Tour Guidelines

1. Only take visitors in areas that have been surveyed (proved by a copy of the safety survey) and are not currently secured or blocked by a warning sign. This could be very limiting when beam is on.
2. Try to orient your group to where the beam is entering (and leaving?) when you enter a vault, since they can get turned around easily (laminated maps are recommended for you to use as reference).
3. More info is available on the tour wiki (Intra Enterprise > Employee Information > Resources for Tour guides).
4. Information for higher-level tours is in red italics (also useful for answering general public questions).
5. Export-controlled information (due to its status as being developed, designed, constructed, repaired) is in green italics.

General points of interest

Things to point out when it’s appropriate and when you need more info to fill in a stop.

- We build large machines to study tiny particles to understand giant stars.
- Note changes in floor and wall colors, indicating that we’ve added on to the building (12 additions since 1964, FRIB is #13).
- The electronics: designed to do high-speed, high-volume data acquisition. Most built right here in the lab.
- Pipes around the building carry cooling water (Low-Conductivity Water, or LCW, reduces corrosion in copper equipment) and liquid nitrogen (LN). We consume 3000 gallons (12000 liters) of liquid nitrogen every week, costing only 26 cents per gallon (7 cents/liter). We make liquid helium on-site.
- Power supplies and power cables: when power fails, we are backed up by East Lansing or on-site generators. MSU power plant gives us priority when power returns. We consume 3 MW, equivalent to 6,000 houses, spending about $2 million per year on electricity (from Andreas).
- Ethernet cables: carry commands/feedback to/from the control room experimental data to Data-U.
- Walls: The concrete blocks are stacked around equipment to prevent radiation from escaping. All are at least 6 feet thick, based on calculations that show 200 MeV neutrons produced would still result in less than 10 mRem exposure per year even if we ran experiments 24/7. The wall blocks are not mortared together so they can be easily removed and re-stacked (like big LEGO’s), completely changing the layout of the laboratory as needed! Science and technology change quickly, so the laboratory can change to accommodate new technology or techniques.
- Vault doors: let a volunteer close one partway, show how they must hold the button to close (safety feature!). The open button only needs to be pushed momentarily. The doors are solid concrete, about as thick as the walls to contain the radiation. When they close fully, switches at the top are tripped to inform the operators in the control room that the vault is sealed.
- The vault-seal alarm: in order to run beam in a vault, hit the red button that informs everyone to GET OUT with lights and sound (music from Close Encounters of the Third Kind), then you seal the door. Unsealing the door automatically cuts off the beam to that vault.
- The sticky mats: in the unlikely event of a radioactive spill, some will be tracked onto the mats. Health physicist scans them periodically and can tell where the spill occurred and where it was tracked. Can then identify the person with a hot shoe and contain the problem. You can say that no activity has left the controlled areas since you’ve been here at the lab.
- The 40-ton crane (yellow bridge) that can travel the length of the room. The crane could lift one Apatosaurus (Brontosaurus) plus 2 Tyrannosaurs. The vaults are built of concrete blocks with concrete beams (10+ tons) for roofs. As tall as the room is, it goes as deep under your feet (at ground level) as well.
- The vaults are often noisy because of vacuum pumps like the “roughing pumps” found on the floors next to beamlines. The one in the yellow cage in the Transfer Hall is a diffusion pump. We need to remove the atmosphere from the beam line so the air molecules don’t interfere with the motion of the beam nuclei. Pressures are commonly one-billionth of an atmosphere (10^{-6} Torr) or lower.
- Even when running, the radiation levels are small. You are far more likely to be hurt in a car accident that by radiation in our lab. NSCL does not exceed regulatory radiation exposure limits (from Andreas). Industrial hazards (falling, tripping, etc.) are more common.
- Magnet quenching: there are failsafes/pressure release valves to protect superconductors from an uncontrolled switch to normal conduction. In the event of a large release of boiled-off LN, the Oxygen Deficiency alarms in each vault will alert staff if percentage goes below 19.5%.
- The black disks (occasionally covered by red caps) on the walls in the research area serve as known points in space, and are used with a laser surveyor to position equipment. They serve as the lab’s “GPS”.

Diagram of Tour Location Script

Revised December 2015
INTRA.NSCL.MSU.EDU > OUTREACH
The NSCL Tour Location Script

Revised December 2015


Safety

• Do not take tour groups inside the control room - observe through the windows in the hallway. You can refer to the vault map mounted above those windows.
• If there are users in the Data-U, avoid disturbing them and give your speech in a different section.

The Data-U (1)

• Data-U sometimes contains the complex electronics required to rapidly collect, process and store data, but most equipment is located remotely and computer-controlled.
• Researchers (users) are in here 24 hours a day during their experiment, observing data coming to one of the computer banks from whichever detector they’re using.
• NSCL serves over 1300 users from over 50 countries.
• The racks of electronics are connected to the vaults with many cables so experimenters can make changes without having to stop the beam and open the vault door. There is one Data-U matched to each vault.
• Could discuss the cost to operate (effectively $5000/hr), which is not required of the user but comes from NSF.
• Anyone in the user community can propose an experiment, and those proposals are reviewed by a committee (PAC) featuring some of the nation’s top nuclear scientists. (Note: NSCL representatives on that committee are non-voting) The PAC selects the most critical and achievable research and approves beam time. They can only accept about 1/3 of the proposals (~40 experiments/year).
• Running an experiment requires that you apply for beam-time, set up about one month in advance, have group monitoring in Data-U for length of experiment (average 120 hours), then spend months analyzing the data with the goal of publishing, and writing Ph.D. dissertations.
• Beam time is free to the user, but they must “pay back” by publishing their results, adding to human knowledge.
• The floor tiles can be lifted up (using the suction cup or handle cutout) to show visitors how the raised floor is used to transport air conditioning and run cables underneath the computer equipment.

