nuclear structure inputs to constrain reaction-rate calculations.

Spectroscopic information, such as excitation energies, spin assignments, and spectroscopic factors, derived from neutron-transfer measurements, can be particularly useful. Spectroscopic factors to the bound states in the final-state residual nuclei can be used to constrain the direct-capture contribution to the cross section, which is described by capture through the tails of the bound-state wave functions [49].

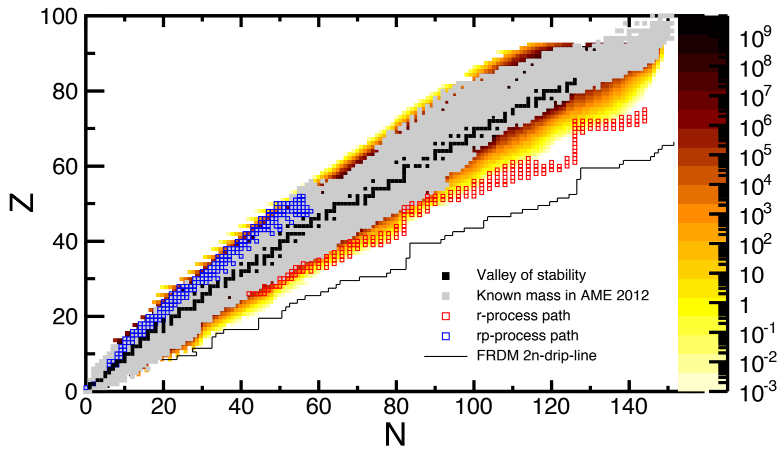


Figure 2.6: The chart of nuclides with known masses, estimated FRIB rates (ReA rates are typically factors of a few to a hundred lower), and estimated *rp*- and *r*-process paths. Figure from Ref. [50].

In addition, the excitation spectrum above the neutron separation energy must be determined, since the resonant contribution to the reaction rate depends exponentially on the resonance energies [49]. The possibility of using ($d$,$p\gamma$) as a surrogate for the ($n$,$\gamma$) reaction has also been explored using the Apollo [51] gamma-detection array coupled to HELIOS. The same array, or a modified version, could be coupled to SOLARIS.

Explosive hydrogen burning occurs in several astrophysical environments, most notably in cataclysmic binary systems. Classical novae outbursts and type I X-ray bursts are the most prominent stellar explosions driven by charged-particle reactions [52]. Both phenomena arise from thermonuclear ignition in the envelopes of compact objects in close binary star systems. The two primary reaction networks involved in explosive hydrogen burning are the Hot CNO (HCNO) cycle and the rapid proton capture process (*rp*-process). The latter is shown in Figure 2.6. After breakout from the HCNO cycle, the *rp*-process proceeds by successive proton capture ($p$,$\gamma$) reactions and $\beta$ decays. Measurements of the relevant ($p$,$\gamma$) reaction cross-sections are therefore critical to our understanding of the outburst phenomenon itself. These, in combination with direct astrophysical observations, provide constraints for theoretical models of hydrogen burning.

Direct measurements of ($p$,$\gamma$) cross-sections are planned using devices such as the SECAR separator [53] at FRIB. However, there are cases in which the cross sections at the relevant low-energy regimes will be too small for direct measurements, even with FRIB intensities. In such cases, indirect studies of the analogous single-step proton transfer reactions, e.g., studies of the ($^3$He,$d$) reaction, can provide the necessary nuclear-structure inputs to constrain ($p$,$\gamma$) reaction rates and provide guidance to future direct measurements. Of importance is a description of the energy spectrum of the residual nucleus, in which the states just above the proton separation energy will appear as narrow resonances in the proton-capture process. Like neutron capture, the reaction rate will depend exponentially on the excitation energy of these states and proportionally to their spin and decay widths.

Due to the angular momentum barrier, the capture process will be dominated by low-lying resonances that are populated via low angular-momentum transfer. The ($d$,$n$) transfer reaction, with $Q = -2.22$ MeV at the proton separation energy, is better suited than the ($^3$He,$d$) reaction, $Q = -5.6$ MeV, as it is better matched for lower angular momentum transfers and will preferentially populate the same states that impact the ($p$,$\gamma$) cross section.

The resonance energies, as well as decay widths, can be precisely determined by studying resonant elastic scattering of protons in inverse kinematics. This technique was previously used to unambiguously identify the "missing" $3^+$ state in $^{18}$Ne, which was found to be a narrow resonance at $E_{\text{c.m.}} \sim 600$ keV. With this guidance, a direct measurement of the resonant contribution to the $^{17}$F($p$,$\gamma$)$^{18}$Ne cross section could be performed [54]. Studies of proton elastic scattering, as well as ($d$,$p$) and ($^3$He,$d$), could be performed in either the AT-TPC mode or Si-array mode of SOLARIS.

In cases where the particle-decay width is much larger than the gamma-decay width, the contribution to the reaction rate becomes almost solely dependent on the gamma-decay width. In the case of the $^{15}$O($\alpha$,$\gamma$)$^{19}$Ne reaction, measurement of the decay branching ratios for the 4.033-MeV state in $^{19}$Ne is important. By combining the high-intensity beams of FRIB with the counting efficiency of SOLARIS, measuring these very small branching ratios ($< 10^{-3}$) should be feasible. In the AT-TPC mode of SOLARIS, measurements of both the breakout ($\alpha$,$p$) and ($p$,$\alpha$) reactions, which can be measured both directly or in time-inverse on neutron deficient nuclei, will be possible.

The region of the nuclear chart south of $^{208}$Pb is still terra incognita. It is this region that will yield insights into the location of the $r$-process path and the presence of the third $r$-process mass abundance peak. ReA will provide access to neutron-rich beams *close* in mass to this region. With SOLARIS, the properties of nuclei around, e.g., $^{206}$Hg, $^{204}$Pt, and possibly some lighter $N = 126$ nuclei, can be probed via transfer reactions. Such data will be significant as the first probe of nuclear structure in this region and for constraining our understanding of the $r$-process for heavier nuclei [55]

Operating in both modes, SOLARIS will be an essential tool for nuclear astrophysics and relevant to studies relating to all astrophysical processes, from those involving the very lightest nuclei, to the very heaviest.

## 2.7 Fundamental Symmetries

Charged-particle reactions have proven to play an important role in testing fundamental symmetries in stable nuclear systems, where relevant. There is an urgency to push these well-established techniques into the radioactive-ion-beam domain. Two examples given below benefit from the improved resolution and versatility of SOLARIS.

The first example highlights how high-precision measurements of nuclear-decay properties can be a critical tool in the quest to identify possible physics beyond the Standard Model (BSM) [56]. Superallowed $0^+ \to 0^+$ nuclear $\beta$-decay data are among the most important to these tests, as they currently provide the most precise determination of the vector coupling strength in the weak interaction, $G_V$, as well as limits on any scalar contributions to the vector part of the weak interaction [57, 58]. In fact, the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, $V_{\text{ud}}$, is the most precisely known (0.021%) [58], and relies almost entirely on the high-precision superallowed $\beta$-decay $ft$-values determined through measurements of the half-life, decay $Q$-value, and branching fraction of the superallowed decay mode [57]. For the decay branching ratios in particular, the location of any excited, "non-analog" $0^+$ states is critical for observing (or placing limits) on any decays away from the superallowed channel. Among other techniques, recent works, for example [59], have used two-neutron pair transfer reactions to search for, or rule out, the presence of excited states in the daughters of superallowed $\beta$-decay nuclei. These reactions are sensitive probes of $0^+$ states, and have distinctive forward-peaked angular distributions allowing for robust assignments. In the case of $^{50}$Mn [59], the daughter $^{50}$Cr was probed via the $^{52}$Cr($p$,$t$) reaction, which is accessible with stable beams and targets. Other systems, such as $^{74}$Rb$\to^{74}$Kr (the heaviest high-precision case in the review of Ref. [57]) are not accessible and require studies with radioactive ion beams. While studies of

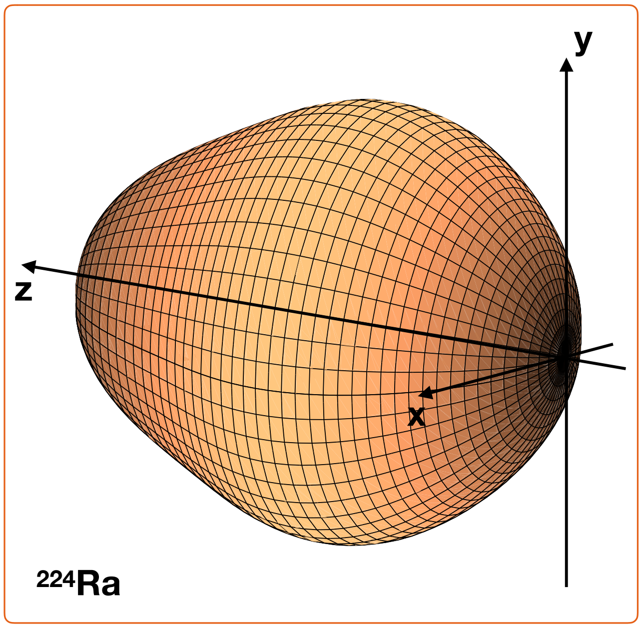


Figure 2.7: A schematic representation of the octupole deformed or 'pear-shaped' nucleus $^{224}$Ra. Additional information is available in Ref. [60].

neutron-deficient nuclei via ($p$,$t$) reactions are hampered by the prohibitively large negative $Q$ values, the use of the ($t$,$p$) reaction is possible. To probe $0^+$ states in $^{74}$Kr, the $^{72}$Kr($t$,$p$)$^{74}$Kr reaction would be ideal.

Further, in order to extract $V_{\mathrm{ud}}$ from the high-precision experimental data, corrections to the almost nucleus-independent $ft$-values for superallowed $\beta$ decay must be made for radiative effects as well as isospin symmetry breaking (ISB) by Coulomb and charge-dependent nuclear forces [57]. Although these corrections are small ($\sim 1\%$), experimental measurements have provided such precise $ft$-values [57] ($\pm 0.03\%$) that the uncertainty on $G_V$ is currently dominated by the precision of the theoretical corrections. One- and two-neutron transfer reaction studies can be used to both test and guide the ISB correction calculations [59], which are particularly difficult to perform in heavy systems. These heavy $N = Z$ systems are not accessible for reactions in normal kinematics with a stable target, and are currently only accessible with radioactive ion beams such as those that ReA is able to provide. SOLARIS will allow for detailed spectroscopic studies of these nuclei, pushing this field into a new era. These reaction studies have also been used to advance the calculation techniques into the heavy *ab-initio* regime [59], which will allow for better tests of the Standard Model using nuclei.

The second example concerns the search for larger-than-Standard-Model values of an electric-dipole moment (EDM) in nature. These are the subject of major international searches [61]. Several recent works have shown enhanced octupole correlations, via deductions of their $E3$ moments, in two regions of the chart, at $^{224}$Ra [60] (and see Figure 2.7) and at $^{144,146}$Ba [38, 39] using Coulomb excitation and radioactive ion beams from CERN's ISOLDE facility and ANL's ATLAS + CARIBU facility, respectively. Odd-$A$ nuclei with large octupole deformation and low-lying parity doublets result in an enhanced collective nuclear Schiff moment and potentially provide orders of magnitude more sensitivity for atomic EDM searches. There are regions of the nuclear chart where such enhanced octupole deformation is anticipated, namely in nuclei with protons and neutrons occupying different valence spaces, such that the $\Delta j = \Delta \ell = 3$ condition can arise [62, 63]. These regions are those where $Z \approx 34$, 56, and 88, and $N \approx 34$, 56, 88, and 134.

While Coulomb excitation studies have shown that it is possible to determine the $E3$ moments, some measurements have suffered large uncertainties due to low intensity beams and the inefficiency of $\gamma$-ray detectors. Further, $E3$ transitions are not directly seen, rather inferred from competing $E1$ transitions, for example. In some cases, the density of levels near the ground state might make measurements challenging. An attractive alternative is to directly probe these states via inelastic scattering reactions, as discussed in Section 2.5. In this case, the measured cross sections are proportional to the deformation length squared, which in turn is proportional to the reduced transition strength, without having to introduce a squared term. At ReA, essentially all theoretically favorable candidates are available for study via this technique provided that an instrument like SOLARIS is available.

## 2.8 Education, Applications, and Societal Benefits

The AT-TPC mode of SOLARIS requires sophisticated analysis software to unravel the trajectories of particles under the influence of a magnetic field. As an active target, the incident radioactive beam will gradually lose energy until coming to a stop inside the chamber. The reactions under study will only occur a small fraction of the time and the data-sorting algorithms must be able to extract these rare events from large and complex datasets. The students and post-docs that are responsible for the analysis of AT-TPC data, and the development of such algorithms, will have on-the-job training for data sorting and data-visualization techniques that are substantially more complicated than most other experimental setups in nuclear physics. The learned imaging techniques would easily prepare a student for a career involving medical imaging and radiation effects.

On the other hand, the Si-array mode of SOLARIS capitalizes on the focusing effects of the magnetic field to simplify the analysis procedure. Technical difficulties are encountered when attempting to implement auxiliary detectors in the magnetic field and to couple them with the Si array. As a result, novel devices must be developed which are, by necessity, both compact and capable of operating in and around the field. A research award has recently been approved for the development of a gas-jet target that will require innovative engineering to successfully implement. Results from the testing of the mechanical infrastructure, electronics, and radiation detectors from such planned devices could be of use to industries that make use of strong magnetic fields.

Neutron-capture reactions on short-lived exotic nuclei are critical for understanding the energy generation in nuclear reactors, nuclear weapons and in stellar nucleosynthesis. Recently, a research program began at ANL which involves the study of neutron-capture reactions via the surrogate $(d,p\gamma)$ reaction with HELIOS and the Apollo gamma-ray detection array. This work is led by the LANSCE group at Los Alamos National Laboratory, and is meant to provide complementary information to the direct neutron-capture measurements that are studied with the Detector For Advance Neutron Capture Experiments. This program, which currently utilizes the radioactive beams delivered by the ATLAS + CARIBU facility, will eventually lead to a future program at FRIB.

