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Recent results from GEANIE at LANSCE

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Abstract. GEANIE, the Germanium Array for Neutron Induced Excitations, is an array of 26 high-resolution γ-ray and X-ray detectors at the WNR broad spectrum neutron source at LANSCE. The neutron source is driven by the pulsed 800 MeV proton beam of the LANSCE accelerator, enabling use of the time of flight technique to determine incident neutron energies. The time structure of the pulsed beam allows lifetime measurements during ~8 milliseconds between beam bursts. Reactions induced by neutrons in the energy range from 100 keV to over 200 MeV are measured. The γ-ray energy range covered is from 15 keV to 4 MeV. GEANIE has been in operation for over 10 years. Here we present an overview of recent results from GEANIE including neutron-induced γ-ray production cross sections, microsecond and millisecond isomer lifetimes, identification and quantification of possible neutron-induced γ-ray backgrounds in underground double beta decay measurements, and preequilibrium reaction studies. The observation of many new levels in ^{197}Au, population of isomeric states in ^{190}Ir, ^{197}Au, and ^{202}Tl, and cross sections for γ rays from ^{48}Ti are presented. Measurement of neutron induced γ rays from Te, Pb, Cu and ^{76}Ge that may contribute to backgrounds of underground neutrino-less double-beta decay experiments due to cosmic-ray induced neutrons are in progress.

1 Introduction

The Germanium Array for Neutron Induced Excitations or GEANIE array of high-resolution γ-ray detectors has been in operation at the Los Alamos Neutron Science Center (LANSCE) for over 10 years. Using neutrons in the energy range from 100 keV to over 200 MeV, GEANIE has provided information on partial γ-ray cross sections, nuclear structure and lifetimes, and fission. Following a brief description of the neutron source and the spectrometer, we describe results of some recent measurements that include half-life measurements in the μs to 10's of ms time range, cross section measurements, new levels and γ rays for ^{197}Au, and measurements to establish backgrounds for neutrino-less double beta decay experiments.

2 Experiment

A brief description of the WNR spallation neutron source and the GEANIE array is given below. Further information is available in refs. [1–3].

2.1 The WNR facility at LANSCE

The pulsed 800 MeV proton beam from the LANSCE linear accelerator is used to produce a broad spectrum of neutrons by spallation on a small tungsten cylinder. The proton beam has a structure consisting of sub-nanosecond wide micropulses grouped into macropulses that are typically 625 to 775 microseconds long. The macropulse repetition rate is typically in the range from 40 to 100 Hz. The useful range for spacing of the micropulses usually is from 1.8 μs to 7.2 μs, depending on the flight path length and lowest incident neutron energy of interest. Macropulses are spaced 8.3 to 16.6 ms apart according to the accelerator repetition rate of 60 or 120 Hz. Data are acquired during the beam-off periods for measurements of lifetimes and decay γ rays for states with longer lifetimes. Proton beam currents on the spallation target are generally in the range from 1.5 to 5 μA. Neutrons are collimated with several approximately 2-meter long steel collimators. Portions of the flight path are under vacuum while the sample of interest and the permanent magnets to remove charged particles from the beam are in air.

2.2 The GEANIE array

GEANIE consists of 26 high-resolution high-purity germanium (HPGe) detectors. Up to 11 of the detectors are planar in geometry with good efficiency and resolution in the x-ray region, and up to 20 coaxial, n-type HPGe detectors provide useful efficiency for γ rays to 4 MeV and higher. BGO escape-suppression shields surround 20 of the Ge detectors. GEANIE was constructed in 1996 using the detectors, mounting frame and some electronics of the former HERA spectrometer [4] from Lawrence Berkeley National Laboratory as a collaborative effort between Lawrence Livermore National Laboratory and Los Alamos National Laboratory.

Incident neutron energies are determined by the time-of-flight technique. The sample is located 20.34 m from the center of the neutron production target. This flight path length gives "frame overlap" of low-energy neutrons from a previous micropulse arriving at the same time as higher energy neutrons and γ rays from the next proton micropulse

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at about 650 keV for typical 1.8 μs proton micropulse spacings. For 3.6 μs spacing the "frame overlap" occurs at an incident neutron energy of about 150 keV.

Two parameter, γ-ray pulse height and neutron time-of-flight, data are stored for both beam-on and beam-off data. Fast time spectra are stored with 0.5 ns resolution, while beam off data are stored with times from a precision 100 ns clock based on a Stanford Research Systems Model SC10 (J grade) stabilized oscillator. Recently, fast time data have also been stored for fast coincidence measurements during the beam-off periods to allow identification of prompt decay cascades following the decay of long-lived states.

Gamma-ray spectra are stored in 16 000 channels. Typical γ-ray energy ranges are $0.02 < E_\gamma < 1.0$ MeV for the planar detectors and $0.07 < E_\gamma < 4.0$ MeV for the coaxial detectors. For γ-ray production from light nuclei the coaxial detectors have been used successfully in the energy range up to 9 MeV.

The neutron fluence is monitored using a fission ionization chamber containing ^{235}U and ^{238}U deposits [5].

