National Superconducting Cyclotron Laboratory

Forefront national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

280 employees, incl. 41 undergraduate and 52 graduate students, 24 faculty (+ 3 open faculty positions)

New CCF user group formed in 2001: 700 registered members (439 from 101 US institutions, 261 from 113 foreign institutions and 35 countries) as of Feb. 17, 2006
Key Elements of Coupled Cyclotron Facility

Coupling of superconducting K500 and K1200 cyclotrons provides large intensity gains.

Additional gains in rare isotope beam intensities from superconducting A1900 fragment separator – the largest-acceptance fragment separator world-wide (technology adopted by RIKEN).

Completed in 2001 – on schedule and within budget.

Projected gains in primary beam intensity: CCF vs K1200

<table>
<thead>
<tr>
<th>Isotope</th>
<th>CCF</th>
<th>K1200</th>
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</thead>
<tbody>
<tr>
<td>Ca</td>
<td>10^6</td>
<td>10^9</td>
</tr>
<tr>
<td>Ar</td>
<td>10^7</td>
<td>10^8</td>
</tr>
<tr>
<td>Xe</td>
<td>10^10</td>
<td>10^11</td>
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<tr>
<td>U</td>
<td>10^12</td>
<td>10^13</td>
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</table>

Beams Produced with CCF/A1900

Research program requires large number of beam tunes

2001 through 2005: 503 invited talks by NSCL users and staff, 426 papers in refereed journals, including 68 in Physical Review Letters
Major Research Thrusts

• Production of nuclei with unusual ratios of protons to neutrons and the measurement of their properties
  What are the limits of nuclear existence? What are the properties of nuclei with extreme ratios of protons and neutrons (neutron skins and halos)? Modification of shell structure, new doubly magic nuclei: $^{48}\text{Ni}$, $^{78}\text{Ni}$, $^{100}\text{Sn}$, $^{132}\text{Sn}$…

• Exploration of the nuclear processes that are responsible for the chemical evolution of the universe through the ongoing synthesis of most elements in the cosmos
  Where are most of the nuclei heavier than iron made? How do supernovae explode? Are Type 1a SN good standard candles?

• Exploration of the isospin dependent properties of hot nuclear matter and how they affect supernovae and neutron star properties – connection to JINA
  What is the equation of state (EOS) of neutron-rich nuclear matter?

• Exploration and tests of novel superconducting accelerator and beam transport concepts and the dynamics of high-intensity beams
  Alignment with 3 of the 5 key questions identified in the 2002 NSAC LRP: What is the structure of the nucleon? What is the structure of nucleonic matter? What are the properties of hot nuclear matter? What is the nuclear microphysics of the Universe? What will be the new Standard Model?

C.K. Gelbke, 3/3/2006, p. 4
Scientific Program

With CCF running well, the 5-year perspective is superb.
State-of-the-art apparatus: A1900 fragment separator, $4\pi$-Array, 92-inch chamber, S800 magnetic spectrograph, large aperture sweeper magnet spectrograph, large area $(2\times2 \text{ m}^2)$ position sensitive neutron detectors, segmented Ge and Si-strip-CsI arrays, $\beta$-NMR and $\beta$-counting station, Gas cell (1 bar He) for stopping rare isotopes, 9.4 Tesla Penning Trap, …
Attractive Features of Fast Beams of Rare Isotopes
produced by projectile fragmentation or fission and separation in flight

• Economic production of medium-energy (E/A > 20 MeV) beams of rare isotopes, without reacceleration

• Chemistry-independent separation and transport to experiment
  – Short beam development times
  – Negligible losses from decay (separation and transport in microseconds)

• Increased luminosity from use of thick secondary targets (typical factors of $10^3$-$10^4$)
  – Enhanced scientific reach

• Reduced background from beam tracking
  – Use of particle tagging and cocktail beams

• Efficient particle detection from strong forward focusing
Development of ultra-fast, radiation-hard detectors for timing and particle tracking made from single-crystal diamond. Diamonds are grown by chemical vapor deposition (CVD) on iridium at MSU's Keck Microfabrication Facility.

