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Abstract. GEANIE at LANSCE/WNR combines the precision energy resolution of germanium detectors with the advantages of a "white" source providing neutrons with energies $1 < \mathrm{E}_n(\mathrm{MeV}) < 250$ to address a variety of topics in nuclear physics. We present the analysis of two data sets, n+^{235}U and n+^{92}Mo, acquired at GEANIE during the 1998 beam cycle. These data showcase the breadth of subjects under study at this facility, including the spectroscopy of stable and near-stable nuclei, reaction dynamics, fission studies, and the relative population of isomer and ground states in neutron-induced reactions.

INTRODUCTION

The GErmanium Array for Neutron-Induced Excitations (GEANIE) consists of 11 Compton-suppressed planar detectors, 9 Compton-suppressed and 6 unsuppressed coaxial detectors situated at a distance of $\approx$ 14 cm from the scattering sample at the spectrometer focal point. The planars are grouped at mostly forward and backward angles, while the coaxials are located about 90°. The efficiency of the array has been calibrated through a series of source measurements, supplemented by detailed modeling [1] by the transport code MCNP [2].

A white neutron source is produced at the LANSCE/WNR facility by spallation from an 800 MeV proton beam incident on a natural tungsten target. The proton beam is bunched into 625 μs trains of micro-pulses 1.8 μs apart. The macropulses are typically generated at a frequency of 100 Hz, giving a 6% duty cycle. The neutrons travel through air along shielded neutron flight paths of different lengths, and at various angles, to the appropriate experimental area. The GEANIE spectrometer is located at the end of the flight path 60 degrees to the right (60R) of the proton beam direction, 20.34 m downstream from the spallation target. A fission chamber [3], placed in the beam $\approx$ 2 m upstream from the GEANIE spectrometer, serves as a neutron flux monitor. Neutron energies are determined

TABLE 1. Experiments carried out at GEANIE since its inception.

Year	Sample	Physics	Analyzed by
96	^{196}Pt	reaction dynamics	L.A. Bernstein
97	^{208}Pb	reaction dynamics	R.O. Nelson
97	^{27}Al	spectroscopy/chaos	W.S. Wilburn
97	^{170}Er	$\gamma\gamma$ vibrations	W. Younes
97	^{181}Ta	spectroscopy/astrophysics	S.W. Yates
97	^{175}Lu	radiochemistry	D.E. Archer/E.A. Henry
97	^{252}Cf	SF yields	T. Ethvignot
98	^{175}Lu	radiochemistry	P.E. Garrett/E.A. Henry
98	^{196}Pt	spectroscopy/reactions	E. Tavukcu
98	^{92}Mo	spectroscopy/reactions	P.E. Garrett
98	^{112}Sn	spectroscopy/reactions	C.A. McGrath
97-99	^{235}U	(n,2n)/(n,f) cross section	W. Younes
97-99	^{238}U	(n,2n)/(n,f) cross section	G.D. Johns/R.O. Nelson
97-99	^{239}Pu	(n,2n) cross section	L.A. Bernstein
98-99	^{238}U	(n,f) yields	T. Ethvignot
99	^{209}Bi	reaction dynamics	L.A. Bernstein
99	^{56}Fe	(n,n$'$) cross section	D.P. McNabb

by the time-of-flight technique, using the gamma flash from the spallation reaction as a reference time.

The data acquisition system and software in use at GEANIE are extensions of the Michigan State University 4π-array setup [4]. Additional software was developed to automate the data acquisition and provide monitoring and alarms, all of which are necessary due to long run times. Routines were also developed to reduce the raw GEANIE data while automatically maintaining energy and time alignments of the detectors. In addition, the complex gamma-ray spectra that often result from neutron-induced reactions on actinide targets led to the development of analysis software designed to extract peaks and automatically produce excitation functions for the hundreds of lines typically observed at each neutron energy. A detailed description of GEANIE and the white neutron source at LANSCE/WNR can be found in reference [5].