# 3. The Instrumentation and Facility

As discussed in Section 2, the science opportunities for a high-resolution charged-particle spectrometer system are wide ranging and form a key component of the science to be addressed with FRIB and re-accelerated beams. In many instances there is no plausible method for pursuing the described research other than to develop a dual-mode charged-particle spectrometer as proposed here. The following section highlights the challenges associated with pursuing various measurements and technology choices selected to overcome these in the SOLARIS project: a Si-array solenoidal spectrometer; an AT-TPC for use in a solenoidal field; the ReA facility at NSCL and later FRIB; and auxiliary target and detection systems.

With direct reactions clearly identified as an essential tool for revealing the properties of atomic nuclei, significant effort has gone into developing instruments to measure reactions in inverse kinematics with radioactive ion beams.

The challenges are numerous:

- Radioactive ion beams typically have low intensities, from a few to $10^7$ ions per second,
- The outgoing ions at forward center-of-mass angles, typically those of interest, are at relatively low energy making particle identification challenging,
- The $Q$-value spectrum, if recorded as a function of laboratory angle, is kinematically compressed, by a factor of 2 to 3, which in many cases limits the information one can gain from a given measurement,
- For negative $Q$-value reactions, the presence of two kinematic solutions demands a high degree of angular resolution,
- Weak beams often demand thick targets, many of which contain other atomic species (e.g., proton and deuteron targets are often plastic compounds).

Several pioneering instruments have been developed to overcome these challenges. Si arrays have led the way, often with annular Si detectors covering both forward and backward center-of-mass angles. Examples include MUST2 at GANIL [64], T-REX at ISOLDE [65], SHARC at TRIUMF [66], ORRUBA at various sites [67], TIARA [68] (formerly of GANIL, now at Texas A&M), HiRA at NSCL [69], and others. Some of these operate in conjunction with gamma-ray arrays. While this approach can offer additional information on gamma-ray transitions and aid in resolving given states, it is limited. For example, not all levels decay via gamma-ray emission (ground state, and so on). Isomers can be a challenge, as the decaying nucleus may have exited the spectrometer before it decays. Furthermore, at the limits of nuclear stability, the spectroscopy of unbound states is essential to understand weakly-bound systems, which is not possible when relying on gamma rays. Beyond that, these detector systems are typically complex in terms of electronics, data acquisition, and analysis.

To attain excellent $Q$-value resolution, one has to operate in heavily-constrained geometries and have high-intensity beams. These situations are rare [70] and not feasible for the vast majority of radioactive ion beams expected at ReA. Regardless of the technology it is not possible to remove kinematic compression, a feature of the kinematics of transfer reactions in inverse kinematics where the energy spectrum of ions in the lab frame is compressed, leading to poor $Q$-value resolution and resolving power. For light-ion reactions at energies around 10 MeV/u, this factor is typically around 2-3.

## 3.1 Solenoidal Spectrometers

An attractive alternative to the use of Si detectors are fixed laboratory angles is provided by transporting the outgoing ions through a solenoidal field to the detector. In this arrangement, the beam enters the solenoidal field on axis. The beam axis and the field axis are coincident. The reaction occurs at a given position along the axis where a target is situated. The outgoing ions follow helical trajectories, returning to the axis one cyclotron period of time later characterized by their mass-to-charge ratio. The energy, flight time (from a defined reference, e.g., the radio frequency of the accelerator or from a recoiling ion), and distance from the target can be recorded by a Si array that surrounds the magnetic axis. The time signature identifies the outgoing ion, not relying on telescope arrangements which can be challenging to use with low-energy ions.

Transporting the outgoing ions through the solenoidal field removes the kinematic compression associated with transfer reactions in inverse kinematics [2]. This leaves a simple linear relationship between the spectrum of outgoing ions in the laboratory frame and the $Q$-value spectrum of interest. This effect is shown in Figure 3.1. This method also yields a large geometrical acceptance. All ions emitted at backward or forward laboratory angles are focused onto the array. For reactions such a $(d,p)$ at beam energies of 5-15 MeV/u, center-of-mass angles between $\sim$5-30 degrees are recorded with excellent efficiency, limited only by the geometry of the on-axis Si array.

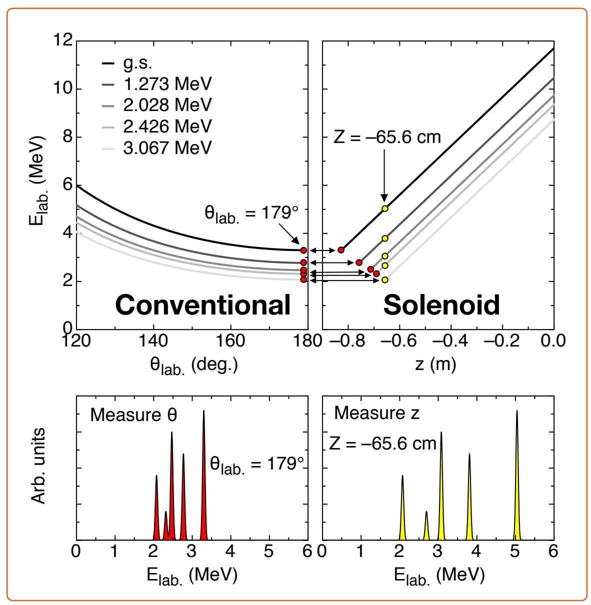


Figure 3.1: The kinematics of outgoing protons following the $^{28}$Si$(d,p)$ reaction at 6 MeV/u in inverse kinematics as a function of laboratory angle ("Conventional") and position in a solenoidal field. The resulting $Q$-value spectra are also shown.

This technique was realized as HELIOS at ANL in 2008 [3] following previous design studies [2]. A schematic of the instrument is shown in Figure 3.2. In just shy of 10 years of operation, the instrument has proven remarkably successful in the study of many light exotic species produced using the in-flight technique (see, for example, Refs. [71, 72, 73]) at ATLAS, and in the study of heavier stable species in anticipation of beam from ATLAS's CARIBU system [74, 75]. For the latter, studies with beams of Kr and Xe have shown that a $Q$-value resolution of better than 100-keV FWHM can be achieved.

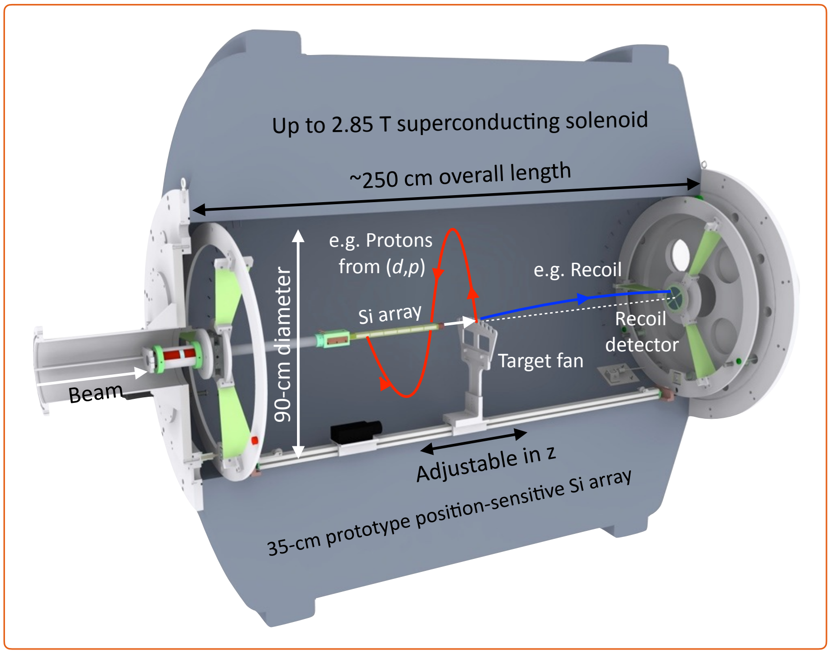


Figure 3.2: A schematic of the HELIOS spectrometer at Argonne National Laboratory [3]. Example trajectories are shown.

The solenoidal spectrometer approach is also highly versatile and flexible, both in terms of the variety of reactions that can be studied and in the implementation of auxiliary equipment that can be coupled to the spectrometer for additional selectivity or to monitor other probes. To date, single-nucleon transfer reactions such as $(d,p)$, $(d,t)$, and $(d,^3\mathrm{He})$ have been studied. Multi-nucleon transfer reactions, such as neutron pair transfer via $(t,p)$ and $(d,\alpha)$ have been used to probe pairing properties in nuclei, and more complex reactions such as $(\alpha,p)$ have been used to constrain astrophysical reaction rates. Collective modes can also be probed by inelastic scattering, such as $(p,p')$ reactions. We expect this list to expand in the coming years.

The flexibility of the instrument lies in the fact that it is a large, mostly empty cylindrical scattering chamber. The on-axis Si array can be mounted upstream or downstream of the target and providing that the trajectories of interest are not blocked, other instrumentation can be installed. For example, gas targets [16] and gamma-ray detectors have been used. The Apollo array [51] is a hemisphere of LaBr and CsI detectors used in conjunction with the HELIOS on-axis Si array to determine photon strength functions with radioactive ion beams. A variety of recoil detectors and monitor detectors have been implemented into HELIOS, including fast counting ionization detectors [76]. These are discussed further in Section 3.4.

The success of the HELIOS program has been recognized internationally. A similar device, the ISOLDE Solenoidal Spectrometer (ISS), is in the advanced stages of assembly at CERN's HIE-ISOLDE facility [77]. A conceptual drawing of the ISS is shown in Figure 3.3. The solenoid for ISS is also a decommissioned MRI magnet made by Oxford Instruments, and is one of a small number of solenoids made for MRI purposes with a large bore and length (around 90 cm in diameter and over 250 cm long) and a maximum field of 4 T. As will be discussed in Section 4.3, the same model of solenoid will be used for the SOLARIS project. The increase in field strength from 2.85 T for HELIOS to 4 T available for ISS and SOLARIS expands the scope of the physics program of the instrument, allowing more negative $Q$-value reactions such a $(p,d)$ and $(p,t)$ to be studied.

A version of a solenoidal spectrometer has also been developed at Notre Dame, called the Solenoidal

Spectrometer for Nuclear AstroPhysics (SSNAP) [78]. It represents a modified usage of the TwinSol system at the Nuclear Science Laboratory. SSNAP exploits the large 6-T field of TwinSol with a compact Si array to measure reactions relevant to nuclear astrophysics, a schematic of which is shown in Figure 3.3

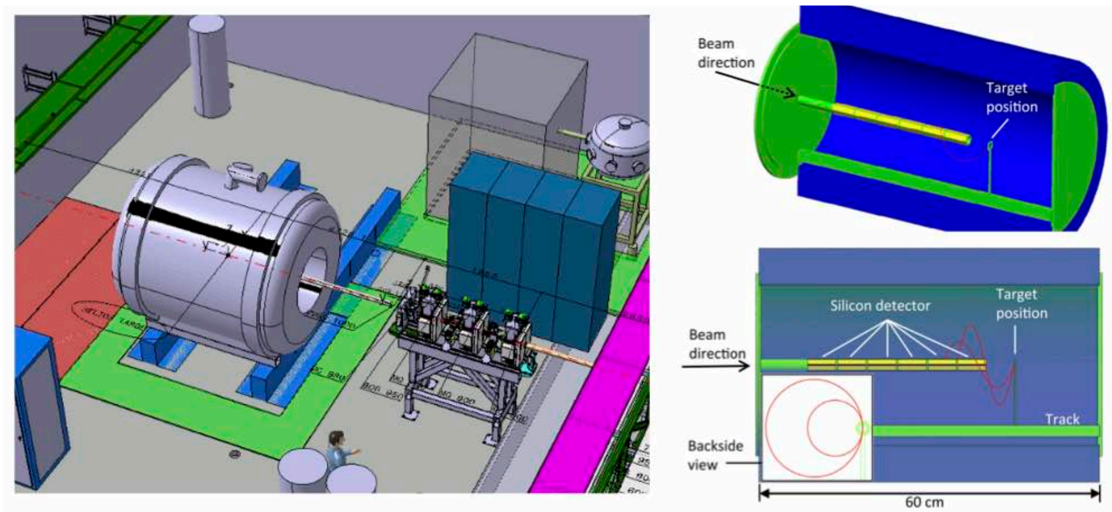


Figure 3.3: (Left) The ISOLDE Solenoidal Spectrometer (ISS) at CERN [77] and (right) the SSNAP spectrometer at Notre Dame [78].

The success of HELIOS and the development of new solenoidal spectrometers, coupled with the science opportunities available with ReA beams and direct reactions, is what motivates the development of SOLARIS. In its vacuum mode with an on-axis Si array, it will be the premier instrument at ReA for the study of transfer reactions with beam intensities greater than approximately $10^4$ particles per second. The advantages are given in the box below.

Advantages of a Si-array mode solenoidal spectrometer are:

- outstanding $Q$-value resolution,
- simple kinematics regardless of the reaction $Q$ value,
- large acceptance and high efficiency,
- the ability to run several measurements simultaneously,
- particle-identification of low-energy ions via time rather than energy loss measurements,
- and a simple treatment of isomeric and unbound states.

For weaker beams, or for more complex reactions with many-body final states, there are other attractive solutions such as the Active Target Time Projection Chamber, AT-TPC, at the NSCL. This instrument is coupled to the SOLARIS project as it is intended to be housed in the same 4-T solenoid when SOLARIS is not being used in vacuum mode with a on-axis Si array.

The two operating modes of SOLARIS are highly complementary and together cover an impressively broad range of physics. The AT-TPC mode solenoidal spectrometer is discussed next.