Detector successfully tested up to particle rate of $5 \cdot 10^7 /s$

$\text{76Ge, 100 MeV/u, 10}^6 /s$

signal risetime: $\sim 0.5$ nsec

$\text{2nd particle within one cyclotron extraction pulse}$

$\text{time resolution: } \sigma = 20.5 \text{ ps}$

$\text{Intrinsic detector resolution: } \sigma = 15 \text{ ps}$

A. Stolz et al., Diamond & Related Material, in press
First Observation of $^{60}\text{Ge}$ and $^{64}\text{Se}$


3 events of $^{60}\text{Ge}$, 4 events of $^{64}\text{Se}$ observed

$^{60}\text{Ge}$ is heaviest $N=28$ isotope

half-life limits:
$T_{1/2}(^{60}\text{Ge}) > 110$ ns, $T_{1/2}(^{64}\text{Se}) > 180$ ns

cross sections ($< 1$ pb) smaller than expected

Non-observation of $^{59}\text{Ga}$ and $^{63}\text{As}$

half-life limits: $T_{1/2}(^{60}\text{Ge}) < 40$ ns
Coulomb Excitation of $^{72}$Kr


Heaviest N=Z nucleus for which $B(E2;0_1^+ \rightarrow 2_1^+)$ has been measured

$B(E2;0_1^+ \rightarrow 2_1^+) = 5000(650) \text{ e}^2\text{fm}^4$

Comparison to theory $\rightarrow$ oblate ground state, $|\beta| = 0.33$

Test case: $^{78}$Kr

Measurement: $^{72}$Kr

S800 + SeGA

Purity of $^{72}$Kr beam was only 1.7%

- Event-by-event tracking with clean PID in S800
  - Improved purity with future RF separator (under construction)
Exploring $^{42}$Si


S800 + SeGA: $^{48}$Ca → $^{44}$S → $^{43}$P

Only one low-energy $\gamma$-ray transition is observed → near degeneracy of $\pi d_{3/2}$ and $\pi s_{1/2}$ states

Relative population of the two states determines that excited state has higher orbital angular momentum → ordering of the $\pi d_{3/2}$ and $\pi s_{1/2}$ states

Small 2p-knockout cross section to $^{42}$Si
→ $Z=14$ gap persists for $N = 28$ at $^{43}$P
Breaking of Z=N=50 Core Near $^{100}\text{Sn}$?

Emerging discrepancy: do we need to open the proton space near $^{100}\text{Sn}$ or do we need to improve the effective interaction?

![Graph showing the comparison between different models and experimental data for the $B(E2; 0^+ \rightarrow 2^+)$ transition.](chart)

- **Seniority (fit)**
- **ENSDF Data Base**
- **NSCL**
- **NSCL (prelim)**
- **Shell Model**
- **EP + 1 broken pair**

Courtesy C. Vaman and K. Starosta
A.Volya and V. Zelevinsky
Nuclear Spectroscopy with Knockout Reactions

Different $P_\parallel$-distributions for individual states, tagged by $\gamma$-rays: cross section is sensitive to wavefunction; shape identifies $l$ of knocked-out nucleon

→ Breakdown of N=8 shell closure in $^{12}\text{Be}$: only 32% (0p)$^8$ and 68% (0p)$^6$-(1s,0d)$^2$
Occupation of Single-Particle States

Shell model: Deeply-bound states are fully occupied by nucleons. At and above the Fermi sea, configuration mixing leads to occupancies that gradually decrease to zero.

Correlation effects (short-range, soft-core, long-range and coupling to vibrational excitations): Beyond effective interactions employed in shell model and mean-field approaches. Occupancies will be modified.

Reduction factor with respect to the shell model:

\[ R_s = \frac{C^2 S_{\text{exp}}}{C^2 S_{\text{th}}} \]

In stable nuclei, a reduction of \( R_s = 0.6-0.7 \) has been established from \((e,e'p)\) reactions

V. R. Pandharipande et al, Rev. Mod. Phys. 69, 981 (1997)

Expanded Purview from Rare Isotopes

Occupation of Single-Particle States

\[ R_S = \frac{\exp}{\text{th}} \]

\[ S = S_p - S_n \]

\( R_S \) (e,e'p): \( S = S_p - S_n \)

\( R_S \) p-knockout: \( S = S_p - S_n \)

\( R_S \) n-knockout: \( S = S_n - S_p \)

Courtesy A. Gade and J.A. Tostevin

MoNA (Modular Neutron Array)