Experiments carried out at GEANIE since 1996 have addressed a variety of nuclear physics interests. Table 1 lists some of the experiments carried out to date. This paper will focus on the analysis of two of these data sets acquired during the 98 beam cycle with enriched samples of ^{235}U and ^{92}Mo. Results from these runs will be used to highlight GEANIE's strengths and limitations and its expected contributions to the field in the future.

THE N+^{235}U EXPERIMENT

The n + ^{235}U experiment was carried out over two separate runs in October and December 1998 respectively. During each run, thin (12-mil) and thick (24-mil) samples of 93.2%-enriched ^{235}U were used for a total of $\approx$ 8 days of beam time for each. The analysis presented here uses the thin-target planar-detector data for singles and the combination of planar and coaxial data for coincidences. In the E_n = 1-20 MeV range, 1.02×10^8 single and higher-fold full-energy-peak counts were acquired. These raw counts in the measured spectrum break down into 45.4% from x rays (mostly from target activity), 43.1% from γ rays due to target activity, and 3.7% from an assortment of common contaminants. The remaining 7.8% of photo-peak counts are likely due to gamma rays from neutron-induced reactions on the ^{235}U sample (e.g. (n,fγ), (n,xnγ), etc$\cdots$).

Fission Studies

Fission-fragment gamma-ray lines constitute about 3.6% of photo-peak counts in the thin-target planar-detector data. In all, 103 fission gamma rays from 33 nuclei were identified based on coincidence relationships. The partial level schemes built from $\gamma - \gamma$ coincidences for each fragment consist primarily of known γ rays in the yrast cascade, with the highest spin observed in the ^{138}Xe fragment at $10\hbar$. A subset of 66 gamma rays could also be extracted from the singles analysis and excitation functions were constructed for these. A sample of these excitation functions is shown in figure 1. An overall scale was deduced for each excitation function by normalizing to $\sigma_{(n,f)}(E_n)$, the measured total (n,f) cross section, in the E_n = 5-20 MeV range, in order to compare shapes. The $\sigma_{(n,f)}(E_n)$ curve is also plotted in figure 1 for comparison. While many of the excitation functions follow the shape of the total (n,f) cross section, there are some noteworthy exceptions. In particular, gamma rays from ^{99}Y and ^{144}Ba show a systematic deviation above $\approx$ 12 MeV, where third-chance fission occurs. Because the multiple-chance fission cross-sections should depend strongly on the ratio of level densities in the particle-emission versus fission channels, the observed depletion of the third-chance fission cross section in particular fragments might be due to nuclear structure effects [6]. Work is currently in progress to account for γ-ray contaminants and beam wrap-around effects.

The (n,2n) cross section

The ^{235}U(n,2n) cross section has previously been measured up to $E_n \approx$ 13 MeV by direct counting of emitted neutrons [7]. A careful subtraction of fission-induced neutron events was necessary, and the technique can lead to sizeable uncertainties because the (n,2n) cross section is obtained as the difference of two large numbers. The problem is even worse for the ^{239}Pu(n,2n) reaction where the (n,f) cross section is larger, and the neutron multiplicity from fission ($\overline{\nu}$) is greater.

Actinide (n,2n) cross-section measurements at GEANIE have been carried out relying on precision γ-ray spectroscopy. In this approach, the fission and activity backgrounds may be separated from the (n,2n) channel through the identification of characteristic gamma rays. Partial cross sections for the lowest observed members of the yrast band following ^{235}U(n,2nγ) reaction are plotted as a function of