The Control Room (2)

• While the NSCL is running the experimental program, operators are here 24 hours a day monitoring systems and maintaining beam output. We run experiments ~4000 hours per year, with maintenance shutdowns making up the remainder of the year. Operating the cyclotrons is done remotely from the control room. Operators maintain the beam by “tuning” devices to produce the highest-current, highest-quality beams possible.

1. An example beam current (for O-16): 10-100 billion particles per second ~ 100 pmA ~ 0.2 kW.

• Explain how some monitors show video from various points in the beam where operators can insert a fluorescent screen to “see” the beam (bright spot) in real time while adjusting its position, size, and shape. This works on the same principle as old TV picture tubes.
• The majority of software used by our operators to control the facility is developed here at NSCL and runs on standard PC’s running Windows Operating system. Operators can adjust settings and turn devices on and off, with the click of a mouse, typing a new value or by adjusting hardware knobs.
• Hallway displays detail the current experiment, accelerated isotope, availability (reliability), vaults security status, etc.
• Statistics on the display generally show that our lab’s availability is > 90%, which is great for a lab our size.
• Operators typically have a bachelor’s or masters degree in physics or engineering, and also possess skills in fields such as programming, maintenance, fabrication and electronics to name a few. When NSCL is not running experiments, we are performing maintenance and upgrades, where the additional skills of the operators are put to use.
• Operators are highly-skilled and trained. In many cases they are the only people with working knowledge of how to control and repair particular a particular piece of equipment. It takes 6 months to a year to become fully qualified as an operator-in-charge.

1. Over 30,000 settings and readings of equipment are recorded constantly throughout the day by the NSCL’s control system.

Approved: Hironori Iwasaki 12/14/15

Approved: Jon Bonofiglio 2/2/16
K500 Cyclotron (3a)
- World’s first superconducting cyclotron
- 10 feet (over 3 meters) wide, 5 stories tall
  1. Dees/Pole tips (look like “fan blades”) at the center are electrical poles, which are charged and discharged millions of times per second up to 60-65 kV. The electric field produced is used to accelerate the nuclei through attraction/repulsion. The frequency can be adjusted to suit the beam by changing the length of the resonator cavities, depending upon on the magnetic field and charge/mass ratio of the nuclei. 23 MHz is one example frequency. The copper pillars (resonators, attached to dees) extending below and above the cyclotron are “tuned” by moving a short to the desired RF frequency. The nuclei inside orbit almost exactly 250 times before leaving at their maximum velocity (0.15 c, 30000 miles/sec, 45 million m/s). The dee shape promotes beam focusing in the vertical direction.
  2. A “helium can” contains 20 miles (32 km) of superconducting wire in coils bathed in liquid helium, like many of the magnets we use to steer the beam. The coil generates a strong enough magnetic field (3-5 Tesla) to keep fast-moving nuclei in an orbit. The magnets typically run at 600-700 amps, depending on the beam (Q/A) to ensure proper path. The two coils shape the field to compensate for relativistic mass of the nuclei.
  - The liquid helium is insulated with layers of liquid nitrogen shields and vacuum. Cold He/N gasses are returned to cryogenics plant for reliquefaction.

K1200 Cyclotron (not accessible)
- 14 feet (over 4 meters) wide, 5 stories tall, superconducting wire extends 38 miles (61 km), dees charge 140 kV.
- Was the worlds highest-energy cyclotron from 1988 until 2009, when RIKEN’s Superconducting Ring Cyclotron began operations.
  1. Coupled with K500 in 2001, dramatically increasing NSCL capabilities. Entering ions pass through a “stripper foil” which removes nearly all electrons. Injection requires a ratio of charge states (k1200/k500) of 2.3-2.7. Stripped ions travel up to two miles inside the K1200, exit at up to half the speed of light (100-150 MeV/nucleon, 93000 miles/s, 150 million m/s, about 4 times around the Earth per second), then smash into a beryllium foil target.
  2. Travel time is 20-25 μs in K500, 30-40 μs in K1200.
Safety
- Do not enter if magnetic field (blue light above door) is on.
- Keep pacemakers/implants away from dipoles/quadrapoles.
- Always have visitors stay an arm’s length away from the dipoles (grey magnets).
- Don’t go beyond area inside north door.

Transfer Hall/
A1900 Fragment Separator (4)
- The A1900 Fragment Separator serves to filter out particles that are NOT the isotope we want to study. In essence, the A1900 is two magnetic spectrometers (four dipole magnets) in a row. It has high acceptance and high-efficiency transmission of specific isotopes.

1. The target is generally a thin foil of beryllium, which is preferred because it doesn’t have a large electron density (only 4 per nucleus) and thus the electrons have less effect on the charged beam passing through. Its low density also allows us to use a thicker foil, which is better for heat dissipation (plus, the melting point of beryllium is 1287 Celsius). The foil is about 1”x2”, though the beam spot is only about 1 mm wide. The foils do wear out, as over an average experiment it is possible for every atom in it to be struck by a beam nucleus! Some experiments use more than one target to avoid damaging targets by beam interaction.

1. The A1900 is about 35 meters (115 feet) long. It is composed of four large dipole magnets (gray, pic on the right) that act on isotopes like prisms act on different colors of light, bending and spreading the beam particles according to their ratio of momentum (mass x velocity) over charge. Only some particles make it around the corner (a 45-degree turn) into the next beam pipe. Quadrupole magnets (green barrels), arranged in eight “triplets” (groups of three), focus the continuing beam like a lens focuses light.

- Beam current is key! It is imperative that the A1900 preserve as many of the desired isotope as possible while efficiently eliminating the vast majority of other isotopes from the beam. As nuclei pass through the separator, it can select one nucleus from a million billion others. It’s like finding one specific person on a million Earths.
- There is a windowed box and camera looking in at a point on the beam line where operators can lower a fluorescent screen and establish where the beam is, size, shape, etc. During the process of “tuning”, this provides visual confirmation. The window is there so people can see the slit drives in motion.

1. “Tuning” to find a particular isotope is done with silicon PIN detectors (identifies element), Parallel Plate Avalanche Counters (PPACs) (measures position/angle of fragments), and a plastic scintillator (measures time-of-flight and particle energy). The combination of all this information allows one to determine the mass and charge (element) for every exiting particle.