3 Results

In this section we present a sample of results for nuclear structure, reaction cross sections, and isomer lifetimes obtained from GEANIE measurements over the last few years.

3.1 Half-life measurements

The first use of the GEANIE beam off data for half-life measurements was done by P. Garrett for ^{175}Lu(n,n$'\gamma$) data [6]. In a study of the ^{191}Ir(n,2n) reaction we observed a 36.2 keV γ ray with a half life of 1.40 (6) μs. This was the first determination of the half life for the 3rd excited state in ^{190}Ir that was identified in ref. [7]. In a study of nuclear levels in Tl isotopes we measured the half-life of the 7^+ 950 keV isomer in ^{202}Tl produced in the ^{203}Tl(n,2n) reaction [8]. Figure 1 shows the measured and evaluated half-lives as a function of year of publication for this level. The most recent two measurements required no change in the evaluated half-life, however the GEANIE result of 591 (3) μs is 4% greater than the evaluated value and with uncertainties about half as large. Results of a similar study on ^{204}Tl from the ^{205}Tl(n,2n) reaction are now being prepared for publication.

3.2 Cross section measurements

The cross sections for neutron reactions on titanium are of interest because of its role as a structural material. However, the available data were rather sparse and did not cover the full 1 to 20 MeV neutron energy range of primary interest. In figure 2 are shown the previous data for inelastic production of the 2^+ to $0^+ \gamma$ ray from ^{48}Ti, and new GEANIE data [9]. The Japanese Evaluated Data Library (JENDL) values for the total inelastic scattering cross section are also shown. The 2^+ to 0^+ cross section represents a lower limit for the total inelastic cross section because the majority of the inelastic decay proceeds through this transition.

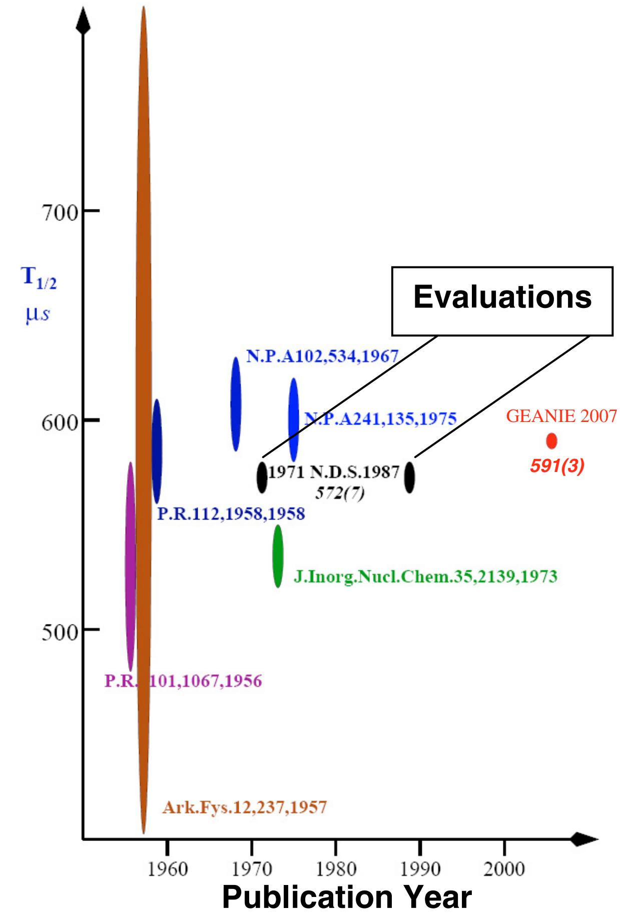

Fig. 1. Half-life measurements for the 7^+ isomer in ^{202}Tl plotted versus publication year.

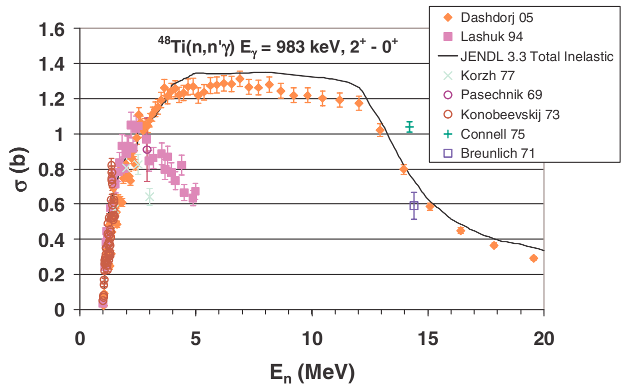

Fig. 2. Cross section measurements of the γ-ray decay of the first excited state of ^{48}Ti are compared with the total inelastic cross sections from JENDL and with previous data.