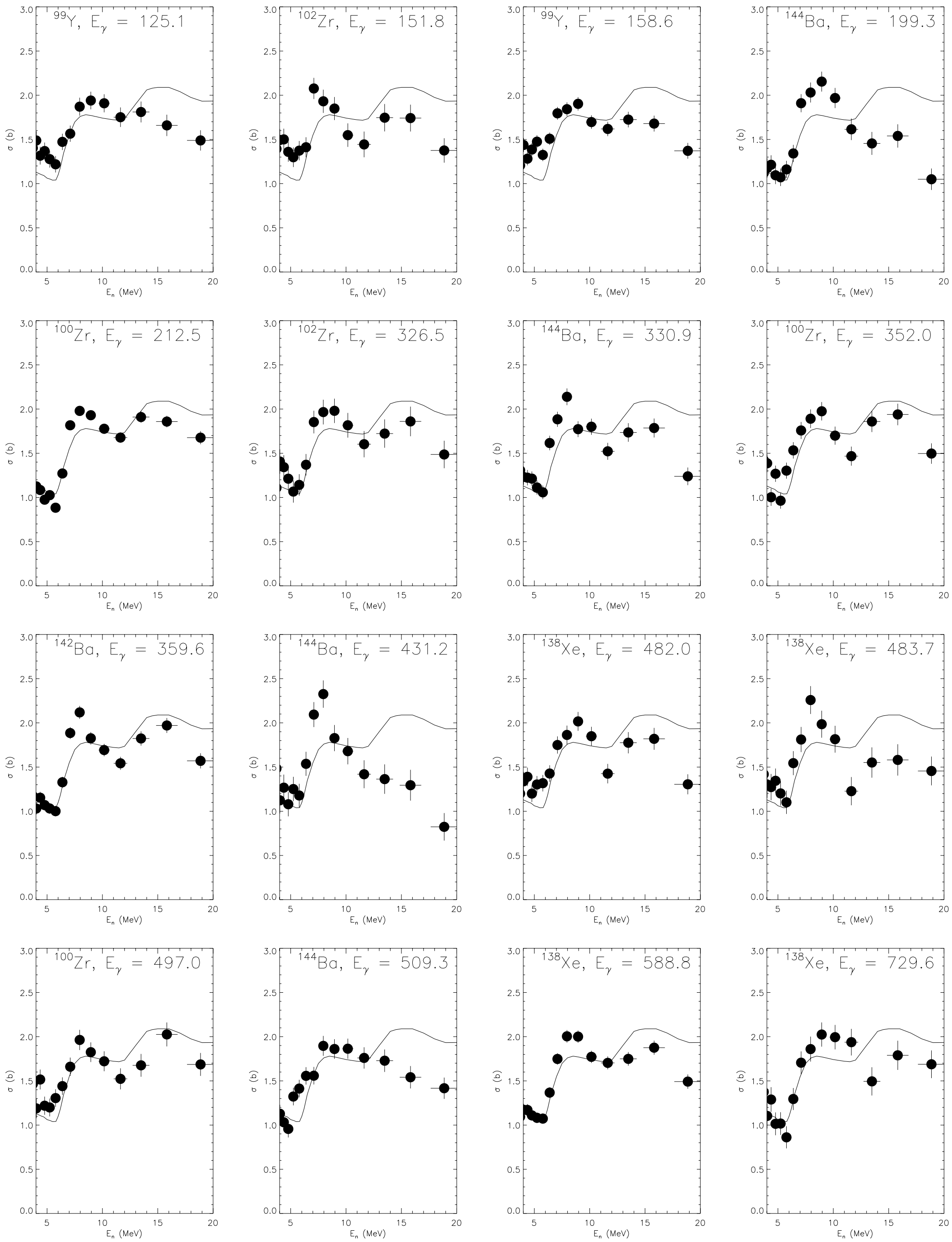

FIGURE 1. Excitation functions for a sample of the observed (n,f) gamma ray lines. The data are normalized to the measured total (n,f) cross section in the 5-20 MeV range. The total (n,f) cross section is also plotted as a solid line for comparison.

incident neutron energy in figure 2a)-d) and compared to GNASH [8] calculations. The agreement between the GEANIE data and GNASH predictions is quite good in general, but for the 4→2, 6→4 and 8→6 transitions, the GEANIE data fall more rapidly above peak cross section than predicted by GNASH. The remaining panels e)-f) in figure 2 show the (n,2n) cross section deduced from individual excitation function by multiplying each data point by the ratio of partial-to-channel cross-section $\sigma_{(n,2n)}(E_n)/\sigma_{(n,2n\gamma)}(E_n)$ predicted by GNASH. The same technique is currently being applied to extract the ^{239}Pu(n,2n) cross section from GEANIE data. There is wide disagreement between both previous measurements and model predictions for ^{239}Pu(n,2n).