Approved: Andreas Stolz 12/10/15
Stop 5: the Modular Neutron Array (MoNA) and Large multi-Institutional Scintillator Array (LISA)

Safety

- Do not approach the red sweeper magnet if blue light is on.
- Photomultiplier Tubes (PMTs) on MoNA bars receive high voltage via the wire marked with red.

N2 Vault: Modular Neutron Array (MoNA) and Large multi-Institutional Scintillator Array (LISA) (5)

- MoNA: the Modular Neutron Array in N2 was designed at NSCL and built by undergrads from a collaboration of many colleges and universities (funded by $1 million from NSF), and members of that collaboration come to NSCL each year to conduct experiments. It's a testament to the research you can do in college.

1. Operation: after secondary collision between rare isotopes and a target, the sweeper magnet diverts all charged particles from the beam into the attached detector box, allowing just neutrons to bombard MoNA and LISA. Note that the neutrons pass right through a metal plate and through the air - while nuclei require a vacuum for transport, neutrons rarely interact with particles because they are neutral. 6-foot walls of concrete are required to contain the neutrons.

2. Each bar of plastic scintillator (like acrylic glass) is wrapped in a black covering so that no light can enter. Neutrons can pass right through, and those that disturb a hydrogen atom can cause emission of light, which travels to the ends of the bar where photo-multipliers (like night vision goggles) amplify it (up to 30 million times) for detection.

3. These photo-multipliers also measure when the light arrives very precisely, so the position of the light emission along the bar can be determined within a few centimeters by measuring the time difference of the signals at the left and the right end. This time difference has to be known to less than a nanosecond (billionth of a second). Additional spatial tracking of neutrons comes from identification of which bar gave the signal (16 per stack, 9 stacks deep for both MoNA and LISA). Each neutron can provide multiple “hits” in the detector.

4. The 576 signals from the bars feed into the Field Programmable Gate Arrays electronics modules in back. The FPGA-based trigger logic needs to tell the neutrons from about 200-400 counts/second of background cosmic ray events, which is done by detecting the neutrons in coincidence with charged particles arriving in the detector box by the sweeper magnet.

5. The computer can tell where neutrons are, what direction they are travelling, and how fast. Information from MoNA-LISA can be used to reconstruct a picture of the interior of rare neutron-rich nuclei, providing a deeper understanding of their structure and, ultimately, answers to astrophysical questions because rare neutron-rich nuclei play a key role in the synthesis of the heavy elements and help drive tremendous stellar explosions, such as supernovae and x-ray bursts.

- When not detecting neutrons from a beam, MoNA-LISA is still counting cosmic rays, which is useful data.
- The total length of all wires between MoNA and the FGAs is 5 miles (8 km), and LISA’s wires stretch 7 miles (11 km). Each wire is specially designed and carries 2000 V, with ends that protect the user from that high voltage. Each wire therefore costs about $50.
- The kind of research opportunities at NSCL afforded by MoNA-LISA is a major reason we have the #1 nuclear science graduate program in the country!

Approved: Thomas Baumann 12/21/15
Stop 6: N4 vault, featuring the Beam Stoppers.

Safety

- This room is often actively under construction, be aware of personnel, equipment and materials!
- Red light indicates that the HV platform is energized - OK if you don’t proceed past the door from the north hallway.
- Blue light indicates magnetic field is on - do not bring visitors into the vault!
- This room is normally blocked off - if you want to stop here, you will likely have to stand outside.
- Do not leave the platform just inside the door.

N4 Vault: Beam Stopping (6)

1. Some experiments require a low-energy beam to perform a precise measurement. This vault is where beam nuclei can be slowed down to velocities similar to the molecules in air and then sent on for an experiment or reacceleration.
2. Three beam lines will be installed in the room with different capabilities to slow down and collect the fast beams for further experimentation. Stopped nuclei and reaccelerated beams will offer entirely new kinds of experiments at NSCL!
3. A new linear gas cell is temporarily installed on the large beam line on the north (left) side of the room. In the longer term the gas cell will be moved to smaller beam line on the south side. The ions slow down by passing through metal plates a few mm thick and then go into helium gas. The stopped ions are extracted from the big gas cell by a combination of electric fields and gas flow. The room has two enclosed high voltage areas, red lights indicate when the HV is active. The High Voltage platforms are necessary to push the stopped ions out of the vault over the relatively long distances to the new precision measurements area and the reaccelerator.
4. A second beamline will be constructed in the center of the room to collect certain ions that can be easily extracted from a hot metal. These ions do not require the helium gas and the system is much smaller.
5. A very large gas-filled reverse cyclotron (sometimes called the cyclotron stopper) is being constructed in the ReA12 high bay and will be installed in the N4 vault in the future. In the “reverse cyclotron” method, the fast exotic beams are injected into a sector-focused cyclotron magnet with a gas-filled central chamber. The fast ions circle around in the magnetic field and spiral towards the center as they lose kinetic energy through collisions with the gas. At the center, RF-based ion guiding techniques are used to collect and extract the ions. Prof. Morrissey’s and Bollen’s research groups have been developing these techniques over many years and used them in the LEBIT mass-measurement program. The new device is about the size of the K1200 cyclotron because it has to collect ions produced by that machine. The steel yoke weighs about 170 tons. The new cyclotron stopper will be used for the most penetrating and highest intensity ions that can not be collected efficiently in a small (1m long) gas cell. The cycstopper will be completed “soonish”

2. Note that gas stoppers reduce incoming nuclei to “thermal energies”, equivalent to the speeds of particles moving in room-temperature air. This is still hundreds of meters per second!
3. After the ions nearly come to rest, the low-energy beam of ions will be passed out of the vault in the beam line that exits the room in the far (south east) corner of the room.
4. Slowing down the fast ions with helium gas can be compared to slowing down a speeding bullet as it flies through a giant cloud of flying gnats. Every collision takes a tiny energy and eventually after billions and billions of collision the bullet will stop.
5. Stopping the rare isotopes allows researchers to make more careful measurements (e.g. measuring their mass - you wouldn’t try to weigh yourself by driving over the scale at 70 mph!)