MSU, FSU, Marquette U., Central Mi. U., Concordia College at Moorhead, Hope College, Indiana U. South Bend, Wabash College, Western Mi. U., Westmont College

Issues and Events

Undergraduates Assemble Neutron Detector

The undergraduates come running.”
So says Ruth Howes about student participation in the Modular Neutron Array, or MoNA, a detector largely conceived and built by undergraduates. Howes, chair of the nuclear physics department at Marquette University in Milwaukee, Wisconsin, says the experiment is unusual and significant because it can work on MoNA without being tied to their home institutions. The detector was assembled last summer at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University and tested at the Brookhaven National Laboratory.

“...Many of the undergraduates had been working in other physics research groups...”

The facilities offering the biggest competition for MoNA, she adds, are GSI in Darmstadt, Germany, RIKEN in Tokyo, and the Ohio State University in Columbus, Ohio, all of which also have large undergraduate programs. Howes says MoNA’s success is due to the NSF’s willingness to support such efforts. “That’s what NSF is about,” she says.

“At NSF, the MoNA collaboration is considered a big success” (Brad Keister, NSF Program Director)

“That’s what NSF is about” (Bob Eisenstein, NSF Assistant Director in 2001)
Momentum Compression of Fragmentation Beams

Detector
Si

Target
C_2H_4

ΔE-E
Si

ε


14O, 82 MeV/u

dipole magnets

14O, 14 MeV/u, 3.2%

energy degrader

14O, 10 MeV/u, 0.8%

monoenergetic degrader

14O, 7 MeV/u, 3.2%

elastic resonance scattering: 14O + p → 15F

detector setup


Improved value for E_G.S. →

Disappearance of the Z=8 Shell

NSCL Beta Counting System (BCS)

High-sensitivity system for correlating fragment implants with subsequent $\beta$-decays on an event-by-event basis

- Suited for use with cocktail beams

1 fragment implant detector:
- $4 \times 4 \text{ cm}^2$ active area, 1 mm thick
- 40 1-mm strips in x and y

6 calorimeter detectors:
- $5 \times 5 \text{ cm}^2$ active area, 1 mm thick
- 16 strips in one dimension

BCS combined with 12 Ge-detectors from SeGA

Prisciandaro et al. NIM A 505, 140 (2003).
No N=34 Shell Gap for Ti Isotopes

Shell model with GXPXF1 effective interaction suggested that N=34 may become a magic number for Ca and Ti isotopes.

High-sensitivity experiment (0.05/s) reveals low value of $E(2^+)$ in $^{56}$Ti, inconsistent with predicted shell gap.

Liddick et al., PRL 92, 072502 (2004); PRC 70, 064303 (2004)
Beta-NMR Apparatus

Small dipole magnet equipped with an rf coil and beta telescopes for nuclear moment measurements

- 10 cm magnet gap; $B_{\text{max}} = 5000$ Gauss, cooled catcher

Mantica et al., NIM A422, 498 (1999)

$\beta$ angular distribution: $W(\theta) = 1 + AP\cos\theta$

- Isotropy after pumping and equalization of m-state population
Polarization of Rare Isotope Beams

Single-nucleon pick-up produces polarization maximum near the peak of the momentum distribution*

→ Tool for measuring nuclear moments of key neutron-deficient nuclei near $N = Z$

* For projectile fragmentation, the polarization is maximal in the wings of momentum distribution:
  Asahi et al., PLB 251, 488 (1990)

9Be($^{36}$Ar,$^{37}$K) @ 155 MeV/A

Groh et al., PRL 90, 202502 (2003)

C.K. Gelbke, 3/3/2006, p. 21
The $^{35}$K-$^{35}$S mirror pair is the heaviest $T=3/2$ system studied to date

- Measured spin expectation value, $\langle \sigma \rangle = -0.284 \pm 0.040$, agrees with $T=1/2$ systematics


Spin expectation values
The $^{57}$Cu-$^{57}$Ni mirror pair is the heaviest T=1/2 system studied to date

- The measured spin expectation value, $<\sigma> = -0.78 \pm 0.031$, is inconsistent with the assumption of an inert doubly-magic $^{56}$Ni core