Isomer Studies

A recent comparison [9] of experimental data and model predictions has shown that the population of isomeric states depends rather sensitively on the discrete levels and spin distribution of the level density in the product nucleus. We have tested GNASH predictions for the population of the isomeric ($\tau \approx 38$ min) level at $E_x = 76.8$ eV in ^{235}U.

Two states, at 393 and 638 keV, which feed the isomer, were populated and observed at GEANIE via ^{235}U(n,n$'\gamma$), and the excitation functions for the transitions from those states to the isomer are displayed in figure 3a) and b) and compared to GNASH predictions. The statistics for the decays from the 393-keV level are too low for a quantitative comparison with GNASH, but data and model are in qualitative agreement. Conversely, the decays from the 638-keV state have sufficient statistics, but the branching ratio between the transitions to the ground and isomer states is not well known and the two gamma rays, which differ by only 77 eV, cannot be resolved by the GEANIE detectors (FWHM ≈ 1.46 keV for the planars at this energy). Nevertheless, it seems clear from figure 3c) that GNASH underestimates the population of the 638 keV state while correctly predicting (within large experimental errors) the population of the 393 keV level.

THE N+^{92}MO EXPERIMENT

The transitional nuclei near A ≈ 90 have been studied with some interest because they often display collective behavior while still being amenable to spherical shell model approaches. The nucleus ^{92}Mo, for example, has been populated in a variety of reactions from inelastic to heavy-ion and as a result, much has been learned about its structure. A recent eight-day run at GEANIE has contributed a significant amount of new information to both the structure of ^{92}Mo and the dynamics of neutron-induced reactions on this nucleus [10].

The spectroscopic analysis of these data was carried out using both $\gamma-\gamma$ coincidences and excitation functions from γ singles. The configuration of GEANIE detectors precludes the measurement of angular distributions for most gamma rays,