Approved: David Morrissey 1/30/13
Safety

- View LEBIT/BECOLA by looking in the window on the southern door facing the East High Bay (near “7” on the map)
- For VIPs, take fewer than 5 people in at once, stay close to the door, and do not test the magnetic field with a wrench.

Low Energy area (Precision Measurements) (7)

Low-Energy Beam Ion Trap (LEBIT)

1. LEBIT has a superconducting magnet (gray barrel with spartan “S” and helmet), note the blue light on top indicating strong magnetic field where the previously-slowed and bunched nuclei are trapped in a circular orbit.
2. You can measure their mass by measuring the frequency of their orbit (like RPM) inside the magnetic (+electrostatic = Penning) trap: heavy ions are slower. Typical frequencies measured are 1-10 MHz. Cyclotron frequency is a simple calculation: \( \omega_c = qB/m \) (cyclotron frequency is equal to charge*field/mass)
3. The mass is measured by probing the ions’ specific (cyclotron) frequency with a radio frequency electric field, seeking the resonant frequency that will eject it from the trap. This measuring technique works best for single trapped ions.
4. LEBIT can measure the mass of a nucleus to one part in 100 million; equivalent to weighing an entire jumbo jet and telling how much change is in a passenger’s pocket.

1. Short-lived isotopes with half lives down to the millisecond range can be addressed. Stopping in the helium gas cell takes 10-100 ms. Cooling/bunching the beam (converting a continuous beam of nuclei to bunches) takes 5-30 ms. Time spent measuring in Penning trap takes between a few milliseconds to a few seconds.
2. World record for precisely measuring mass of short-lived isotope with a Penning Trap at TRIUMF like LEBIT: Lithium-11 (half life of 10 ms)!
3. Mass measurement results can have implications for astrophysics, the r-process path, nuclear structure and fundamental interactions.
4. It’s the strongest magnet you’ll probably ever see (9.4 T, 94000 gauss, about 200,000 times the strength of the Earth’s magnetic field), and it’s always on (note blue light above it), but it’s well shielded. NOTE: you can feel the field near where the beamline enters the barrel, so beware! LEBIT’s superconducting wire coil carries a little less than 100 amps.
5. Once NSCL staff got the current running in the superconducting coil inside, they unplugged it. The current is still going! It’s superconducting, so there’s no reason for the current to stop as long as the niobium wire is kept cold. LEBIT can operate for several thousand years before recharging. It is essentially the best battery you’ll ever see. (note: the penning trap is not kept cold - it has a separate LN2 shield)

1. Helium and nitrogen gas pressure release valves allow vaporized LHe and LN\(_2\) to escape. Oxygen sensors in the room tell you if too much nitrogen is escaping (because N\(_2\) displaces oxygen and creeps along the floor, making it hazardous). Any ice on the LN\(_2\) pipes is just humidity in the air freezing onto the cold surface.

1. The entire LEBIT beam line has been reconfigured and is floated up to 60 kV to match the new gas stopping stations (see the red insulators on the magnet stands). The previous gas cell was at ground potential and only fed LEBIT. After showing that rare isotopes produced via projectile fragmentation can be thermalized and used for precision mass measurements, the new gas stopping stations feed LEBIT, BECOLA, and ReA3.

Approved: Ryan Ringle 2/11/16
Safety

- Currently, there is no good vantage point from which to see BECOLA. For VIPs, take fewer than 5 people in at once, stay close to the door, and do not test the magnetic field with a wrench.

Low Energy Area (7) BEam COoler and LAser Spectroscopy facility (BECOLA)

1. Depending on its electron configuration, an element reacts to a certain color of laser light and fluoresces as a response. The color of the laser light to which the atom reacts varies depending on elements (each element has a “fingerprint” spectrum) and even within the same elements there is subtle variation of the light color among isotopes. It is the slight changes of light color/energy necessary for the atom’s reaction that the experimenter in BECOLA study to deduce information about nuclear structure and fundamental symmetries.

2. Beams from NSCL gas stopper are delivered to the BECOLA beam cooler/buncher. The cooler/buncher is a device that improves the quality of a rare isotope beam from the gas stopper, meaning it emits beams with a small energy spread, small divergence, small diameter and so forth.

3. The cooler/buncher uses a combination of buffer gas (typically He), radio frequency, and DC fields. Collisions with the buffer gas results in a cooled ion beam. If desired, the DC fields may be segmented so that a DC-potential well can be formed, in which the cooled ions would gather. By quickly lowering the voltage applied to the last electrode segment, the well can be opened and the ions extracted as a cooled, bunched beam. The cooled and bunched beam (60 kV) will then be transported to the collinear beam line in BECOLA, where laser light is collinearly overlapped with the ion beam.

4. The laser system consists of a 15 W green laser to pump a Ti:Sapphire ring laser (~2 W, 700-1000 nm). The light from the Ti:S laser can be frequency doubled to generate second-harmonic light (~250 mW, 350 – 500 nm). An optical fiber is used for laser light transport from the laser room to BECOLA beam line by about 25 m. Laser light is introduced into beam line through a laser window on the 2-way bend using optic components on the breadboard by the bend.

5. Resulting fluorescence is collected using a fluorescence detection system. The heart of the system is an ellipsoidal mirror. The laser light and beam passes one of the focal point of the ellipse. The fluorescence emitted at the focal point is re-focused at the other focal point, where a fluorescence detector is placed. This is a similar concept to a parabolic antenna for satellite TV. It’s an efficient fluorescence detector thanks to the ellipsoidal mirror.

6. The fluorescence detection system is turned on only when there are beam bunches from the cooler/buncher, in order to increase signal to noise ratio. The technique makes it possible for experimenters to perform measurements with incoming ion beam rates as low as ~ 100 ions per second, which enlarges the accessible number of nuclei in the nuclear chart.