## 3.2 Active Target Time Projection Chambers

There are many situations where it is necessary to forgo the high resolution and simplicity of the Si-array mode solenoidal spectrometer. These include: very low-intensity beams (less than approximately $10^4$ particles per second); small-step excitation-function measurements that require many beam energy changes where it is not possible to retune the linac over a number of small incremental energy changes; close to $4\pi$ solid-angle coverage is desired; and when the reaction of interest has a many-body final state and it is necessary to measure them all [4]. A time-projection chamber can address many of these challenges. The AT-TPC developed at NSCL is designed to operate under these conditions [79, 5, 6].

The AT-TPC is a large-volume (250 liters) gas-filled detector. A schematic of the detector volume is shown in Figure 3.4. The nuclei of the gas molecules act as the target isotopes. This results in an effective luminosity which can be as much as 100 times greater than can be achieved in a conventional 'thin' solid-target experiment. The luminosity is tunable, by adjusting the gas pressure and gas type. It is this large luminosity that allows direct reactions, with typical cross sections on the order of a few mb, to be carried out with beams as weak as hundreds of particles per second—a few orders of magnitude weaker than required for conventional approaches.

The gas volume is also the tracking medium. Primary electrons released from the ionization of the gas are drifted along an electric field and collected on a sensor plane. This plane is equipped with an electron multiplication device that creates an avalanche for each of the collected electrons. The resulting signals are registered on an array of pads connected to digital electronics. The time evolution of the signals is recorded, the arrival time of each primary electron providing the position measurement along the drift direction (time projection chamber operation). The resulting image provides a 3-dimensional snapshot of all the charged particle trajectories within the active volume for each event.

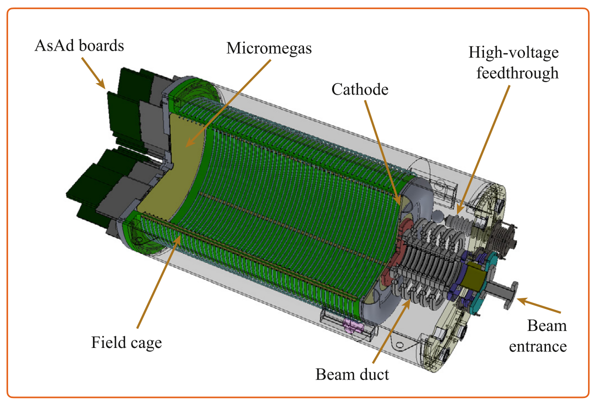


Figure 3.4: A schematic of the AT-TPC from Ref. [5].

The reaction vertex is located within the gas volume and is determined for each event, from which the energy of the beam at the time of the reaction can be deduced. This is in stark contrast with passive targets where the beam energy can only be averaged over the energy loss of the whole target thickness, often the main limitation in the achievable energy resolution. Therefore, the resolution achievable with active targets is not only better than with passive targets, but also independent of the target thickness. In addition, particles with low recoil energies can be detected with very low thresholds as long as their tracks can be identified outside the vertex region.

Given that the gas slows down the beam, reactions occur at different incident energies along the length of the detector. This allows for excitation energy functions to be measured in one go, using a single incident beam energy. Properties such as angular distributions and reaction $Q$ values can be extracted from the data.

The AT-TPC can be operated both with and without an axial magnetic field. An image from the recent commissioning of the AT-TPC in a 1.7-T large-bore solenoid is shown in Figure 3.5, along with the tracks of ions in both the $xy$- and $zy$-planes [5]. The field offers two advantages over operation

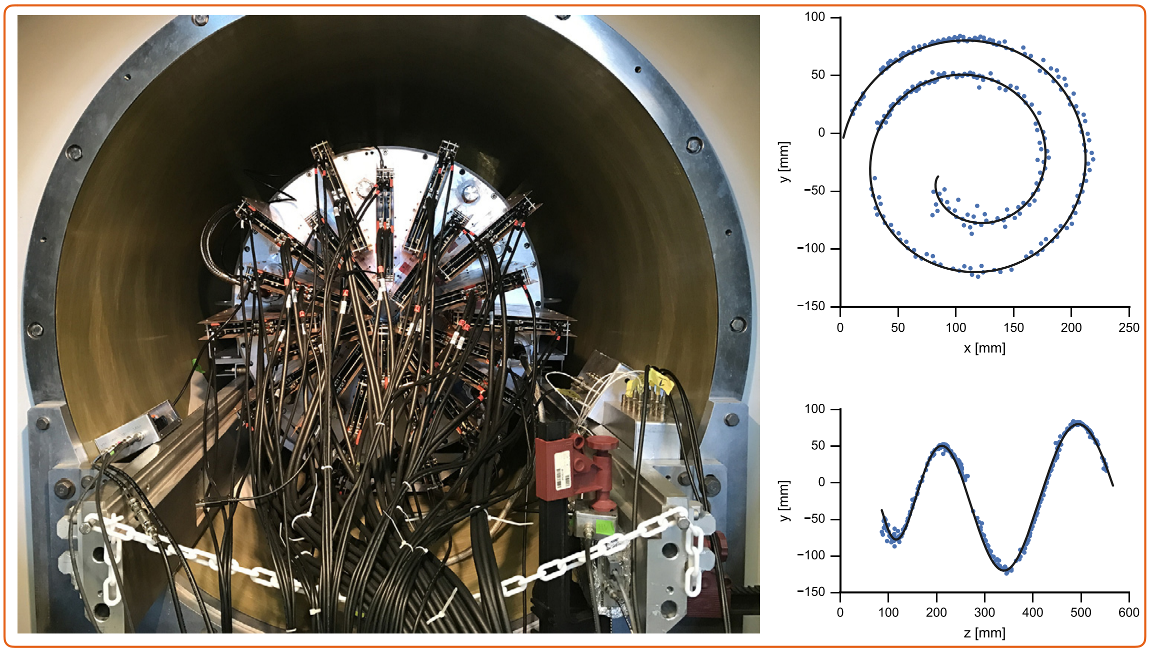


Figure 3.5: The AT-TPC inside a large-bore solenoid (left) at the NSCL, and example tracks following proton resonant scattering induced by an $^{46}$Ar beam on the target gas within a 1.7-T solenoidal field [5, 80].

without a magnetic field, namely that longer trajectories can be recorded as they spiral around inside the volume. The radius of curvature of the spirals also lends itself to particle identification in much the same way the cyclotron period of the ions in the Si-array mode relates to the mass and charge of the outgoing ion. Measuring the magnetic rigidity of the recoil particle can also provide a means to identify and separate states populated by the reaction. This is especially true of reactions using light targets in inverse kinematics, where the kinematical properties of the recoil track can only be measured accurately. The magnetic rigidity provides an orthogonal measurement of its energy that allows a determination of the $Q$-value of the reaction. In addition, longer trajectories provide a better measurement of the energy loss profile of the particles, up to the entirety of the range, which gives yet another determination of the total energy of the recoil particle. The importance of using the 4-T field of SOLARIS instead of the present 2-T field is critical in that regard.

Another advantage includes the ability to have isotopically pure targets. Among many other types of gases, the AT-TPC can be filled with gases such as $H_2$,$D_2$, He, Ar, etc., as required by the reaction to be studied. Pure gases have the advantage of eliminating reactions on unwanted isotopes. They also increase the luminosity of experiments when using light targets by reducing the energy loss per number of scattering centers. For example, common deuterium targets used in conventional set ups include plastic compounds such as $CD_2$. This results in reactions on the carbon in the target which can have a large cross section, and larger energy loss compared to a $D_2$ target due to the larger number of electrons in carbon. The advantages of the AT-TPC are summarized below.

Advantages of a AT-TPC mode solenoidal spectrometer are:

- the gas is both the target and detector providing a thick target without loss of resolution,
- vertex determination, $\sim 4\pi$ angular coverage, very low-energy threshold,
- excitation functions from the beam slowing down in the gas and vertex determination,
- ability to run several measurements simultaneously,
- with a solenoidal field, capture longer tracks and robust particle identification.

It is expected that SOLARIS will run in a campaign mode. For certain periods of time it will run as a Si-array mode solenoidal spectrometer, while the AT-TPC can be stationed on another beam line in standalone mode, and at other times with the AT-TPC inside the solenoid. As will be discussed in the Section 4, the design will be such that operation in both modes can be set up with minimal effort.

## 3.3 The ReA Facility

The SOLARIS project is singularly focused on exploiting the outstanding opportunities afforded by the ReA facility at NSCL now, and FRIB in the future. The ReA facility is discussed in this section.

The present ReA3 facility at NSCL [81] has been delivering rare-isotope beams with energies up to approximately 3-5 MeV/nucleon as a part of the NSCL user program since the fall of 2015. A wide mass range of reaccelerated beams has been developed [81] and routinely delivered to scientific users to study nuclear reactions with rare-isotope beams at and below the Coulomb barrier. Rare-isotope beams are produced at the NSCL by the fragmentation of stable heavy-ion beams with in-flight separation of the rare isotopes. The re-acceleration of precision beams of such rare isotopes is based on the combined operation of in-flight separation, beam thermalization in gas, charge-breeding to high charge states and subsequent reacceleration in a linac. Novel physics programs have started at ReA3 with major equipment such as the ANASEN [82] and AT-TPC [79] active-target devices, the JENSA gas-jet target [83], the SeGA gamma-ray detector [84], and the Indiana [85] detector systems. Additional major state-of-the-art equipment such as GRETINA/GRETA [86] and the ISLA recoil separator [12], as well as a wide variety of complementary detection systems are envisioned to begin significant scientific programs only with higher-energy reaccelerated beams [1]. The SOLARIS projects adds its unique capabilities to the suite of equipment. The maximum beam energy available from the current reacceleration facility (ReA3) is limited to Coulomb-barrier energies or below. This limits the science program with reaccelerated beams to a few reaction probes such as Coulomb excitation, fusion reactions, and resonance scattering as illustrated in Figure 3.6 (left). An extensive science program, in particular, using direct transfer reactions, is anticipated from the user community for the energy-upgraded ReA [1], which can take immediate advantage of the unique beams once the ReA6 energy upgrade is completed. This forefront program will then continue many years into the future with completion of the FRIB accelerator.

The implementation of ReA6 is underway at the NSCL to significantly extend the scientific reach by providing world-unique beams with energies up to at least 6 MeV/nucleon for all species. The proposed extension of the ReA3 accelerator system will be realized by adding two major components: an existing additional FRIB-style accelerating cryomodule and a new beam delivery system to host a new experimental area. The energy specification of the ReA6 cryomodule is given in Figure 3.6 (right), together with values for the existing ReA3 and future possible ReA9 and ReA12 upgrades. The

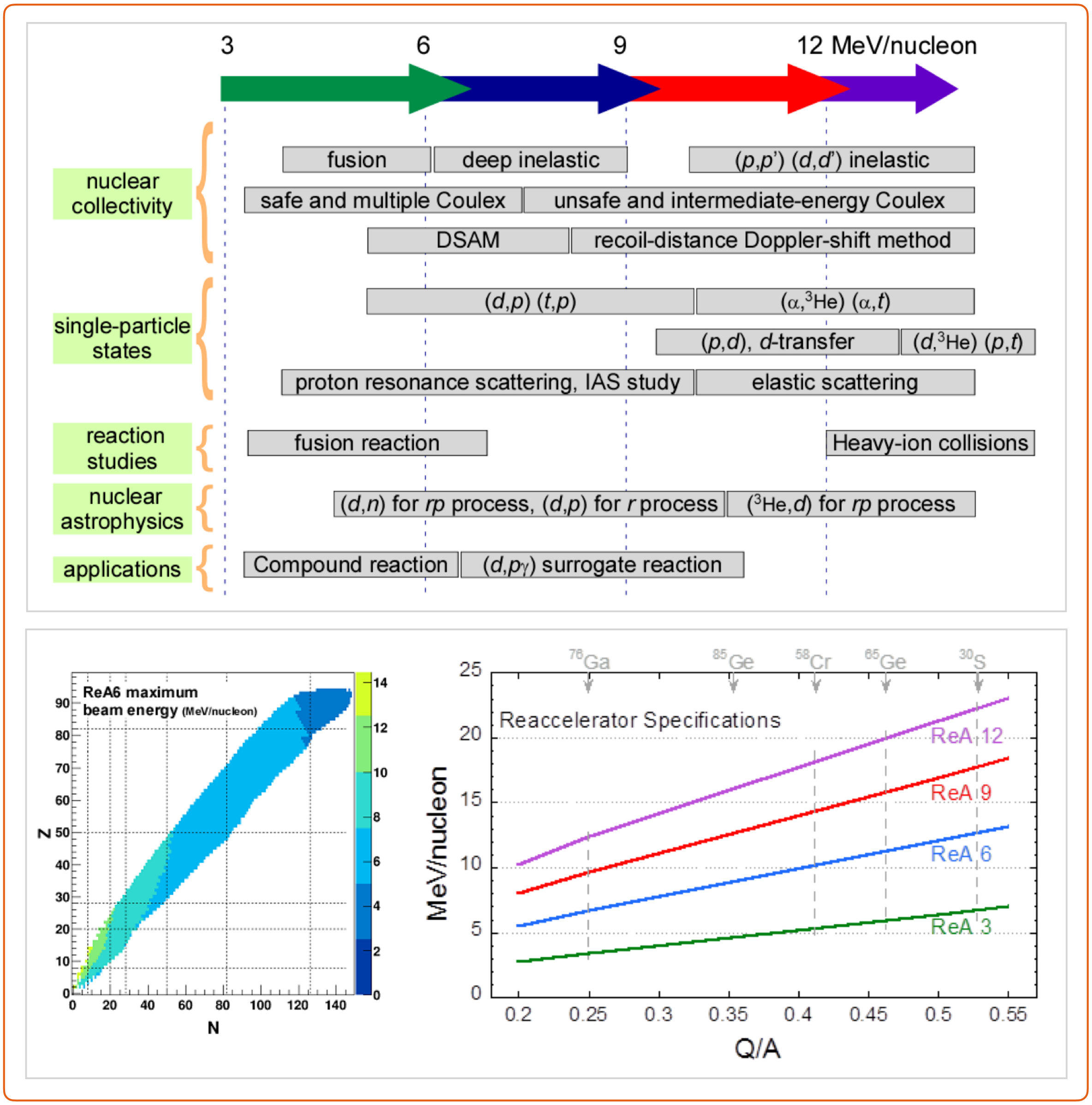


Figure 3.6: (Top) The scope of the science programs with ReA [1] illustrated via reactions and techniques as a function of radioactive-ion beam beam energy. SOLARIS can be used for measurements in all ReA energy ranges. (Bottom) Maximum beam energies with ReA6 in MeV/nucleon and energy specifications of different ReA cryomodules.