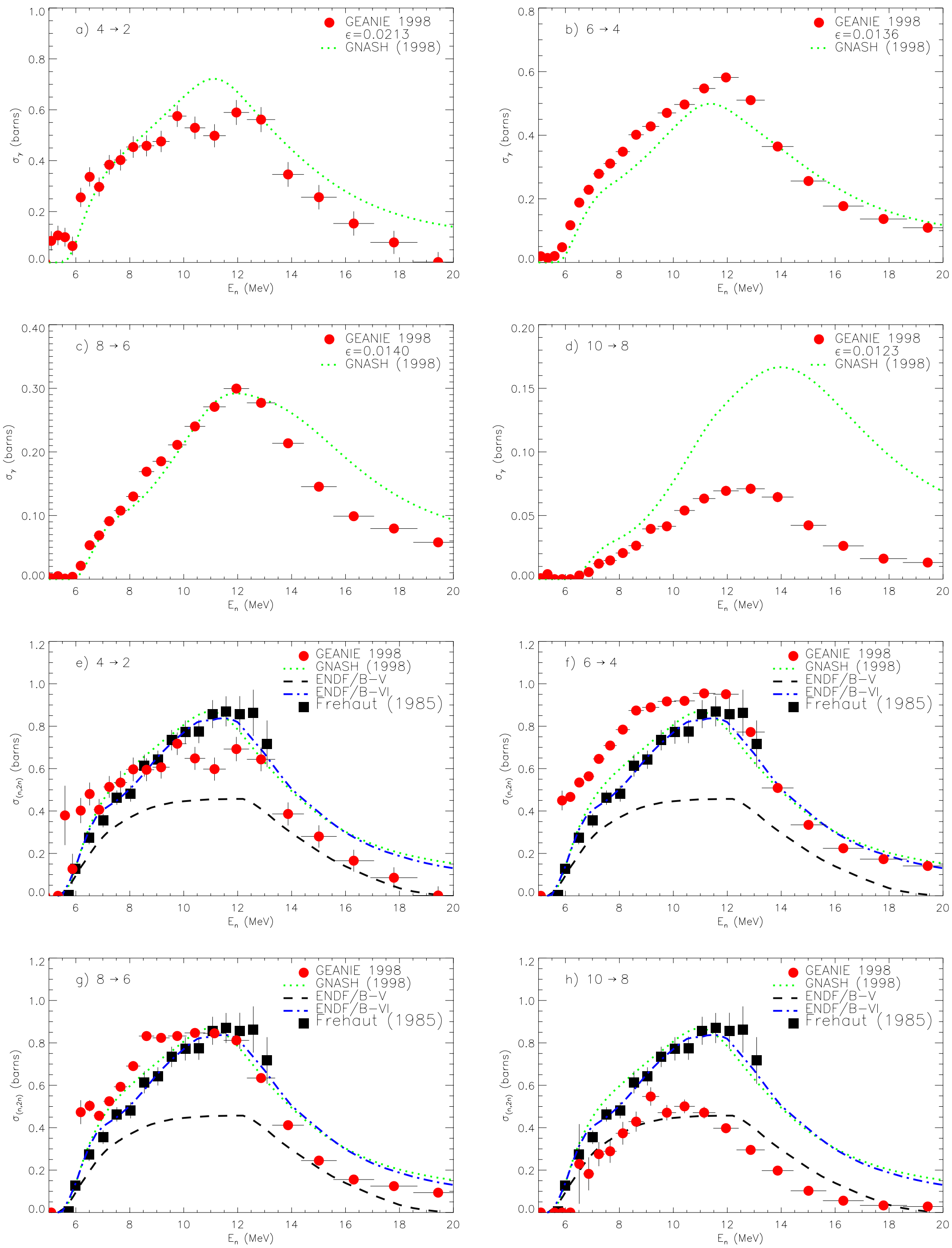

FIGURE 2. a)-d): Measured ^{235}U(n,2nγ) excitation functions for members of the yrast band in ^{234}U compared to GNASH predictions. The array efficiency ϵ is indicated for each line. Only statistical uncertainties are included in the error bars. e)-h): Deduced ^{235}U(n,2n) cross section compared to GNASH predictions and other evaluations.