7. Experimenters can also produce polarized beam (all spins are pointing at the same direction) using optical pumping technique with circularly polarized laser light. The bike rim coils along the beam line produce magnetic field to maintain the polarization. The polarized beam is required for the beta-particle-detecting nuclear magnetic resonance (β NMR) technique, which has much higher sensitivity than the conventional NMR due to the polarization and beta particle detection. The technique may be applied to rates as low as ~ 100 ions per second as well.

8. Within BECOLA facility there is a Penning Ionization Gauge (PIG) offline ion source. The PIG source is a discharge sputtering source and can generate many of stable isotopes including refractory elements (transition metals). Experimenters can use beams produced at the PIG source offline to develop best suited laser excitation schemes for spectroscopy that will be used in online experiments at BECOLA.

Approved: Kei Minamisono 12/3/15
Safety

- Don’t lean over the rail!
- It is recommended to not take groups downstairs for safety and comfort purposes; however, if you do, advise them to watch their step carefully because it is steep. They must be wearing proper shoes. The downstairs is not usually surveyed either!
- Notify visitors who don’t like heights that they can wait off the catwalk.

S3 Vault: S800 Spectrograph (8)

1. The S800 spectrograph is three stories high, 300 tons, designed to detect fragments coming from a collision between the rare isotope beam and a thin foil target. The basic idea of the S800 is that it allows the measurement of the velocity and angles of the fragments with great accuracy. The S800 combines two key factors to achieve its performance:

2. High resolution (at best 0.01% of the particle’s energy), meaning it is capable of distinguishing between two particles of only slightly different energies. This is equivalent to 0.005% of the velocity... for example, measuring the velocity of a car at about 50 mph, one could determine the speed to within 13.2 feet (4 meters) per hour, or 0.04 inches (1 mm) per second.

3. Large acceptance, meaning it collects and measures inside a large momentum range (~5% of the central energy) and angular range of the particles after they have reacted with the target.
- The S800 acts much like the A1900 in that its two brown dipole magnets filter out many products and allow only the fragments of interest to reach the white detector box at top. By establishing the identity of those particles, their energies, and their trajectories, researchers can model what the rare isotopes were like before the collision: the structure of the nucleus.

1. Particles are detected (tracked) in 2 focal plane detectors placed inside the detector box. The position in each detector is determined, and from those two positions, the angle of the track. The angle and position in the focal plane are then used to calculate (raytrace) the velocity and angles of the particles just after the collision. The detector box contains a scintillator used to time the particle and measure the amount of energy lost in material, an ion chamber to also measure delta-E, and hodoscope to measure particle energy. From that information, the particle type (charge & mass) can be determined.

2. Using another detector around the collision point (target) at the bottom, one can correlate the gathered information with the detected particles at the top to get more information. The Segmented Germanium Array (SeGA), GRETINA, HiRA and LENDA have been employed there to collect gamma rays, neutrons, or charged particles from nuclei that are excited in the reaction.

3. Because the S800 Spectrograph is so versatile, over one-third of the experiments performed at NSCL use it!

4. To check different scattering angles of post-collision fragments, the S800 can rotate over 150°, although this is rarely used nowadays; the particles in the beam are usually much heavier than those in the target and thus tend to continue their forward-directed motion without being deflected much.

Approved by Hironori Iwasaki 12/14/15
Safety
- Stay on the platform inside the door.
- Watch for items on the floor.

S2 Vault (9)

Radio Frequency Fragment Separator
(RF Kicker)

1. (by Ana Becerril) The Radio Frequency Fragment Separator in S2 (a.k.a. RF-Kicker) is a velocity filter that separates proton-rich ions (very far from stability) that cannot be purified using the A1900 Separator alone. The RF-Kicker uses a time varying vertical electric field to induce a transverse deflection on the beam depending on the velocity of the different species, i.e. it gives a little kick to the unwanted isotopes (which are then stopped with a set of vertical slits), and lets only the desired fragments through the detection system.

2. The RF Kicker decreases the contamination in our secondary beam by several orders of magnitude without affecting the intensity of the fragment of interest. Beam purity is crucial to allow β-ion correlations in decay studies, and also to prevent overloading of our detectors.

Approved: Daniel Bazin 2/11/16

Miniball and HiRA (8 or 9)

1. NOTE: Miniball and/or HiRA are only set up for one month out of the year, and sometimes in S3 instead of S2... often, there will be no detector at the end of this vault’s beamline.
- Detectors are placed in a vacuum vessel and evacuated down to 10^-6 Torr. Beam enters the vessel and strikes a target at the center of the miniball. The collision releases many protons, neutrons, and fragments.

1. The miniball is made of about 100 CsI crystals surrounding the target so they can pick up particles released in almost any direction. This lets researchers determine the violence of the collisions. (Less violent collisions give out fewer particles. In very violent collisions, the colliding nuclei disintegrate.)

2. HiRA is made up of several “telescopes” designed to pick up the charged particles that pass through its matrix of silicon strips. The strips form pixels of less than tenth of an inch square. From the position, the experimenters can deduce the angles of the emitted particles. HiRA is a state of the art detector which can measure the charge, mass, energy, and position of a particle to very high resolution.
- The neutron walls (like MoNA, but using liquid scintillator) detect the neutrons striking them from the fragmented nuclei. These walls are special because they can distinguish light specifically generated by neutrons.

1. Combining information from walls and detector in the vessel allows researchers to reconstruct the directions and energies of most particles especially the protons and neutrons from the collision. The information can then be used to work backwards and learn more about the properties of the colliding regions between two heavy nuclei. We use the results of the experiment to learn about astrophysical objects such as neutron stars because the colliding region simulates the matter in these objects.

Approved: Betty Tsang 2/25/11
Safety
- If you must enter the Machine Shop (a very rare occurrence), do not cross the barrier wall without goggles. Ensure all visitors have them on before passing the “warning” sign!
- In the South High Bay, everyone must wear a hard hat if the crane is running (yellow light flashing)!
- In the South High Bay, keep your group within 30 feet of the entryway to avoid most hazards.