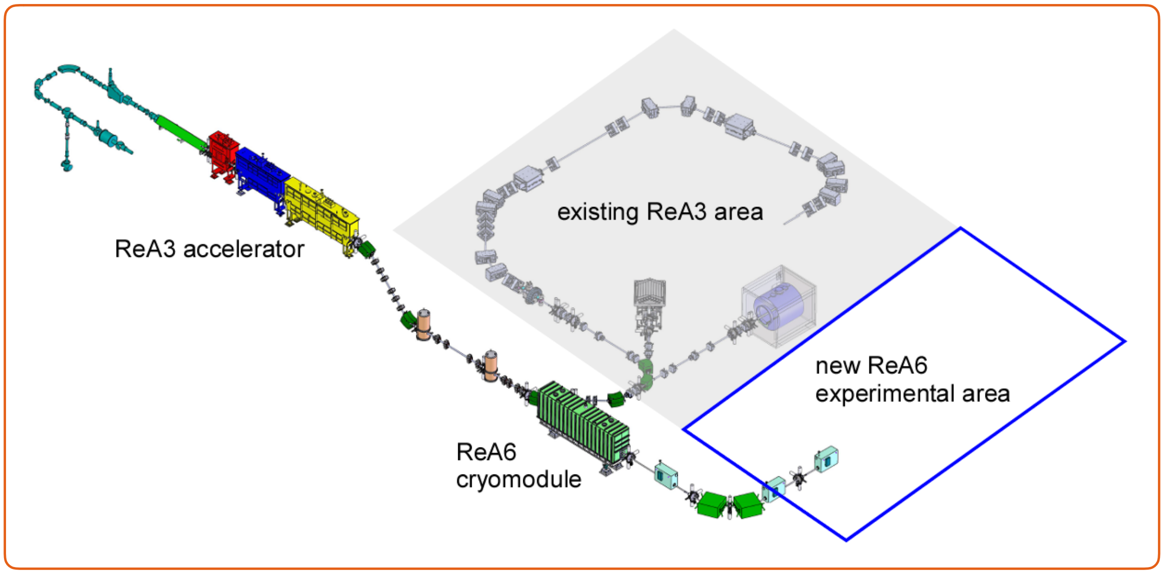


Figure 3.7: Layout plan for the ReA6 experimental area at the NSCL. At this time, one end station for experiments is considered as a general-purpose beam line to host a diverse set of user-developed devices.

available maximum energy depends on the Q/A ratio of the beams and ReA6 is designed to provide at least 6 MeV/u for very neutron-rich isotopes with Q/A of 1/4. This specification results in much higher beam energies for proton-rich or $N = Z$ nuclei. The maximum energy reaches up to 12 MeV/nucleon for light proton-rich nuclei [Figure 3.6 (right)], enabling a full set of reaction probes (Figure 3.6) to be utilized in experiments at ReA6.

A possible layout plan considered for a new ReA6 experimental area is shown in Figure 3.7. Initially, one beam line will be prepared to accommodate a large-scale experimental system. Considering the science opportunities discussed in the ReA Energy Upgrade white paper [1] and associated workshops [87, 88], the proposed area would allow the location of SOLARIS [88], where the solenoidal magnet could accommodate either a HELIOS-like silicon-detector system [3] or the active target-time projection chamber [79]. The beam lines can also accommodate a diverse set of complementary user-developed equipment, including, e.g., GRETINA/GRETA gamma-ray system [86], the ANASEN [82], ORRUBA [67], or Indiana [85] detector systems. The new area does not fill the existing high bay, and the east wall (right side of Figure 3.7) can be extended with more experimental space and additional beam lines as needed.

The use of radioactive isomer beams for transfer and inelastic scattering studies offer many attractive options. Studies with reaccelerated isomer beams are currently quite limited. About 10 years ago, Coulomb excitation of Cu isomer beams was carried out at REX-ISOLDE [89]. Recent studies with HELIOS have demonstrated the power of this technique for transfer reactions. For example, a composite beam of both $^{26g}$Al and $^{26m}$Al was produced in-flight via the $(p,n)$ reaction on $^{26}$Mg, and was used to provide insights into the role of galactic Al in the universe [90] via a study of the $(d,p)$ reaction. Similarly, a study of the $^{18m}$F$(d,p)$ reaction has led to the first instance of essentially all members of a rotational band being probed via single-nucleon transfer. Here, the large difference in spin between the ground state and the isomer allows access to both low and high-$j$ states using the same probe, in this case $(d,p)$, which is matched for low-$\ell$ transfer [91]. Other works at higher energies at the NSCL have also exploited the presence of isomer secondary radioactive ion beams, for example, neutron knockout reactions on $^{53m,g}$Co to probe high- and low-$j$ states in $^{52}$Co [92].

This opens up fascinating possibilities, such as single- and two-nucleon transfer, inelastic scattering, and cluster transfer on isotopes in both their ground and isomeric states. This could profoundly impact all areas of the science opportunities discussed in Section 2. SOLARIS, with its dual mode of operation, will be the ideal instrument to capitalize on this opportunity. Figure 3.8 shows known isomers as a function of $N$ and $Z$ across the nuclear chart, with lifetimes longer than 100 ms and isomers separated by greater than 100 keV from their ground state. This is a nominal limit. In some instances, shorter-lived beams would be available for study depending on the stopping, extraction, and charge-breeding times. Using the in-flight technique, as done at ATLAS when delivering radioactive-ion beams to HELIOS, it is possible to assess *a priori* what the isomer fraction of a given radioactive ion beam will be, as the production method typically involves simple reactions. This is not likely to be the case with ReA, and so each fraction of isomer to ground-state beam would have to be assessed prior to an experiment.

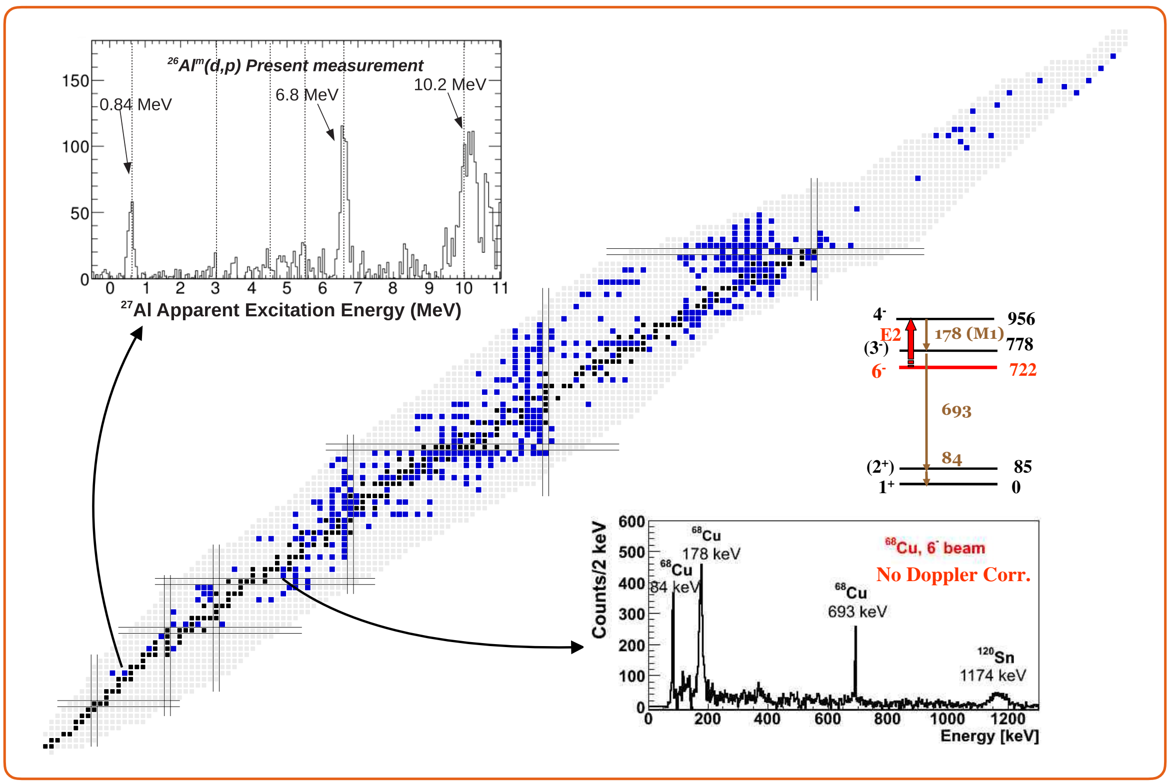


Figure 3.8: The ∼460 known isomers across the chart of isotopes with, somewhat arbitrarily, lifetimes longer than 100 ms and excitation energies greater than 100 keV. Examples of some of the few studies done with re-accelerated isomeric beams in the past, $^{26m}$Al($d$,$p$) [90] and Coulomb excitation in $^{68m}$Cu [89], are inset.

## 3.4 Targets and Auxiliary Detection Systems

For reactions in inverse kinematics, targets have typically been limited to a few elements. Common probes of nuclear structure, such as the ($d$,$p$), ($p$,$d$), ($p$,$p$), and ($d$,$^3$He) reactions, have largely depended on plastic targets—compounds such as polyethylene and deuterated polyethylene. While these are simple to make at the specified thicknesses [93] and cost effective, they are dominated by carbon. For example, a 100 $\mu$g/cm$^2$ deuterated polyethylene target has an deuteron areal density of just 25 $\mu$g/cm$^2$. The carbon can result in large fusion-evaporation backgrounds, of the order of barns of protons and alpha particles. Furthermore, these plastics are fragile under beam strike. For heavier, more intense beams, the targets can quickly deteriorate and the ratio of hydrogen or deuterium to carbon can alter substantially with beam dose [74, 94].

For SOLARIS, many of the challenges of using plastic targets can be overcome in the Si-array mode, and of course, the AT-TPC mode avoids them altogether. However, in the AT-TPC mode, it is not always possible to use pure gases and so similar challenges are faced [5]. While the use of plastic targets in the Si-array mode are expected to dominate the early part of the SOLARIS project, there are many other possibilities, several of which have already been demonstrated in the HELIOS spectrometer and in other setups.

For example, a key reaction for study of neutron pairing properties in nuclei (discussed in Section 2.4), will be the ($t$,$p$) reaction. This reaction is likely to be favored over ($p$,$t$) reactions as the $Q$ values are generally small and positive and protons are substantially less rigid than tritons. For neutron-rich systems, the final states are also in even more neutron-rich systems. A tritium target, procured by Western Michigan University (and subsequently the University of Connecticut) has been used in HELIOS in a demonstration experiment. The target was a tritium-implanted titanium target, loaded such that the ratio was about 1:1 (the 450 $\mu$g/cm$^2$ of titanium contained about 30 $\mu$g/cm$^2$ of tritium). A new target is currently being made, and it could serve as a target for SOLARIS. It might be that other tritium-loaded targets could be explored. Tritium targets also open up the possibility of other interesting probes that in general have been lost from the field since many accelerator facilities that used to deliver tritium beams have ceased to do so. Reactions of interest include ($t$,$d$), ($t$,$\alpha$), and ($t$,$^3$He).

Gaseous targets are likely to be essential for physics with ReA. In many instances, it is expected that the AT-TPC mode will be ideal for use in reactions induced by He species, and in many cases for pure H species. However, where high intensity beams are available, it will be desirable to use a gas-target system in the Si-array mode. One such target has been developed for HELIOS at ANL [16] (see also Figure 3.9) by the Louisiana State University group and has been successfully used in an ($\alpha$,$p$)-reaction measurement. There is some compromise in terms of $Q$-value resolution, where windows and depth of the target contribute, typically worsening the resolution by a factor of two to three. A similar target system could be developed for SOLARIS. An exciting prospect is the development of a gas-jet target like JENSA [83], but for a solenoidal spectrometer. Gas jets, created by remote pumps, could provide a thin, dense target of a hydrogen or helium species without the need for thick windows. The benefits of this can be seen in Figure 3.9 [95], where the same reaction was studied with a composite target and with a pure gas-jet target. This endeavor, in connection with the SOLARIS project, is being pursued in the form of a DOE Early Career award [96] and will be led by a group at Oak Ridge National Laboratory.

Finally, solid pure targets could also be considered. This is an area where significant R&D would be required to use such a target system in a solenoid. Some groups have already demonstrated the use of solid targets for transfer-reaction studies with radioactive beams, for example the IRIS facility at TRIUMF [97], which utilizes solid hydrogen condensed on a Au foil. It would also be interesting to investigate whether a polarized target could be made for use in a solenoid [98].