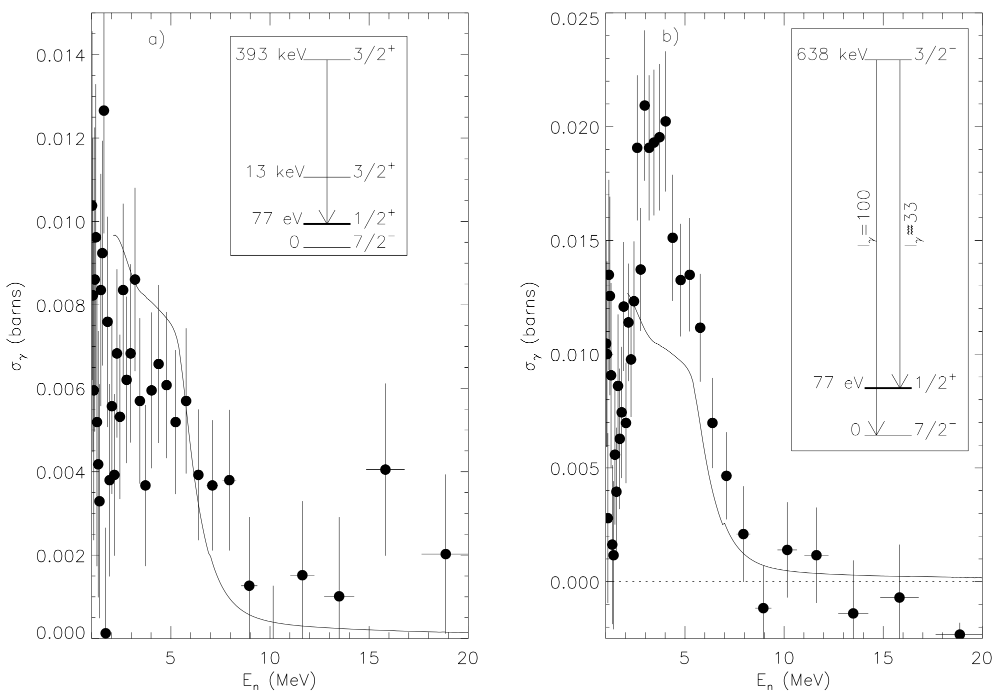

FIGURE 3. Excitation functions for gamma rays populating the τ = 38 min isomer in ^{235}U from states at a) E_x = 393 keV and b) E_x = 638 keV compared to GNASH predictions (solid line). Since the transitions to the ground and isomer states from the 638 keV level cannot be resolved, both the data and GNASH calculations are for the sum of the two contributions.

however, some spin assignments can be made based on comparisons between measured and calculated excitation functions. An efficiency calibration was carried out using well-known gamma-ray lines from β and electron-capture (EC) decays in the beam-off spectrum, and an internal energy calibration was performed using well-known lines in the beam-on spectrum. In all 50 new gamma rays and 20 new levels have been placed using the GEANIE ^{92}Mo(n,n$'\gamma$) data.

In addition to (n,n$'$), a variety of reactions on ^{92}Mo have also been observed up to E_n = 250 MeV including (n,xn) with x $\leq$ 5 and (n,xnyp) with x $\leq$ 7 and y $\leq$ 4. Other nuclei, such as the $^{84-88}$Sr isotopes were also populated by subsequent β and EC decays. The light-particle emission channels in this experiment are especially interesting because the Feschbach-Kerman-Koonin (FKK) model, the only fully quantum-mechanical description of the pre-equilibrium reaction process to date, is only formulated for single-nucleon emission. Extensions of the FKK theory to other types of ejecta will require data several MeV above the reaction threshold [11].

CONCLUSION

Since first beam in August 1996, the GEANIE spectrometer has been used for a variety of experiments lasting from a few days to several weeks. The data have been analyzed for both γ singles and $\gamma\gamma$ coincidences, and for both spectroscopy and reaction dynamics needs. As a result, a picture of the strengths and limitations of GEANIE at LANSCE/WNR has emerged. Perhaps the most significant constraint on GEANIE experiments is imposed by the 6 % duty cycle of the accelerator. The resulting neutron flux at GEANIE is $\sim 6\times10^5$ n$\cdot$MeV^{-1}s^{-1} at $E_n \approx 5$ MeV (based on fission-chamber data for the 1998 thin-target ^{235}U runs), and drops by a factor of ≈ 0.86 for each additional MeV of energy up to 20 MeV. Beyond 20 MeV, the flux falls only by a factor of ≈ 0.99 for each additional MeV, until the end point. The problem is compounded by the intrinsic efficiency of the array (≈ 2 % for planars at 100 keV and ≈ 2 % for coaxes at 1 MeV) and, for the lowest-energy γ rays, by attenuation in the sample material. However, the combination of the white neutron source and time-of-flight technique yields the equivalent of several experiments performed simultaneously. This ensures economy of time as well as consistency between measurements at different neutron energies. In addition, a wide range of nuclei can be studied, thanks to the use of both planar and coaxial detectors to cover γ-ray energies from tens of keV to several MeV. Safety protocols are already in place for running experiments with actinide targets. Recently, accelerator upgrades have doubled the proton current and increased the duty cycle to 8 %, and upgrades in the GEANIE acquisition system are planned to reduce deadtime and take better advantage of the available beam time. Because of these strengths and limitations, the most fruitful applications of GEANIE to date have been for reaction dynamics studies, actinide cross section measurements, and standard spectroscopy in the (n,n$'$) channel. In the future, GEANIE could be used to improve our understanding of reaction processes up to several hundred MeV, to study isomers in the μs-ms range and to measure cross sections for a multitude of data needs.

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