Machine Shop (11)
1. The Machine Shop: The shop contains Computerized Numerical Control (CNC) Machines, many are mills and have automatic tool changers. Another CNC, the Haas machining center with rotary table capable of traveling 150” x 72” x 36” is housed in the South High Bay. There are several manual machines as well.
   - Our machine shop staff consists of 7 full time journeyman machinists and one full-time trades assistant to purchase material and prepare stock for manufacturing.
   1. Machinists undergo continuous education in CAD/CAM upgrades and have a total of 200 years experience among them. The manufacturing staff is rounded out by six qualified welders who support fabrication and cryogenics assembly...
   - Common materials worked in the shop: copper, steel, stainless steel, aluminum, titanium, niobium
1. The Machine shop provides service from 6am - 4:30pm on weekdays, and occasionally weekends when needed.
1. The Machine shop and Welding shop support all of NSCL and our outside users. Our shop is directly connected with our design department and receives all of our part files electronically.

South High Bay (11)
1. The South High Bay is an assembly area, where we put together new equipment. It also serves as storage for fabricated parts and ongoing projects.
1. At any one time you’ll likely see new dipole/quadrupoles at some stage of construction. Superconducting and normal wires are made into magnets at the coil winding station (on the far left as you enter). Cryomodules are often under construction here.
1. The crane here serves the same purpose as the one in the research area, but it can only lift 30 tons.
1. The windows face south onto the FRIB construction area.

Approved: Jim Wagner 10/8/12

What this means is all tool and cutter paths are generated directly off from the designer’s solid part model. This method of manufacturing virtually eliminates any discrepancy between a designed part and the finished parts. Much of NSCL’s equipment was designed and built right here since it has a very specific purpose! We are always building replacement and prototype parts.

For approval: Ken Plath 1/26/16
Stop 12: East High Bay, featuring ReA3 and Clean Room.

Safety
- Hard hats must be worn if crane is in operation.
- Watch for objects on floor.
- Do not take visitors upstairs.

East High Bay (12) Clean Room
1. The cleanroom is where NSCL builds equipment that must meet very high cleanliness specifications in order to operate at high accelerating voltages. The cleanroom is separated into two rooms of different classes, a Class 100 and Class 10,000. “Class” refers to a measure of the cleanliness of the room. To certify a Class 100, there must be less than 100, 0.5 μm particles, per cubic foot of area. In comparison, the East High Bay measures at over 350,000, 0.5 μm particles, per cubic foot. Occupants of the cleanroom are required to wear “bunny suits” to keep body contaminants from escaping into the clean environment.

1. Inside, you’ll see parts used in the next-generation accelerators. The structures or “cavities” you see are fabricated from high purity niobium (element 41), a metal used for its superconducting properties. When the cavities are completed, they are aligned in a linear array, making up a superconducting linear accelerator or Linac. When in operation, the cavities are energized with large electric fields (millions of volts) on the internal metal surfaces, requiring the surface to be dust-free.

1. High-purity niobium takes 5-6 months between ordering and receiving, cavity dies and tooling are fabricated in 1-2 months. One cavity take about 4-6 months to construct, depending on electron-beam welding availability.

1. The NSCL has prototyped several new cavity types, in collaborative efforts with other national laboratories for future accelerator designs. The new SRF cavities will be used in ReA3, and revised designs are destined to form the linear accelerator of FRIB.

Approved: Chris Compton 10/16/12

ReA3 (12)

1. Some experiments can’t be done while the nuclei are travelling at half the speed of light. This upgrade lets us stop the beams (in the gas stopper), ionize them (strip them of electrons to high charge states in EBIT, the Electron Beam Ion Trap), and reaccelerate them to about 8% of the speed of light. This is approximately the speed of nuclei you’d find in a star, so this reaccelerated beam lets you do nuclear astrophysics experiments with star-like nuclei. ReA3 will make NSCL the only facility of our kind (fast-beam fragmentation) with this capability. Researchers have been asking to do this type of experiment, and will want to come here.

1. The ReA3 accelerator is made of 15 superconducting cavities made of pure niobium. These next-generation accelerators are of a brand-new design, developed in collaboration with some other labs around the country, and we’ve built the first ones ever. As nuclei pass through, the center part is charged to +/- one million volts, shooting the nuclei out the other side. There are different sizes/shapes of cavities, all operating at 80.5 MHz, each optimized to operate at either 4.1% or 8.5% of the speed of light.

2. The cavities are in cryomodules (cold boxes) behind the green lead shielding.

3. Resulting beam energies from ReA3 will be variable and relatively low (from 0.3 MeV/u to 6 MeV/u), 3.2 MeV/u (8% of c), appropriate for astrophysics-type experiments. By comparison, the cyclotrons accelerate nuclei up to 140 MeV/u (50% of c) and FRIB will achieve 200 MeV/u for uranium beam (57% of c).

1. What we learn in building ReA3 will be invaluable when it comes time to build the FRIB linac, which will include 300 such cavities in a 400-yard-long (360+ meter) tunnel about 30 feet (8 meters) underground.

Approved: Antonio Villari 2/3/16
Stop 13: ReA12 High Bay and Low Energy Experimental Area, featuring parts of the cycstopper and AT-TPC.

Safety
- Hard hats must be worn if crane is in operation.
- Watch for objects on floor.
- Do not take visitors upstairs.

ReA12 High Bay
1. Note that parts of the cyclotron gas stopper are currently being tested in the ReA12 High Bay. Details on page 6.
2. This addition to the Experimental area (you can see the walls are a different color than by ReA3) will allow the reaccelerator to be extended and bring rare isotope beams up to and beyond 12 MeV/u. This energy is analogous to that expected in a supernova, and high enough to overcome electric repulsion between nuclei (Coulomb barrier), thus allows for more transfer reaction experiments.