Minamisono et al., Phys. Rev. Lett. in press

- Shell model, FPD6, 3p-2h excitations allowed in pf shell
- Shell model, GXP3F1, $g^\text{PF}_i = 0.9g^\text{free}_i$
  $g^\text{PF}_i(\pi) = 1.1$, $g^\text{PF}_i(\nu) = -0.1$
Perturbation of $\gamma$-ray angular distribution by $\Delta \theta$ due to interaction of magnetic moment ($g=\mu/I$) in large hyperfine field

$$\Delta \theta = g \phi \quad \phi = -\frac{\mu N}{\hbar} \int_{T_f}^{T_1} B(t) e^{-t/\tau} dt$$

Fast fragment velocities are too large for transient field measurements

Use thick Au interaction target to slow down and Coulomb excite the secondary beam and pass through magnetized Fe layer to induce transient field

The Fe layer is polarized and induces the transient field
Measurement of $g(2^+)$ Factor for $^{38,40}$S

High-Velocity Transient Field Method

Observed small g factors
$\rightarrow$ spin contributions dominate
$\rightarrow$ protons and neutrons contribute to onset of deformation

Doppler-corrected spectra

Davies et al., Phys. Rev. Lett. in press

Stop rare isotopes of ~100 MeV/A in ultra-pure He gas cell (~1 bar, 50 cm)

- High precision mass measurements since May 2005: $^{37}$Ca, $^{38}$Ca, $^{65}$Ge, $^{66}$As, $^{67}$As, $^{80}$As, $^{81m+g}$Se

High precision 9.4 T Penning trap
Precision Mass Measurements

$^{38}$Ca: $T_{1/2} = 440$ ms, $0^+ \rightarrow 0^+$ $\beta^+$-emitter
- new candidate for the test of the conserved vector current (CVC) hypothesis

$\Delta E_{\text{LEBIT}} = -22058.53(28)$ keV
$\delta m = 280$ eV, $\delta m/m = 8 \cdot 10^{-9}$
- AME 03: $\delta m = 5$ keV

$^{66}$As: $T_{1/2} = 96$ ms
- one of the two shortest-lived isotopes investigated in an ion trap up now

LEBIT: $\delta m \approx 20$ keV, $\delta m/m \approx 3 \times 10^{-7}$
- 20-fold improved masses in region critical to rp process

Beam Separation and Manipulation (DOE, NSF, MSU)

- Range compression studies
- Capture and extraction from a gas cell
  - Typical stopping fraction: ~ 0.2 – 0.5
  - Extraction efficiency decreases with implantation rate

\[
\frac{^{38}\text{Ca}/^{37}\text{K}}{93 \text{ MeV/u}} \Delta P/P = 0.5\%
\]

Planned R&D:
- Develop improved gas-stopping scheme for rare isotopes from projectile fragmentation: gas-filled cyclotron magnet for high (>\(10^8\)/s) beam intensities and fast (<10 ms) extraction
- Develop high efficiency charge breeder
- Investigate beam-cooling for improved and cost-efficient high-resolution mass separation

Rapid Neutron Capture Process (r-process)

Synthesis of about half of all nuclei heavier than Fe

- Occurs at temperatures greater than $10^9$ K and free neutron densities greater than $10^{20}$ cm$^{-3}$
- Astrophysical site not yet known; may be associated with type II supernovae, merging neutron stars, or other yet to be determined sites

X-ray image of Crab Nebula (Chandra)

Optical image of Crab Nebula (Mt. Palomar)
Doubly Magic $^{78}$Ni Accelerates Heavy Element Synthesis

Particle identification

- different types of nuclei in the beam

$^{78}$Ni

Model calculation for heavy element synthesis (r-process in supernova explosion)

- Observed Solar Abundances
- Model Calculation: Half-Lives from Moeller, et al. 97
- Same but with present $^{78}$Ni Result

Mass (A)

Abundance (A.U.)

Measured half-life of $^{78}$Ni with 11 events
This is the most neutron rich of the 10 possible classical doubly-magic nuclei in nature.