Numerous auxiliary detectors exist for use with the HELIOS spectrometer at ANL, the most important among these are the recoil detectors. A challenge to many measurements in inverse kinematics

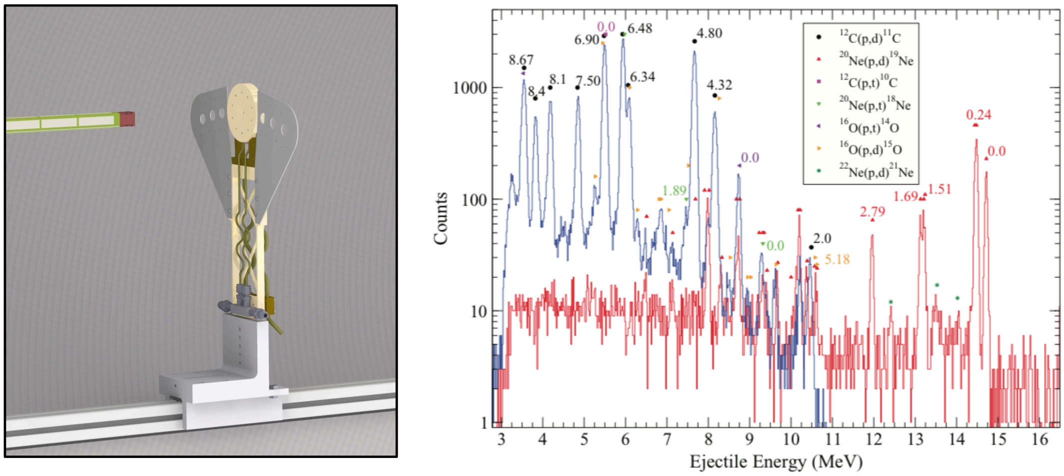


Figure 3.9: (Left) Rendering of the HELIOS gas target [16] and (right) an example of the outgoing deuteron spectrum from the $^{20}$Ne($p$,$d$) reaction on neon-implanted carbon foil (in 'normal' kinematics, blue histogram) and on a pure gas-jet target of hydrogen in inverse kinematics, the red histogram [95].

is the detection and identification of recoiling ions at angles close to zero degrees, and thus close to the unreacted beam. This is a challenge for HELIOS when studying reactions with mass greater than approximately $A = 30$. For the lighter systems, where recoiling nuclei have a recoil cone that subtends larger angles, an annular Si telescope is the preferred approach.

To deal with reactions induced by heavier mass beams, a position-sensitive fast ionization chamber was built by Louisiana State University [76], the design of which is based on several previous fast-counting ionization chambers. It has been demonstrated to have a $Z$ separation of better than 5% at rates less than about 50 kHz, and operable up to about 500 kHz with better than 10% resolution, as shown in Figure 3.10. This makes it an essential device for a broad range of anticipated measurements. In many cases the counting rate can be limited by placing blockers on the beam axis, removing the dominant contributions from the beam. A similar design is under construction for the ISS project, and

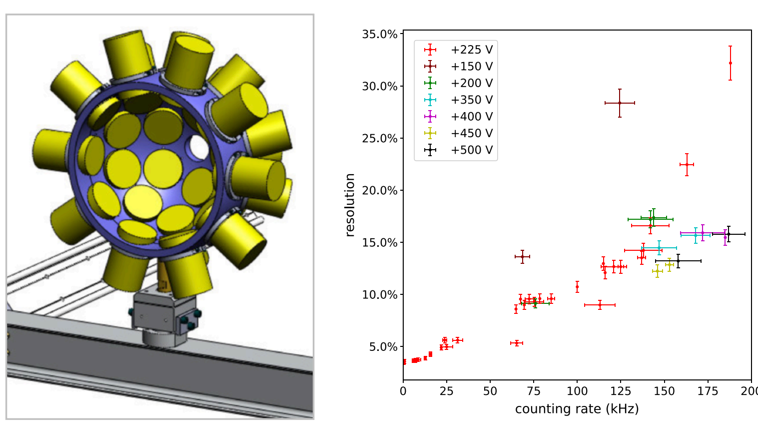


Figure 3.10: (Left) An image of the Apollo $\gamma$-ray array for use inside of HELIOS [51] and (right) a plot of the resolution of different segments of the LSU fast-counting ionization chamber as a function of incident beam rate [76].

it is expected that one will be built for the SOLARIS spectrometer.

The approach to equip the HELIOS spectrometer with auxiliary detectors systems has proven successful. A gamma-ray detection system, Apollo [51], was developed by the a group at Los Alamos National Laboratory in order to study $\gamma$-ray emission following direct population of highly excited states in the $(d,p)$ reaction. This approach allows for the study of emission patterns in nuclei that cannot be investigated directly by the $(n,\gamma)$ reaction. University groups have also played essential roles in the success of the HELIOS program by contributing key target and recoil detector solutions in order to enhance the scientific reach of the instrument. A similar approach is anticipated for the SOLARIS project. Figure 3.10 shows an example of auxiliary instrumentation that has been developed for the HELIOS spectrometer. It is possible that some of it could be repurposed for SOLARIS, such as the Apollo array.

# 4. The SOLARIS Project

## 4.1 The SOLARIS Project Overview

In the following sections we define the SOLARIS project, the intended capabilities and scope of the project, and discuss future upgrades. Upon completion of the SOLARIS project, SOLARIS will be a dual-mode charged-particle spectrometer operating in either an AT-TPC mode or a Si-array mode coupled to the ReA6 beam line. To achieve this the project much complete the following steps.

The SOLARIS project comprises:

- The transportation of the ANL 4-T solenoid from Argonne to the ReA6 hall,
- Operation and characterization of the solenoid,
- Staging of the solenoid on the ReA6 beam line, development of mechanical infrastructure to support a vacuum, and a Si array detector system,
- Housing and mechanical infrastructure such that the AT-TPC can be mounted in the solenoid and connected to the ReA6 beam line,
- Development of a dual Si-array system based on proven technology and providing good $Q$-value resolution,
- Successful execution of a Si-array mode experiment and an AT-TPC mode experiment with ReA prior to the NSCL ceasing operation.

The timeline, costs, designs, and so on, are discussed in detail in the following sections. We expect that certain auxiliary equipment, such as certain types of recoil detectors and advanced target systems, will be developed by other institutions. The HELIOS spectrometer at ANL prospered from the addition of community-developed auxiliary detectors. There is substantial interest for similar contributions to the SOLARIS project. Possible auxiliary instrumentation is discussed in Section 3.4.

## 4.2 SOLARIS Capabilities and Scope

The goal of the SOLARIS project is to enable the best possible science at ReA, with a high degree of versatility, efficiency, and reliability for a broad range of reaction studies at beam energies above and below the Coulomb barrier, and with beam intensities from as few as 100s per second to $10^7$ ions per second or greater. From the project description above, the SOLARIS project will provide several capabilities at ReA.

In the Si-array mode, the spectrometer will operate with a simple Si-detector array comparable to the design and functionality of the HELIOS position-sensitive Si array [3]. Modest recoil detection capabilities for light beams, below about mass 40, will be included in this base package. A large range of transfer reactions, with primary focus on ($d$,$p$), will be possible in the early experimental campaigns. Unlike the current HELIOS setup, however, SOLARIS will feature two Si arrays, one upstream of the target position and one downstream. This is to maximize efficiency, in many cases allowing for multiple reaction channels to be studied in each experiment.

The instrument will allow for the operation of the spectrometer both in the AT-TPC and the Si-array mode. The goal of the project is to complete an experiment in each mode with the ReA facility operating with primary beams from the NSCL prior to the cessation of NSCL operations.

## 4.3 The 4-T Solenoid

A 4-T solenoid has been acquired by ANL in anticipation of this project. It is a decommissioned MRI magnet that will be repurposed to serve as the SOLARIS solenoid. It is an OR66 Oxford Instruments solenoid, similar to the one used for the HELIOS spectrometer and identical to the one used for the ISS project at HIE-ISOLDE, CERN. It comes with so-called ‘Active-Shield’ technology which minimizes stray magnetic field. Images of the solenoid in its storage location are shown in Fig. 4.1. This solenoid is available for transport to the ReA experimental area immediately. However, its movement is contingent on the cyclotron stopper being moved from its current location in the ReA6 hall. This is likely to happen towards the middle of 2018, as discussed in Section 4.6. The solenoid comes with a dedicated power supply.

Once transported to the ReA6 hall, the solenoid will have to be cooled (estimated costs are given in Table 4.1), undergo energizing and de-energizing tests, and have the field mapped prior to implementation as a spectrometer. Once cooled, the solenoid will remain in this state, with He top offs as needed. In static conditions, using data from the identical solenoid operating at HIE-ISOLDE, liquid helium consumption is estimated to be around 200 liters every two months (0.144 liters per hour), or 1200 liters per year. If the field is frequently ramped, LHe consumption increases slightly.


Figure 4.1: The solenoid for the SOLARIS project, currently in storage at ANL.

The solenoid is similar in dimension to the HELIOS spectrometer at ANL. It has a bore of diameter 900 mm, and length of 2450 mm. Its external dimensions are 2550 mm in height (extending to approximately 2725 mm for the quench pipe) and 2340 mm in width. It is beneficial to have several meters of clearance in all directions around the solenoid, when in use as a spectrometer. It has a weight of 19000 kg when filled with helium.

## 4.4 Preliminary Designs

Preliminary designs of SOLARIS have been completed for both the Si-array and AT-TPC mode, and are shown in Fig. 4.2.

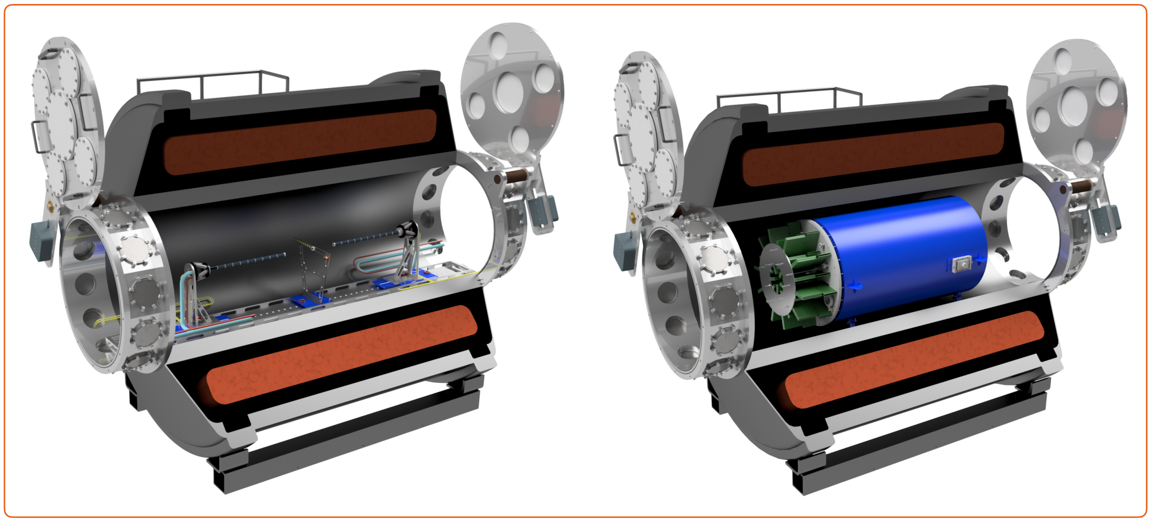

Figure 4.2: A 3-D model of SOLARIS in Si-array mode (left) and in AT-TPC mode (right).

SOLARIS is designed to be inherently flexible, capable of utilizing the entire volume of the bore without modification. Spools are installed at each end of the solenoid, each equipped with an integral access flange. These flanges are mounted on linear-rotary bearings, enabling the flanges to pull out, clear of the sealing surface and then rotate upward, allowing unrestricted access to the solenoid bore. The spools also perform another critical function by providing standard ISO bulkhead ports which are isolated from the motion of the access flange. By standardizing ports, modular flange and feedthrough systems may be developed to service the inner volume of SOLARIS. The spool design also allows the bulkhead ISO ports to house mechanically-rigid support and alignment mounts recessed clear of the full bore diameter, for the installation of experimental equipment in the bore of SOLARIS. These mounts can be left in place while reconfiguring operating modes, increasing the efficiency and speed of conversion.

In the Si-array mode, a kinematic bed spanning the length of the solenoid is installed and aligned to the magnetic field axis. This is accomplished by utilizing the mounts recessed into the spool as previously described. Once aligned, the kinematic bed may be easily removed and reinstalled with a high degree of repeatability. This bed serves as the foundation of the Si-array mode. It provides precise, repeatable kinematic mounting positions along its full length at 50-mm intervals. The Si arrays and target station will each be built upon their own “table” which directly interfaces with the kinematic bed. Knowing at which position each individual piece of equipment allows for simple spacing and alignment of various detectors by the end user. The standardized mounting system permits simple integration of other equipment into the system.

The Si-array table includes linear bearings, piezoelectric motors, and optical encoders to enable precise array positioning along the magnetic field axis while the system is under vacuum. The Si array is also directly supported by a high-rigidity, precision piezo hexapod. The hexapod system enables alignment in all six degrees of freedom and can be programmed to perform complex motions, if necessary, for alignment or troubleshooting. Additionally, the Si table acts as a distribution center for all supporting systems of the array; routing controls, detector bias/signals, and detector cooling, making installation and removal of the detector array simple and safe. Two identical Si systems will be built, enabling dual upstream/downstream array operation and offering a backup system during single array operation. Piezoelectric motors and encoder systems will also be leveraged on the target table, allowing control of target position, change of targets, and insertion of beam diagnostic/tuning devices.

Conversion of SOLARIS to AT-TPC mode is made straightforward by the flexible design of the SOLARIS experimental system. The full diameter of the bore is available for installation of the AT-TPC. Linear supports and guides are readily installed, mounting directly to recessed supports in the spool ports. A critical aspect for maximizing performance of the AT-TPC system is the ability to deliver beam askew to the geometrical axis of the device. This is presently accomplished by adjusting the pitch of the entire device within the bore of the solenoid in which it resides. The bore of SOLARIS does not have the room to accommodate such a motion. Instead SOLARIS will be built on a support and alignment platform which not only provides the necessary stability and adjustment for alignment to beam axis, but will allow the entire device to yaw with respect to the beam axis, providing the necessary angular separation of beam axis to AT-TPC geometrical axis.

## 4.5 Estimated Budget

The estimated budget is based on the project as described in Section 4.1. An overview of the costs are given in Table 4.1, showing the total costs by item. The project is assumed to start in calendar year 2018 and run for just short of three years such that commissioning experiments, using the spectrometer in both modes, can be completed by October 2020.