ReA3 High Bay (13)
1. The AT-TPC magnet and yoke is currently in place!
2. The magnet was originally constructed to serve as part of an MRI, but was repurposed for a nuclear detector (which MRIs were invented to be) at TRIUMF in Vancouver, then donated to NSCL.
3. The AT-TPC is a large gas volume located inside the magnetic field of the detector. Secondary beam particles will enter the detector through a thin window. If they interact with the active target gas (by a nuclear reaction) the resulting products will leave an ionization track. The electrons of the ionization track drift to the anode and are amplified (Micro Mesh Gas Amplifier). The ionization track is read out via a high granularity micropattern by 10 thousand electronic channels on the back of the detector. A three dimensional picture of such an event is generated. It is planned to be used, among other things, for the study of nuclear structure far from stability and for the study of reactions of astrophysical interest either by (d,p) or (3He,d) transfer reactions.

I. (from the NSCL website) The AT-TPC combines time projection and active target functionality in a single device thus allowing measurements of rare processes that require high detection efficiency and large acceptance. Low energy processes that are traditionally difficult to measure due to the short range of the reaction products in matter can be observed by using low pressure. As the name implies, the AT-TPC will operate in two different modes. In the active target mode, the AT-TPC counter gas acts as both a target and detector, allowing investigations of fusion, isobaric analog states, cluster structure of light nuclei and transfer reactions to be conducted without significant loss in resolution due to the thickness of the target. The high efficiency and low threshold of the AT-TPC will allow investigations of fission and giant resonances with fast fragmentation rare isotope beams. Operating the AT-TPC in the detector mode, the reaction products created in collisions between isospin asymmetric heavy ions will allow the density dependence of the symmetry energy term of the nuclear equation of state to be explored. To accommodate this range in experimental programs the AT-TPC is designed to be portable to allow the chamber to be installed at a variety of NSCL beam lines, including the new reaccelerator area.

Approved: Wolfgang Mittig 10/31/14
Safety

- Blue light in hallway by Atrium door indicates that the magnet is on. Do not approach ECR area or K1200.
- Tours should not enter this area without approval.

Superconducting Source for Ions (SuSI) (near 3a)

1. Accelerators only work on charged particles; therefore, the stable nuclei we accelerate must be slightly ionized so they have a net positive charge. The acceleration depends on the voltage times the charge, so depending on their charge, the ions produced will leave the ion source going a little less than 1000 km/s.

2. If accelerating a metallic element, it will be heated in a little oven (200-2000 Celsius, depending on the element) to produce a vapor, and the gas is injected into a magnetic bottle. SuSI’s magnetic field (up to 2.5 T) is far higher than our other ion sources (Artemis about 1.5 T).

3. Inside, the neutral atoms are bombarded with electrons from a plasma (created by microwaves) to knock electrons away from the atom, creating an ionized state.

4. The goal is to have a large number of ions in the same ionized state (e.g. 3+ for oxygen), though the ion source produces many different states (10 states for light ions, could be more than 30 states for heavier elements). The more ions you can have in a single state, the more beam you will have to accelerate into the target. The plasma is optimized to produce most nuclei in a specific charge state. The first magnetic dipole along the extraction line selects only one charge state to pass through... so only some of the produced ions can be used.

5. The ions are extracted by an electric field of 25-30 kV and sent to the K500 cyclotron.

6. Primary beam currents range from 175 pA (O-16) to 0.2 pA (U-238)

Approved: Guillaume Machicoane 10/15/12

The Segmented Germanium Array (SeGA) could be placed in either the bottom of S3 (stop 8) or in S2 (stop 9).

Segmented Germanium Array (usually 8 or 9)

- After the nucleus is excited, it will often de-excite by emitting energy in the form of high-energy light: gamma rays. With arrays of gamma-ray detectors, this light can be collected to learn about the properties of that rare nucleus. The detectors at the NSCL are unique for detecting gamma rays from very rare nuclei that travel at very high velocities.

1. The segmented germanium array (SeGA) allows “high-resolution” in-beam γ-ray spectroscopy of intermediate-energy beams from the Coupled Cyclotrons. Each of the eighteen detectors in the array is a single-crystal 75% relative-efficiency germanium counter with the outer surface electronically divided into 32 segments. By using the segment information, the interaction of the γ-ray can be localized within the detector, therefore reducing the uncertainty in the Doppler correction due to the finite opening angle of the detector. A detector frame is available and allows the detectors to be placed at several distances, so the experimentalist can decide on the compromise between efficiency and resolution for their particular needs. The standard configuration is 18 detectors at 20 cm, which gives an approximate 3% photo peak efficiency at 1.3 MeV with about 2% in-beam energy resolution. The detectors are also available for stopped beam experiments such as β-delayed γ-ray decay studies.

(from NSCL website)

Approved: Dirk Weisshaar 2/2/16
CAESium iodide ARray (CAESAR) (usually 5 or 9)

1. (from NSCL website) The structure of rare isotopes has been found to be significantly different from that of stable ones and new results continue to surprise researchers. Many NSCL experiments react a beam of a rare isotope with stable targets at >0.3 c to elucidate its structure. The photons emitted during and after the reaction provide invaluable information on the energy levels of the exotic nuclei and allow detailed studies of their properties.

2. CAESAR is a very efficient detector that is tuned to collect and measure these photons. It consists of 192 individual CsI(Na) scintillation crystals that cover 95% of the solid-angle surrounding the target. The large number of detector elements is needed since the photons emitted by moving nuclei are subject to the well-known Doppler phenomena that can only be corrected if the relative direction of emission is known. Each individual CAESAR detector that responds to a photon has a specific angle relative to the beam direction that is used in the Doppler reconstruction to calculate the spectrum of emitted photons in the rest frame of the moving nucleus. CAESAR was successfully commissioned in May 2009.