Result: $110^{+100}_{-60}$ ms

P.T. Hosmer et al.
PRL 94, 112501 (2005)

$\Rightarrow$ Heavy element synthesis in the r-process proceeds faster than previously assumed

$\Rightarrow$ One step towards a better understanding of the origin of the elements in the cosmos
Spin-Isospin Response of Nuclei

Weak transition rates are important for stellar evolution

Measure of Gamow-Teller strengths via charge exchange reactions

- NSCL: \((t,^{3}\text{He})\) at \(E/A = 120\ \text{MeV}\): \(0.4-1 \times 10^7/\text{s}\) \(^3\text{H}\) via fragmentation of \(^{16}\text{O}\)
  - Better resolution than \((n,p)\)
- Accompanying \((^{3}\text{He},t)\) program at RCNP, Osaka, Japan

Proof of principle: measured GT strength constrains theoretical uncertainties of e-capture rates in pre-supernovae


Recently achieved resolution

C.K. Gelbke, 3/3/2006, p. 31
The EOS for symmetric matter has been constrained by nucleus-nucleus collision experiment, but little is known about symmetry energy term.

Neutron star radii, neutron skins of nuclei, and isospin diffusion processes are sensitive to the asymmetry term of the EOS.

At $\rho = 2\rho_0$, more than 70% of the pressure in neutron star crusts comes from the asymmetry energy.

$\rightarrow$ Asymmetric nucleus-nucleus collisions offer the only option to explore the asymmetry term of the EOS at $\rho \neq \rho_0$.

Possible approach: Investigate isospin diffusion in nucleus-nucleus collisions

$$R_i = \frac{2O_{PT} - O_{PP} - O_{TT}}{O_{PP} - O_{TT}}$$

$O$ = isospin observable, representing the ratio of protons and neutrons of the emitted matter, e.g.: $Y(\text{Li})/Y(\text{Be})$
Approximate representation of the various asymmetry terms used in BUU calculations:

\[ E_{\text{sym}}(\rho) \sim 32(\rho/\rho_0)^\gamma \left[ (\rho_n - \rho_p)/(\rho_n + \rho_p) \right]^2 \]

\( \gamma \sim 0.5, 1.0, 1.6 \) (for cases A, B, C)

Work in Progress: M.B. Tsang
X-Ray Burst (Accreting Neutron Star)

2002 Physics Nobel Prizes: x-ray Astronomy and solar neutrinos

Normal bursts:
Thermonuclear explosions on the surface of accreting neutron star binaries: rp-process

Superbursts:
Re-ignition of the ashes in the neutron star’s crust, carbon-burning and photodissociation of heavier nuclei
p-capture on $^{32}\text{Cl}$ producing $^{33}\text{Ar}$ is an important step in the rp-process powering thermonuclear explosions on surfaces of accreting neutron stars (X-ray bursts).

$\gamma$-rays from predicted 3.97 MeV state establish level energy of 3.819(4) MeV

2 orders of magnitude improvement in uncertainty of level energy reduced uncertainty of calculated $^{32}\text{Cl}(p, \gamma)^{33}\text{Ar}$ stellar reaction rate by 3 orders of magnitude

Clement et al. PRL 92, 172502 (2004)
MSU is one of a few U.S. institutions that trains accelerator physics PhDs.

Expertise in beam dynamics, beam transport systems, fragment separators, ion traps, ECR ion source technology, cyclotron technology, linac technology, including pertinent applications of superconductivity.

Well positioned to make contributions to new projects of national importance.

Developed SRF infrastructure and expertise (funded by State of MI, MSU, DOE). All RIA driver linac SRF cavities prototyped – exceed specifications. Ongoing R&D: SRF cavities for FNAL; recirculating e-linac and high-field $\beta=1$ cavities (ILC).

Important for development of future MSU-based nuclear science program.

Adaptive feed-forward cancellation of SRF-cavity microphonics developed by MSU reduces cavity detuning and RIA power cost by over $600,000/year.
Linac conceptual design complete, including end-to-end simulations* with errors
- 6 cavity types for driver & re-accelerator (→ low number of spares)
- All cavities prototyped – exceed design specs

* MSU, LANL, LBNL, ANL collaboration

Cost-effective Design of Cryostats (DOE, State of MI, MSU)

- Built & tested prototype for elliptical cavities (805 MHz), incl. feed-forward vibration control
  - Constructing prototype low-beta cryostat: $\frac{\lambda}{4} \& \frac{\lambda}{2}$ resonators + 9 T superconducting solenoid, 0.6 T quadrupole (tests in mid 2006)
  - Ready for linac construction