The costs are broken down into three parts: the transport, staging, mechanical infrastructure and operation of the solenoid; the detector array system and data acquisition for the Si-array mode; and the effort needed to execute the project. These subtotals come to \$1791k, \$1718k, and \$1376k, respectively. Costs are relatively evenly weighted by year throughout the period of the project and include overhead and contingency.

It is estimated that the project will cost around \$4885k over the period of three years. The project can start as soon as funding becomes available.

Table 4.1: Estimated costs in \$k of line items for the SOLARIS project assuming funding starts in 2018 to ensure experiments with NSCL-ReA beams. Contingency and overhead are included.

| **Task** | **Total** |
|---|---|
| Transport, staging, and mechanical infrastructure | **1791** |
| Detector arrays and data acquisition | **1718** |
| Effort | **1376** |
| **Total** | **4885** |

## 4.6 Envisaged Timeline

As discussed in Section 4.1, the timeline is coupled to the operation of the NSCL and the use of SOLARIS with ReA beams. Figure 4.3 shows the envisaged timeline for the SOLARIS project. The project is assumed to start during 2018 and will be completed in October 2020, which is the earliest likely date for the shutdown of NSCL. The planned completion of the ReA6 capability at NSCL occurs within a similar timeframe. There is some possibility that NSCL beams could continue through until October 2021, but the plan is made with the former, and most constraining date in mind. In an ideal scenario, the SOLARIS project would benefit from the continuing operation of ReA6 in the period of the NSCL/FRIB reconfiguration. This would allow for a more thorough commissioning period for the device and the opportunity to perform experiments with long-lived, near-stability, isotopes that could be accelerated by ReA6 during the transition period.

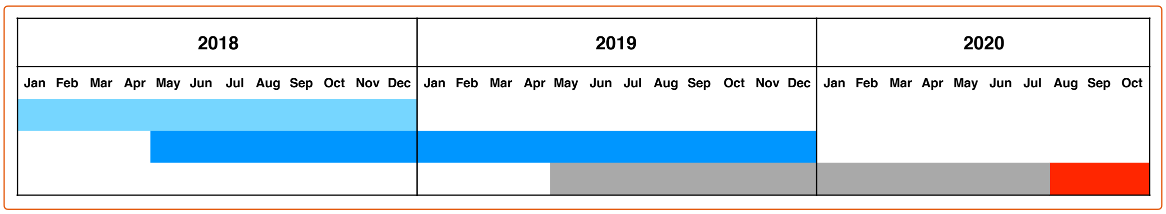


Figure 4.3: A simplified envisaged timeline for the SOLARIS project. The light blue line signifies the initialization of the project and the preparation of the solenoid for transport, and the dark blue bar represents the staging of the solenoid and instrumentation. It is envisaged that AT-TPC runs could start during the grey bar period and the Si-array mode runs close to the end of October 2020. This is consistent with the planned completion of the ReA6 capability at NSCL.

The superconducting solenoid has already been acquired (see Section 4.3) and can be moved from Argonne National Laboratory to the NSCL in the middle of 2018, when space in the ReA6 hall becomes available. This is shown by the light blue line in Figure 4.3. From that point onwards work starts on several fronts, both onsite at NSCL and offsite at ANL and other institutions, shown in blue in Figure 4.3. At NSCL, the solenoid will be mounted on its support stand. It must be cooled and energized and the field needs to be mapped. After this period, work can start on the coupling of the beam line to the SOLARIS vacuum chamber, when in Si-array mode, or to AT-TPC device inside the solenoid. The vacuum infrastructure for the Si-array mode and supports for both the AT-TPC and Si-array inside need to be built in this period. Offsite, the development of the Si array and data acquisition can be done in parallel to the onsite developments. It is expected that this stage will be completed in the first half of 2020, after which the commissioning experiments can proceed.

It is noted that experiments that require the AT-TPC mode of operation can likely start well ahead of the Si-array mode, as once the solenoid has been energized and supports for the AT-TPC installed, it is essentially ready for operation.

Preliminary designs are already available and continue to be advanced. The project can proceed quickly once funding is available. The solenoid has already been procured, and the AT-TPC has been successfully commissioned recently. The HELIOS spectrometer detection systems have recently been upgraded, providing an excellent template for the Si-array designs.

### 4.6.1 Risk Mitigation

There are several components of the SOLARIS project that could lead to a delay. For example, there could be unforeseen delays in the movement of the solenoid to NSCL, or unforeseen delays in the procurement of the silicon detectors for the SOLARIS Si array. In such a scenario, it is possible the existing HELIOS Si-array system, including the data acquisition, could be used in SOLARIS to ensure the commissioning of the instrument occurs prior to the cessation of NSCL.

## 4.7 Forecast for Future Upgrades

The scope of the SOLARIS base project is clearly defined in Section 4.1. While it will provide instrumentation to carry out a world-leading program of research, there are significant opportunities for future upgrade projects. These either improve on key metrics, such as the $Q$ value resolution when operating in the Si-array mode, or the beam rate at which the AT-TPC operates, or a fundamental modification to the mode of operation, for example using SOLARIS in conjunction with fast FRIB beams. These possibilities are discussed in the subsections below. They are not considered as part of the SOLARIS project as defined in Section 4.1 as they do not fit the timeframe nor within a realizable budget at this time. Furthermore, some of the proposed upgrades below require modest research time, mostly in the form of simulations. Several groups have already expressed interest in carrying these out.

### 4.7.1 Advanced Charged-Particle Array

The on-axis Si array for a solenoidal spectrometer is the principal detector system in that mode. The prototype Si array for the HELIOS spectrometer was based on simple analog technology. The array has a square profile, with each side comprised of six position-sensitive Si detectors of ∼50-mm length and ∼10-mm width. Three signals were taken from each detector, the left and right signal from the top and the energy from the bottom. The position of light ions could be determined to within approximately 1 mm [3] along the direction of the beam axis. In the case of the $(d,p)$ reaction, this contributes 10-20 keV to the $Q$-value resolution. Intrinsically, the detectors have ∼50 keV resolution [3]. An upgraded Si array for HELIOS has been recently commissioned, with six sides and position sensitivity offered through a discretized resistive readout, but still required less than 150 channels of readout.

While these Si arrays are relatively simple and cost effective, they are intrinsically limited in terms of resolution due to the relatively large area (capacitance) of the individual Si detectors. An alternative approach would be to use Si strip detectors. Such an array is currently under construction by the University of Liverpool for the ISS project. It is estimated that an intrinsic resolution of the order of 10 keV can be achieved, being about a factor of five improvement over the approach that will be used for the initially planned SOLARIS Si arrays. These detectors can be double-sided, which allows both axial and transverse positions to be determined for each ion, and with a simple algorithm [99] can provide the 'true' interception point of the trajectory with the beam axis, rather than the actual one, which due to the finite size of the detector, happens at a smaller distance. This can significantly improve the analysis of data at low center of mass angles. A schematic of this concept is shown in Figure 4.4.

For this advanced Si Array upgrade, allowing for high intrinsic resolution and vertex reconstruction, a large number of electronics channels will need to be read out. It is anticipated that the Advanced Si Array could share the same electronics used for the AT-TPC, which employs up to 10,000 digital channels of electronics readout.

Using a high-resolution Si array leaves only the target thickness and beam properties that dominantly contribute to the $Q$-value resolution. This offers the user some flexibility in either using thicker targets

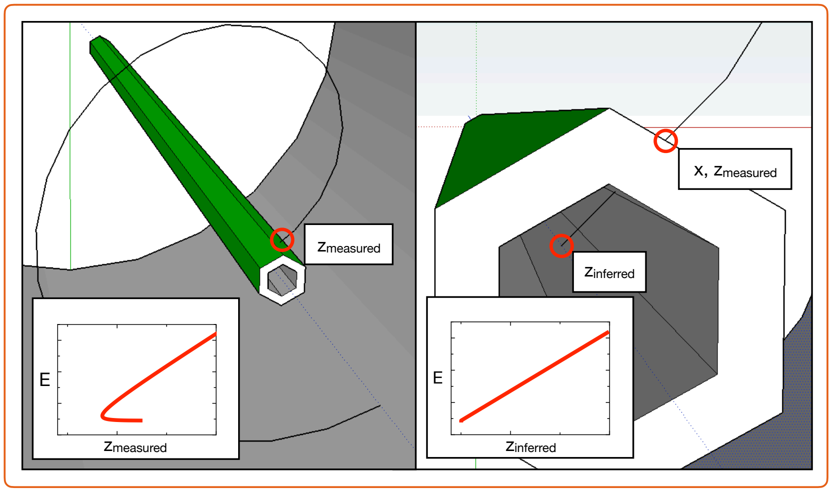


Figure 4.4: Not only could an advanced Si array improve the achievable $Q$-value resolution, it could allow for the the true intercept of the outgoing ion with the beam axis to be inferred, enhancing the analysis of forward center-of-mass data [99]. The left-hand side shows the conventional approach and the right-hand one the advanced Si array

for some experiments with weaker beams while still achieving a nominal 100-keV $Q$-value resolution, or for cases where the beams are intense, using a thinner target to achieve the 'ultimate' $Q$-value resolution.

### 4.7.2 AT-TPC Upgrades

One of the most interesting and unique features of the AT-TPC is the possibility to use pure elemental gases as the target medium without any quencher gas. This is accomplished by means of a novel micro-pattern gas detector (MPGD) based on a stack of multiple thick Gas Electron Multipliers (MTHGEM) developed at the NSCL [100]. This device provides gains around $10^3$ larger than conventional MPGD. Its robust structure makes it ideal to be deployed in larger-area pad planes. The benefits of using pure gases are two fold; removing unwanted carbon scattering events and dramatically increasing the proton density in terms of scattering centers. Future developments include the development of MTHGEM based on ceramic substrates to drastically reduce charge build up effects [101]. This is particularly interesting in order to increase the rate capabilities of the AT-TPC. MTHGEM coupled to a standard MICROMEGAS device is the present configuration of the AT-TPC, however next-generation experiments will require other types of read-out with better granularity such as TimePix or $\mu$-PIC. Future developments are devoted to enhance the current capacities of Active Target detectors in terms of rate, gain and stability.

It is also worth mentioning that the AT-TPC collaboration is leading the efforts to develop a modular data analysis and simulation framework using the most modern computing techniques and object-oriented programming languages. The framework features a set of libraries that are pipelined to realize the complex task of unpacking, sorting, and analyzing the data with a high level of parallelization (multithreading). The framework is being developed as an answer to the needs and demands pointed out by the Nuclear Physics Exascale Requirements report of the DOE [102]. Taking into account the amount of data that the AT-TPC generates during an experiment, the development of this framework is undoubtedly necessary. State-of-the-art pattern recognition and tracking algorithms are being developed to deal with the very specific task of reconstructing non-linear trajectories that particles describe inside the detector under the effect of the magnetic field. Future developments will explore and leverage the most efficient machine learning techniques.

### 4.7.3 Fast Beams

Modifying SOLARIS to be compatible with positioning the instrument on the FRIB beam lines opens up a new frontier, with access to the most exotic systems and to probes that demand a higher incident beam energy. There are ample opportunities both in the Si-array and AT-TPC modes.

Using SOLARIS with fast beams opens up new possibilities, enabling high-precision spectroscopy with:

- fast beams at the neutron-rich and neutron-deficient frontier,
- reactions not possible at energies <20 MeV/u, such as neutron removal reactions on neutron-deficient systems, and the possibility of,
- using the ($p$,2$p$) reactions with excellent resolution,
- and carrying out charge-exchange reactions and inelastic-scattering reactions at the desired high energies.

There are many exciting possibilities in the fast-beam regime. With fast beams, the reach for any given element is typically extended by 1–2 neutrons on both sides of stability when compared with ReA beams.

While there is significant discussion on neutron-rich systems, FRIB will provide unrivaled access to neutron-deficient systems. Reactions such as neutron-removal reactions, like ($p$,$d$) and two-nucleon removal reactions such as ($p$,$t$), are not only essential probes of nuclear structure, but also 'move in the right direction' towards final states in even more neutron-deficient systems. Here, $Q$ values are large and negative, demanding much higher beam energies than are envisioned at ReA, even if it were to be upgrading to, for example, ReA15.

It is also the case that, even when not at the extremes in terms of neutron excess/deficiency, reactions such as ($d$,$^{3}$He) and ($\alpha$,$^{3}$He) can have significantly negative $Q$ values that demand higher beam energies than available at ReA. Further, the cross sections for these reactions, especially reactions like ($\alpha$,$^{3}$He), can be an order of magnitude or more larger, at say 100 MeV/u rather than 10 MeV/u. There is significant interest in carrying out reactions at energies around 50-100 MeV/u as well as at higher energies.

Both modes of operation, the Si-array and AT-TPC mode, would benefit from fast beams. With a modified AT-TPC device in the solenoidal field, new classes of reactions become possible.

For example, light-ion scattering measurements in the range of 100-400 MeV/u are a unique tool to investigate nuclear potentials and radial distributions of nuclear matter, excitation of collective modes in nuclei, dipole polarizability and neutron skin of nuclei, neutron-proton spin correlations or exotic cluster structures. Experiments in normal kinematics with stable beams impinging on light targets such as protons, deuterons, or $\alpha$ particles have provided invaluable in, providing insights into how the nucleus responds under external perturbations. With the advent of FRIB, new exciting opportunities to investigate these phenomena under large proton-neutron imbalance will be available. Of particular interest is the evolution of the multipole response of the nucleus and its structure when moving to more asymmetric systems. Scattering experiments in inverse kinematics will require a device capable of measuring the recoiling target nucleus emitted near to zero degrees in the center-of-mass frame with very low kinetic energy (few hundreds of keV). In this challenging scenario, the AT-TPC offers an unprecedented detection scheme with high luminosity and acceptance. Particles with very low energy and ranges of a few cm can be tracked and reconstructed with almost $4\pi$ efficiency. In addition, the combination of the AT-TPC with a solenoid will greatly increase the precision of the measurement. Recent studies have demonstrated that the AT-TPC operating in a magnetic field of around 2 T, provides energy and angular resolutions of the order of a few tens of keV and 0.3 degrees [5, 6], respectively. Since the ionization density of a fast beam is comparable to that of the recoil and scattered particles, saturation and space charge effects, present in low-energy beam experiments, are greatly diminished. In addition, the AT-TPC possesses multiple-track reconstruction capabilities that allow for a complementary and simultaneous determination of the kinematics of the reaction in those cases where high multiplicity and large phase space are expected (i.e., cluster studies). Other types of reactions, such as charge-exchange will benefit from these capabilities as well. Measurements like ($d$,$^{2}$He) in inverse kinematics, a new probe for Gamow-Teller strength, are only possible with this kind of detection system.