Approved: Dirk Weisshaar 2/2/16

Gamma-Ray Energy Tracking IN Ar-ray (GRETINA) (usually 9)

1. (from NSCL website) A collaboration of scientists from Lawrence Berkeley National Laboratory, Argonne National Laboratory, NSCL, Oak Ridge National Laboratory, and Washington University has designed and constructed a new type of gamma-ray detector to study the structure and properties of atomic nuclei. Construction started in June 2005 and was completed in March 2011. The detector is built from large crystals of hyper-pure germanium and will be the first detector to use the recently developed concept of gamma-ray energy tracking. GRETINA consists of 28 highly segmented coaxial germanium crystals. Each crystal is segmented into 36 electrically isolated elements and four crystals are combined in a single cryostat to form a quad-crystal module. There are 7 modules in total. The modules are designed to fit a close-packed spherical geometry that will cover one quarter of a sphere. GRETINA is the first stage of the full Gamma-Ray Energy Tracking Array (GRETA). The extra holes in the sphere are to accept more modules in this next step, completing a full 4pi detector.

2. GRETINA is a national resource that will move from laboratory to laboratory. NSCL did host GRETINA in a 12 month campaign in 2012/13, after which it left for Argonne Nat’l Laboratory. Based on the success of the first campaign GRETINA returned to NSCL in summer 2015 for another nuclear science campaign.

Approved: Dirk Weisshaar 2/2/16
K500 wooden model (near Seminar)

- The K500 was designed long before Computer Aided Design (CAD) was available. A wooden model was constructed first to ensure that the parts would fit correctly!
- It is a full-scale mode of the interior that shows all of the critical elements (listed below)
- Hills (high magnetic field regions that together with the valleys provides “flutter” for focusing the beam)
- Valleys (low magnetic field region where the Dees are)

1. Trim coils to make the magnetic field isochronous (the particles stay in phase with the accelerating electric field)
2. Hill liner (copper) that keeps the RF contained in the beam chamber
3. Beam probe track (aluminum) – resides inside of a Dee and follows the shape of the Dee. It provides a way to carry a camera or beam current monitor to observe the beam as it moves out in radius (i.e., higher energy)

D-line (north of S3 Vault)

- This is a good place to point out the complexity of transporting a beam of nuclei.
- The electrostatic bender (which appears in several places along the line – all are one design to be more efficient) is able to divert the beam 45 degrees. It can take the place of a larger and more expensive magnetic dipole because the beam energy is low (slow velocity).

4. The 61-degree dipole magnet (blue, left of the picture) serves to select isotopes of interest like a mass spectrometer, since there can be impurities in the beam when it leaves the gas stopper.
- The electrostatic focusing elements (quad doublet) serve the same purpose as quadrupole magnets in other places; however, they use adjustable potentials (+/- 6 kV) to confine the beam.
- The vacuum lines allow the pumps in the right corner to evacuate the whole D-line.
- The vacuum gate valves break the beam line into several vacuum sections to allow localized maintenance.
- Safety - if the orange warning light is ON, the D-line may be carrying radioactive beam. However, there is no danger to visitors and it is OK to stop here!
LENGA

1. The Low-Energy Neutron Detector Array (LENGA) is used for detecting neutrons with velocities ranging from 2000-20000 miles/s, which is actually not very fast from the point of view of a nuclear scientist. It can be used in a variety of experiments at NSCL, but the main use thus far has been in experiments at the S800 spectrometer that aim to understand processes that take place in exploding stars (supernovae) or that involve neutrinos, which are very weakly interacting particles that can help us learn about fundamental properties of matter and forces.

2. In the experiments at the S800, beams of rare isotopes are injected onto a target (usually a cryogenic target of liquid Hydrogen), and the neutrons from reactions taking place at the target are detected in LENDA. Heavy beam-like fragments are detected in the S800, with the goal of tagging specific reaction channels.

Approved - Remco Zegers 12/2/15

JENSA

- Jet Experiments in Nuclear Structure and Astrophysics
- Designed by Colorado School of Mines and ORNL, funded by DOE and JINA, see jensajet.org for a complete list of collaborators. Current collaboration is led by Kelly Chipps from ORNL.
- High density windowless gas jet target for nuclear astrophysics studies (radioactive beam with astrophysical energies hits H or He gas jet with a width of about 4 mm. Reaction products are studied currently with Silicon detectors inside the gas target chamber, or later with SECAR once its built.
- World’s densest He gas jet with $10^{19}$ nuclei per cm$^2$.
- Jet inlet pressure maintained by large compressor is up to 40 Atmospheres.
- The connection to the high vacuum beamlines without any windows is accomplished with a series of differential pumping stages where large pumps bring the pressure stepwise down to high vacuum. These pumping stages are connected with small apertures to restrict gas flow.

- All gas is recirculated in a closed system so we can use expensive gases like $^3$He (a filling of the system is about $100k$)

Approved - Hendrik Schatz 12/6/15
Master-Slave Manipulators (MSM)

1. The “cold test station” here consists of the metal frame and two MSMs, and it will ultimately be installed in the hot cell (the target area of FRIB). The metal frame represents a concrete wall, and the opening is where a 28” thick leaded window will be. The window can handle a temperature change of 5° per hour without cracking. The black boards limit the view as it would be in real practice.

2. One cold test station requires a three-person team to operate—one on each MSM “arm” and a third person to serve as gofer and spotter to monitor the cameras from different angles. There will be 10-12 personnel for this service to fill three shifts.

3. The MSM arms offer no mechanical advantage, they simply transfer the motion of the operator to the clamps on the far side. They have a weight limit of 100 pounds.

4. During this simulation, it’s critical for staff to limit their vision in the same way it will be in the hot cell. Staff are training with the MSM and developing special tools for use with it. They need to understand the challenges and requirements of using it before it’s installed. Problem solving is a critical part of this process.

5. This technology is derived from the Manhattan Project, and further developed by the Navy for use with their nuclear reactors. One MSM costs about $135,000.

6. There will ultimately be up to three MSMs surrounding the FRIB target area to maximize coverage, complemented by a remote-control 20-ton crane with rotary hook, a power rotary jib crane, and plenty of lights and cameras to improve vision (which is the biggest challenge)! There may also be a “pass window” (like a bank teller drawer) to let them move items in and out of the hot cell.

Approved - Doug Miller 1/11/16