There are several challenges to running with fast beams which would require consideration. The use of fast beams would demand a modified Si array, with a larger diameter to allow significantly larger emittance beams to pass on axis through the device. Such an array would benefit from design considerations discussed in Section 4.7.1. It is possible that a modular-design advanced Si array could be used for both the ReA mode and the fast beam mode of operation. Further, to achieve outstanding resolution, the beam would have to be tracked into SOLARIS, similar to what is done with, e.g., HiRA at NSCL [69, 103] or for MUST2 at GANIL [104]. It is conceivable that the deleterious effects of worsened beam energy resolution and transverse emittance can be removed if the beam particles are tracked event by event—something that is commonplace at most intermediate- and high-energy beam facilities. Further, a beam tracking system could be beneficial on both the ReA and FRIB beam lines to serve as an outstanding time reference, which can be of value in the analysis of data from solenoidal spectrometers. It is also likely that in some instances the energy of the beam would have to be degraded to suit the measurement of interest, and in some cases 100s of MeV/u is too high.

In some instances there would be overlap with the capabilities of HiRA [69], but in the case of SOLARIS in the Si-array mode, the effects of kinematic compression would be removed. If, as discussed above, the contributions to the $Q$-value resolution from the beam could be removed by tracking, SOLARIS offers an attractive alternative. For many classes of reactions the existing 4-T solenoid is sufficient, but for more extreme situations, a custom solenoid could be considered.

In summary, the advanced array and fast beam capabilities would make SOLARIS the ultimate charged-particle spectrometer for ReA and for FRIB. Thorough simulations of this mode of operation are needed.

# 5. Appendix

## 5.1 Contributors

At one the earliest FRIB science meetings, "Step Forward to FRIB", held at ANL in May 2009, the first HELIOS results were shown and a discussion of a solenoid spectrometer in the context of the FRIB facility took place. Since then, a "solenoidal spectrometer" Working Group has met in 2010, 2012 [105], 2013 [106], 2014 [107], and 2015 [108]. These Working Group meetings were responsible for the incremental development of the physics cases, scope, and strong community endorsement for what would become the SOLARIS project.

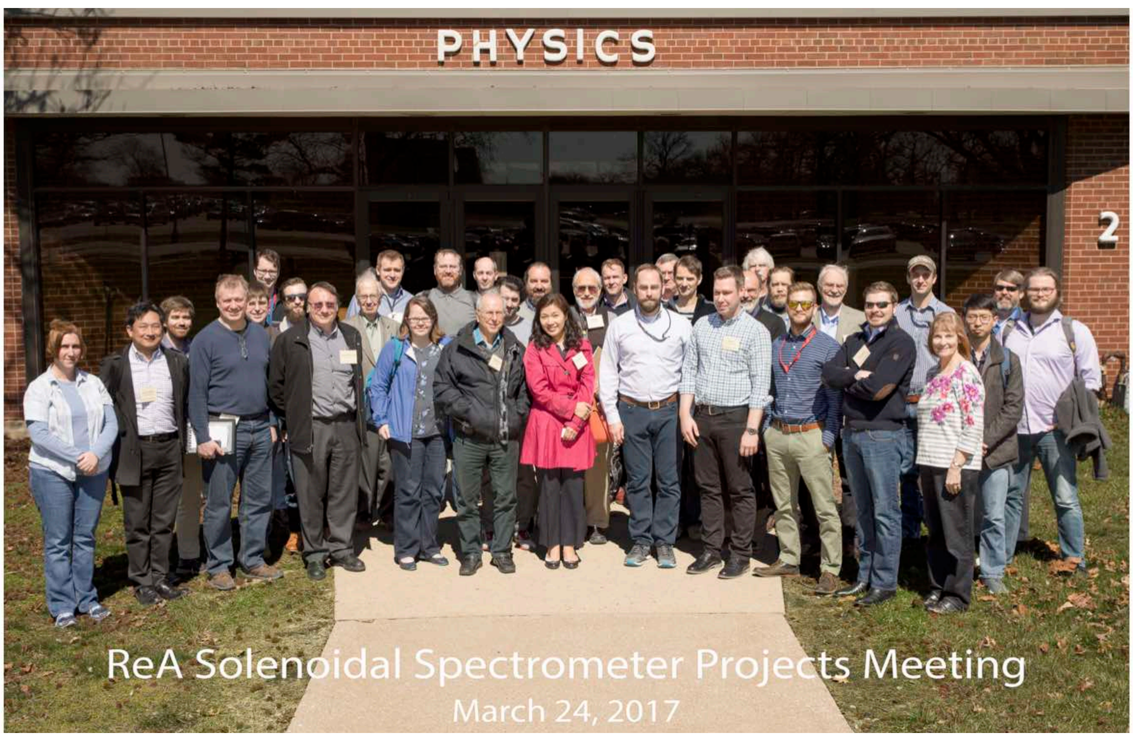


Figure 5.1: Participants of the ReA Solenoidal Spectrometer Projects Meeting held at Argonne National Laboratory on March 24, 2017.

The SOLARIS project was borne out of a meeting at ANL in 2017. A list of people who contributed to the ReA Solenoidal Spectrometer Projects meeting held at Argonne National Laboratory on 24 March 2017 (http://www.phy.anl.gov/lep/rss2017/participants.html [88]), and those who contributed to the preparation of this white paper is given below.

Jacob Allen, University of Notre Dame
Melina Avila, Argonne National Laboratory
Yassid Ayyad, Lawrence Berkeley National Laboratory
Birger Back, Argonne National Laboratory
Sam Baker, Argonne National Laboratory
Daniel Bazin, National Superconduting Cyclotron Laboratory
Jeffery Blackmon, Louisiana State University
Chris Campbell, Lawrence Berkeley National Laboratory
Michael Carpenter, Argonne National Laboratory
Jie Chen, Argonne National Laboratory/FRIB
Kelly Chipps, Oak Ridge National Laboratory
Jason Clark, Argonne National Laboratory
Aaron Couture, Los Alamos National Laboratory
Heather Crawford, Lawrence Berkeley National Laboratory
Brad DiGiovine, Argonne National Laboratory
Sean Freeman, University of Manchester
John Greene, Argonne National Laboratory
Kawtar Hafidi, Argonne National Laboratory
Calem Hoffman, Argonne National Laboratory
Hironori Iwasaki, National Superconduting Cyclotron Laboratory
Robert Janssens, Argonne National Laboratory, Univ. of North Carolina at Chapel Hill
Benjamin Kay, Argonne National Laboratory
Sean Kuvin, University of Connecticut
Jianping Lai, University of Notre Dame
Kyle Leach, Colorado School of Mines
Hye Young Lee, Los Alamos National Laboratory
Jonathan Lighthall, Louisiana State University
Jesus Pereira Lopez, University of Tennessee
Augusto Macchiavelli, Lawrence Berkeley National Laboratory
Scott Marley, Louisiana State University
Daniel McNeel, University of Connecticut
Wolfgang Mittig, National Superconduting Cyclotron Laboratory
Patrick O'Malley, University of Notre Dame
Richard Pardo, Argonne National Laboratory
Riccardo Raabe, KU Leuven
Daniel Santiago-Gonzalez, Louisiana State University
Guy Savard, Argonne National Laboratory
John Schiffer, Argonne National Laboratory
Brad Sherrill, National Superconduting Cyclotron Laboratory
Jaideep Singh, National Superconducting Cyclotron Laboratory
Rashi Talwar, Argonne National Laboratory
Gemma Wilson, Louisiana State University
Jack Winkelbauer, Los Alamos National Laboratory
Alan Wuosmaa, University of Connecticut

A similar sized group comprising largely the same people met at the 2017 Low Energy Community Meeting held at ANL on 3-4 August 2017 [109].

# 6. Bibliography

[1] A. Gade and H. Iwasaki, *White Paper on ReA Energy Upgrade (2016)*.
https://people.nscl.msu.edu/ iwasaki/rea6.html.

[2] A. H. Wuosmaa *et al., A solenoidal spectrometer for reactions in inverse kinematics*.
Nucl. Instrum. Methods Phys. Res. A **580**, 1290 (2007).

[3] J. C. Lighthall *et al., Commissioning of the HELIOS spectrometer*.
Nucl. Instrum. Methods Phys. Res. A **622**, 97 (2010).

[4] S. Beceiro-Novo *et al., Active targets for the study of nuclei far from stability*.
Prog. Part. Nucl. Phys. **84**, 124 (2015).

[5] J. Bradt *et al., Commissioning of the Active-Target Time Projection Chamber*.
Nucl. Instrum. and Methods in Phys. Res. A **875**, 65 (2017).

[6] J. Bradt *et al., Study of spectroscopic factors at N = 29 using isobaric analogue resonances in inverse kinematics*.
Phys. Lett. B **778**, 155 (2018).

[7] National Science Advisory Committee 2007 Long Range Plan: The Frontiers of Nuclear Science.
https://science.energy.gov/np/nsac/.

[8] National Science Advisory Committee 2015 Long Range Plan "Reaching for the Horizon".
https://science.energy.gov/np/nsac/.

[9] J. F. Ahearne *et al., Scientific Opportunities with a Rare-Isotope Facility in the United States*.
Rare-Isotope Science Assessment Committee (RISAC), Report of the National Research Council of the National Academies.

[10] *The Science of FRIB*.
https://www.frib.msu.edu/_files/pdfs/frib_scientific_and_technical_merit_lite_0.pdf.

[11] The HELIOS proposal.
http://www.phy.anl.gov/atlas/helios/helios_web.pdf.

[12] M. Amthor and D. Bazin, *Whitepaper on Isochronous Separator with Large Acceptances (2015)*.
http://fribusers.org/documents/2015/isla_WP.pdf.

[13] O. Sorlin and M.-G. Porquet, *Nuclear magic numbers: New features far from stability*.
Prog. Part. Nucl. Phys. **61**, 602 (2008).

[14] D. Steppenbeck *et al., Evidence for a new nuclear 'magic number' from the level structure of* $^{54}Ca$.
Nature (London) **502**, 207 (2013).

[15] T. Otsuka *et al., The role of shell evolution in shape coexistence*.
J. Phys. G: Nucl. Part. Phys. **43**, 024009 (2016).

[16] J. Lai. *A Direct Study of* $^{20}Ne(\alpha,p)^{23}Na$ *with the HELIcal Orbit Spectrometer (HELIOS)*.
http://digitalcommons.lsu.edu/gradschool_dissertations/2625/ and manuscript in preparation.

[17] *FRIB Estimated Rates Version 1.08*.
https://groups.nscl.msu.edu/frib/rates/fribrates.html.

[18] C. R. Hoffman *et al., Neutron s states in loosely bound nuclei*.
Phys. Rev. C. **89**, 061305(R) (2014).

[19] I. Tanihata *et al., Recent experimental progress in nuclear halo structure studies*.
Prog. Part. Nucl. Phys. **68**, 215 (2013).

[20] C. R. Hoffman and B. P. Kay. *Nuclear Structure of Light Nuclei Near Threshold.*
Nuclear Physics News International **24**, 16 (2014).

[21] G. Hagen *et al., Efimov Physics Around the Neutron-Rich* $^{60}Ca$ *Isotope*.
Phys. Rev. Lett. **111**, 132501 (2013).

[22] I. Hamamoto, *Examining possible neutron-halo nuclei heavier than* $^{37}Mg$.
Phys. Rev. C **95**, 044325 (2017).

[23] X. F. Yang *et al., Isomer Shift and Magnetic Moment of the Long-Lived 1/2*$^{+}$ *Isomer in* $^{79}_{30}Zn_{49}$*: Signature of Shape Coexistence near* $^{78}Ni$.
Phys. Rev. C. **116**, 182502 (2016).

[24] G. Hagen *et al., Structure of* $^{78}Ni$ *from First-Principles Computations*.
Phys. Rev. Lett. **117**, 172501 (2017).

[25] F. Nowacki *et al., Shape Coexistence in* $^{78}Ni$ *as the Portal to the Fifth Island of Inversion*.
Phys. Rev. Lett. **117**, 272501 (2016).

[26] J. P. Schiffer *et al., Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?*
Phys. Rev. Lett. **92**, 162501 (2004).

[27] G. Burgunder *et al., Experimental Study of the Two-Body Spin-Orbit Force in Nuclei*.
Phys. Rev. Lett. **112**, 042502 (2014).

[28] B. P. Kay *et al., Effect of Weak Binding on the Apparent Spin-Orbit Splitting in Nuclei*.
Phys. Rev. Lett. **119**, 182502 (2017).

[29] I. Stefan *et al., Probing nuclear forces beyond the drip-line using the mirror nuclei* $^{16}N$ *and* $^{16}F$.
Phys. Rev. C. **90**, 014307 (2014).

[30] J. P. Schiffer and W. W. True, *The effective interaction between nucleons deduced from nuclear spectra*.
Rev. Mod. Phys. **48**, 191 (1976).

[31] D. M. Brink and R. A. Broglia, *Nuclear Superfluidity*.
Cambridge University Press 2005.

[32] I. Tanihata *et al., Measurement of the Two-Halo Neutron Transfer Reaction* $^{1}H(^{11}Li,^{9}Li)^{3}H$ *at 3A MeV*.
Phys. Rev. Lett. **100**, 192502 (2008).

[33] K. Wimmer *et al., Discovery of the Shape Coexisting* $0^{+}$ *State in* $^{32}Mg$ *by a Two Neutron Transfer Reaction*.
Phys. Rev. Lett. **105**, 252501 (2010).

[34] A. O. Macchiavelli and H. L. Crawford *On the structure of* $^{30}Mg$ *and* $^{32}Mg$.
Phys. Scr. **92**, 064001 (2017).

[35] A. Mutschler *et al., A proton density bubble in the doubly magic* $^{34}Si$ *nucleus*.
Nat. Phys. **13**, 152 (2017).

[36] S. Frauendorf and A. O. Macchiavelli, *Overview of neutron-proton pairing*.
Prog. Part. Nucl. Phys. **78**, 24 (2014).

[37] B. Cederwall *et al., Evidence for a spin-aligned neutron–proton paired phase from the level structure of* $^{92}Pd$.
Nature (London) **469**, 68 (2010).

[38] B. Bucher *et al., Direct Evidence for Octupole Deformation in* $^{146}Ba$ *and the Origin of Large E1 Moment Variations in Reflection-Asymmetric Nuclei*.
Phys. Rev. Lett. **118**, 152504 (2017).

[39] B. Bucher *et al., Direct Evidence of Octupole Deformation in Neutron-Rich* $^{144}Ba$.
Phys. Rev. Lett. **116**, 112503 (2016).

[40] D. Doherty *et al., Triaxiality near the* $^{110}Ru$ *ground state from Coulomb excitation*.
Phys. Lett. B **766**, 334 (2017).

[41] A. Corsi *et al., Neutron-driven collectivity in light tin isotopes: Proton inelastic scattering from* $^{104}Sn$.
Phys. Lett. B **743**, 451 (2015).

[42] R. Kanungo *et al., Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with* $^{10}C$.
Phys. Rev. Lett. **114**, 192502 (2015).

[43] A. Kumar *et al., Evidence of Soft Dipole Resonance in* $^{11}Li$ *with Isoscalar Character*.
Phys. Rev. Lett. **118**, 262502 (2017).

[44] S. A. Kuvin *et al.,* $\alpha$ *decay of the* $T = 1, 2^{+}$ *state in* $^{10}B$ *and isospin symmetry breaking in the* $A = 10$ *triplet*.
Phys. Rev. C **96**, 041301(R) (2017).

[45] F.-K. Thielemann *et al., What are the astrophysical sites for the r-process and the production of heavy elements?*.
Prog. Part. Nucl. Phys. **66**, 346 (2011).

[46] S. Brett *et al., Sensitivity of the r-process to nuclear masses*.
Eur. Phys. J. A **48**, 184 (2012).

[47] R. Surman *et al., Sensitivity studies for the weak r process: neutron capture rates*.
AIP Advances **4**, 041008 (2014).

[48] M. Mumpower *et al., Sensitivity studies for the main r process: $\beta$-decay rates*.
AIP Advances **4**, 041009 (2014).

[49] D. Bardayan. *Transfer reactions in nuclear astrophysics*.
J. Phys. G: Nucl. Part. Phys. **43**, 043001 (2016).

[50] Z. Meisel, *From drip line to drip line: Nuclear astrophysics in the laboratory*.
J. Phys.: Conf. Ser. **742**, 012019 (2016).

[51] A. Couture *et al., The Apollo $\gamma$-ray array for HELIOS*.
For example https://www.phy.anl.gov/atlas/workshop14/APOLLO.pdf.

[52] J. José and C. Iliadis. *Nuclear astrophysics: the unfinished quest for the origin of the elements*.
Rep. Prog. Phys. **74**, 096901 (2011).

[53] *The Separator for Capture Reactions (SECAR).*
http://fribastro.org/SECAR/SECAR.html.

[54] K. Chipps *et al., First Direct Measurement of the $^{17}F(p,\gamma)$ $^{18}Ne$ Cross Section*.
Phys. Rev. Lett. **102**, 152502 (2009.

[55] T. Kajino and G. J. Mathews. *Impact of new data for neutron-rich heavy nuclei on theoretical models for r-process nucleosynthesis*.
Rep. Prog. Phys. **80**, 084901 (2017).

[56] O. Naviliat-Cuncic and M. González-Alonso, *Prospects for precision measurements in nuclear $\beta$ decay in the LHC era*.
Ann. Phys. (Berlin) **252**, 600 (2013).

[57] J. C. Hardy and I. S. Towner, *Superallowed $0^+ \to 0^+$ nuclear $\beta$ decays: 2014 critical survey, with precise results for $V_{ud}$ and CKM unitarity*.
Phys. Rev. C **91**, 025501 (2015).

[58] C. Patrignani *et al.* (Particle Data Group), *Review of Particle Physics*.
Chin. Phys. C **40**, 100001 (2016).

[59] K. G. Leach, *Searching for $0^+$ states in $^{50}Cr$: Implications for the superallowed $\beta$ decay of $^{50}Mn$*.
Phys. Rev. C **94**, 011304(R) (2016).

[60] L. P. Gaffney *et al., Studies of pear-shaped nuclei using accelerated radioactive beams*.
Nature (London) **497**, 199 (2013).

[61] T. Chupp, *Electric Dipole Moments of the Atoms, Molecules, Nuclei and Particles*. arXiv:1710.02504 (and submitted to Rev. Mod. Phys.)

[62] P. A. Butler and W. Nazarewicz, *Intrinsic reflection asymmetry in atomic nuclei*. Rev. Mod. Phys. **68**, 349 (1996).

[63] P. A. Butler, *Octupole collectivity in nuclei*. J. Phys. G: Nucl. Phys. **43**, 073002 (2016).

[64] E. Pollacco *et al., MUST2: A new generation array for direct reaction studies*. Eur. Phys. J. A **25**, 287 (2005).

[65] V. Bildstein *et al., A new setup for transfer reactions at REX-ISOLDE*. Prog. Part. Nucl. Phys. **59**, 386 (2007).

[66] C. Aa. Diget *et al., SHARC: Silicon Highly-segmented Array for Reactions and Coulex used in conjunction with the TIGRESS $\gamma$-ray spectrometer*. J. Instrum. **6**, P02005 (2011).

[67] S. Pain *et al., Development of a high solid-angle silicon detector array for measurement of transfer reactions in inverse kinematics*. Nucl. Instrum. Methods Phys. Res. B **261**, 1122 (2007).

[68] M. Labiche *et al., TIARA: A large solid angle silicon array for direct reaction studies with radioactive beams*. Nucl. Instrum. Methods Phys. Res. A **614**, 439 (2010).

[69] M. S. Wallace *et al., The high resolution array (HiRA) for rare isotope beam experiments*. Nucl. Instrum. Methods Phys. Res. A **583**, 302 (2007).

[70] V. Margerin *et al., Inverse Kinematic Study of the* $^{26g}Al(d,p)^{27}Al$ *Reaction and Implications for Destruction of* $^{26}Al$ *in Wolf-Rayet and Asymptotic Giant Branch Stars*. Phys. Rev. Lett. **115**, 062701 (2015).

[71] A. H. Wuosmaa *et al.,* $^{15}C(d,p)^{16}C$ *Reaction and Exotic Behavior in* $^{16}C$. Phys. Rev. Lett. **105**, 132501 (2010).

[72] C. R. Hoffman *et al., Experimental study of the* $^{19}O(d,p)^{20}O$ *reaction in inverse kinematics*. Phys. Rev. C **85**, 054318 (2012).

[73] C. R. Hoffman *et al., Single-neutron excitations in* $^{18}N$. Phys. Rev. C **88**, 044317 (2013).

[74] B. P. Kay *et al., Single-neutron energies outside* $^{136}Xe$. Phys. Rev. C **84**, 024325 (2011).

[75] D. K. Sharp *et al., Neutron single-particle strength outside the N=50 core*. Phys. Rev. C **87**, 014312 (2013).

[76] J. Lai *et al., Position-sensitive, fast Ionization Chambers*. Nucl. Instrum. Methods Phys. Res. A **890**, 119 (2018).

[77] *The ISOL-SRS project*.
http://npg.dl.ac.uk/isol-srs/.

[78] X. Fang *et al., Development of a solenoid spectrometer for nuclear astrophysical studies of fusion reactions near stellar energies*.
Nucl. Instrum. Methods Phys. Res. A **871**, 35 (2017).

[79] D. Suzuki *et al., Prototype AT-TPC: Toward a new generation active target time projection chamber for radioactive beam experiments*.
Nucl. Instrum. Methods Phys. Res. A **691**, 39 (2012).

[80] J. Bradt. *Measurement of Isobaric Analogue Resonances of* $^{47}$*Ar with the Active-Target Time Projection Chamber*.
PhD Thesis, Michigan State University.

[81] *List of ReA3 beams at the NSCL*.
http://www.nscl.msu.edu/users/beams.html.

[82] E. Koshchiy *et al., ANASEN: The array for nuclear astrophysics and structure with exotic nuclei*.
Nucl. Instr. Meth. A **870**, 1 (2017).

[83] K. A. Chipps *et al., The Jet Experiments in Nuclear Structure and Astrophysics (JENSA) gas jet target*.
Nucl. Instrum. Methods Phys. Res. A **763**, 553 (2014).

[84] W. F. Mueller *et al., Thirty-two-fold segmented germanium detectors to identify* $\gamma$*-rays from intermediate-energy exotic beams*.
Nucl. Instrum. Methods Phys. Res. A **466**, 492 (2001).

[85] J. Vadas *et al., High-rate axial-field ionization chamber for particle identification of radioactive beams*.
Nucl. Instrum. Methods Phys. Res. A **837**, 28 (2016).

[86] S. Paschalis *et al., The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA*.
Nucl. Instrum. Methods Phys. Res. A **709**, 44 (2013).

[87] *ReA3 Upgrade Workshop, August 20, 2015, NSCL/MSU, East Lansing*.
https://people.nscl.msu.edu/ iwasaki/rea6.html.

[88] *ReA Solenoidal Spectrometer Projects Workshop, March 24, 2017, Argonne National Laboratory*.
http://www.phy.anl.gov/lep/rss2017/index.html.

[89] I. Stefanescu *et al., Coulomb Excitation of* $^{68,70}$*Cu: First Use of Postaccelerated Isomeric Beams*.
Phys. Rev. Lett. **98**, 122701 (2007).

[90] S. Almaraz-Calderon *et al., Study of the* $^{26}Al^{m}(d,p)^{27}Al$ *Reaction and the Influence of the* $^{26}$*Al* $0^{+}$ *Isomer on the Destruction of* $^{26}$*Al in the Galaxy*.
Phys. Rev. Lett. **119**, 072701 (2017).

[91] D. Santiago-Gonzalez *et al., Single-particle properties of collective excitations in $^{19}F$*.
Manuscript in preparation.

[92] S.A. Milne *et al., Isospin Symmetry at High Spin Studied via Nucleon Knockout from Isomeric States*.
Phys. Rev. Lett. **117**, 082502 (2016).

[93] M. Febbraro *et al., Improved technique for preparation of deuterated-polyethylene targets*.
Nucl. Instrum. Methods Phys. Res. B **410**, 53 (2017).

[94] K. E. Rehm *et al., Study of radiative capture reactions with radioactive ion beams*.
Nucl. Instrum. Methods Phys. Res. A **418**, 355 (1998).

[95] S. D. Pain, *Advances in instrumentation for nuclear astrophysics*.
AIP Adv. **4**, 041015 (2014).

[96] K. A. Chipps, *Next-Generation Particle Spectroscopy at FRIB: A Gas Jet Target for Solenoidal Spectrometers*.
Abstract **here**.

[97] R. Kanungo *et al., IRIS: The ISAC charged particle reaction spectroscopy facility for reaccelerated high-energy ISOL beams*.
Hyperfine Interact. **225**, 235 (2014).

[98] A. Galindo-Uribarri and J.P. Urrego-Blanco, *Spin observables in reactions with radioactive ion beams*.
Rev. Mex. Fís. S **53**, 35 (2007).

[99] P. A. Butler *et al., TSR: A storage and cooling ring for HIE-ISOLDE*.
Nucl. Instrum. Methods Phys. Res. B **376**, 270 (2016).

[100] M. Cortesi *et al., Multi-layer thick gas electron multiplier (M-THGEM): A new MPGD structure for high-gain operation at low-pressure*.
Rev. Sci. Instrum. **88**, 013303 (2017).

[101] Y. Ayyad *et al., Overview of the data analysis and new micro-pattern gas detector development for the Active Target Time Projection Chamber (AT-TPC) project*.
J. Phys.: Conf. Ser. **876**, 012003 (2017).

[102] *Nuclear Physics Exascale Requirements Review*.
https://science.energy.gov/ /media/ascr/pdf/programdocuments/docs/2017/DOE-ExascaleReport-NP-Final.pdf.

[103] A. M. Rogers *et al., Tracking rare-isotope beams with microchannel plates*.
Nucl. Instrum. Methods Phys. Res. A **795**, 325 (2015).

[104] S. Ottini-Hustache *et al., CATS, a low pressure multiwire proportionnal chamber for secondary beam tracking at GANIL*.
Nucl. Instrum. Methods Phys. Res. A **431**, 476 (1999).

[105] *2012 Low Energy Community Meeting, August 16-18, 2012, Argonne National Laboratory*. http://meetings.nscl.msu.edu/CommunityMeeting2012/program.htm.

[106] *2013 Low Energy Community Meeting, August 23-24, 2013, NSCL/MSU*. http://meetings.nscl.msu.edu/CommunityMeeting2013/program.htm.

[107] *Joint DNP Town Meetings on Nuclear Structure and Nuclear Astrophysics, August 21-23, 2014, Texas A&M*. http://www.lecmeeting.org/workinggroups.html.

[108] *Satellite Workshop on ReA6, the case direct reactions with a solenoid*. https://people.nscl.msu.edu/ iwasaki/rea6_slide.html.

[109] *2017 Low Energy Community Meeting, August 3-4, 2017, Argonne National Laboratory*. https://indico.fnal.gov/conferenceDisplay.py?confId=14088.