Partial γ-ray cross sections were measured for ^{197}Au(n,xγ) reactions. There is an $11/2^-$ isomeric state in ^{197}Au that is consistent with an h11/2 proton hole plus even-mass core configuration [10]. We observed four γ rays that strongly feed this isomer as shown in figure 3. By summing these four γ-rays we obtain an estimate of the total isomer population. Figure 4 shows the cross section for population of the isomer in ^{197}Au

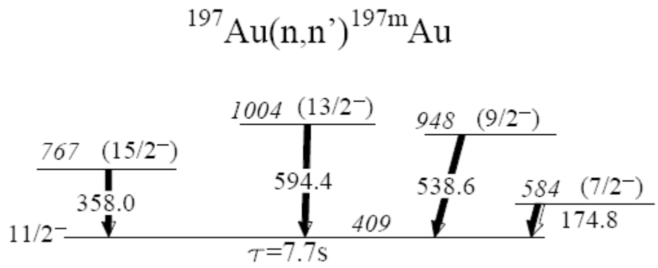

Fig. 3. Level scheme showing the four strong transitions that are observed to feed the 409-keV, $11/2^-$ isomer in ^{197}Au. The white portion of the arrows indicates the fraction of the transition that proceeds by internal conversion.

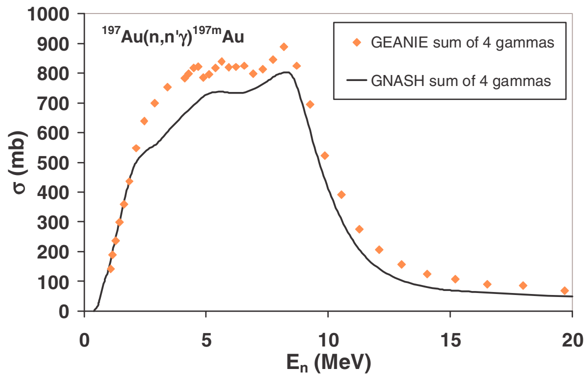

Fig. 4. The cross section for population of the isomer in inelastic scattering of neutrons on ^{197}Au as determined from the strong feeding transitions. The solid line is a GNASH model calculation.

from the four strong transitions that feed it. The GNASH model [11] calculation shown is the result of recent work on improving the description of angular momentum in pre-equilibrium reactions [12]. The calculation agrees reasonably well with the data.

3.3 Nuclear reaction studies

Recent developments in nuclear reaction theory include the incorporation of angular momentum based on a quantum mechanical description of the preequilibrium reaction mechanism into model codes such as GNASH [12]. Examples of such calculations for nuclear reactions in ^{48}Ti are given in ref. [13] and for ^{150}Sm in ref. [14]. GEANIE data can provide tests of such models over a wide range of energies and for a number of different reaction channels.

Gamma-ray cross sections measured as a function of incident neutron energy for states of different spins can provide insight into the angular momentum dependence of the reactions.

An indication of the effects of angular momentum in excited nuclei that is similar to traditional isomer ratios is obtained by taking the ratio of the observed γ-ray decay to an isomer and to the ground state. In contrast to isomer ratios that are usually measured by activation techniques and thus limited to radioactive product nuclides, the γ-ray ratio gives similar information for stable product nuclides as well.

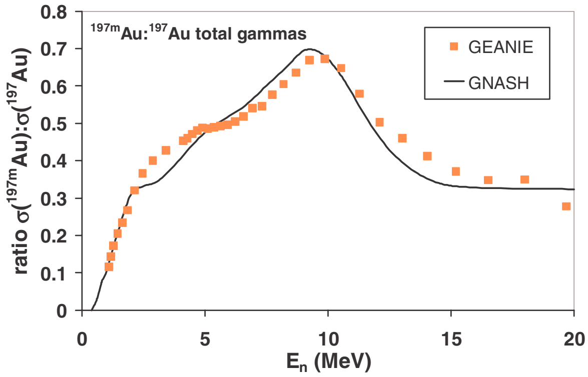

Fig. 5. The ratio of independent partial γ-ray cross sections feeding the $11/2^-$ isomer to those feeding the $3/2^+$ ground state of ^{197}Au are shown. This is somewhat similar to an isomer ratio and indicates changes in the angular momentum of the excited nucleus. The relative population of the high-spin isomer peaks at 10 MeV, about 2 MeV after the opening of the (n,2n) channel. This ratio is expected to be higher than a traditional isomer ratio because more of the transitions to the ground state are missed in the γ-ray cross section sum than to the isomer. Also the number of missed transitions increases with increasing incident neutron energy.

Figure 5 shows the ratio of γ rays feeding the $11/2^-$ isomer divided by the sum of observed independent γ rays feeding the ground state.

The corresponding ratio of sums from a GNASH calculation reproduces the observed ratio well. The calculation of the isomer population in particular benefits from the quantum mechanical treatment of the preequilibrium spin distribution.

3.4 Nuclear structure

GEANIE measurements of inelastic scattering on ^{197}Au have greatly enriched our knowledge of the levels and γ rays. Thirty-two levels and 52 γ rays have been added to the level scheme based on GEANIE data [15].

In addition, such data are complemented by heavy-ion reaction data that populate higher spin states, but for which assignment of a γ-ray decay sequence to a particular nucleus may be difficult. An example where a new assignment could be made is given by ref. [16] where C. Wheldon et al. were able to extend the level scheme for ^{197}Au to include higher spin states and a new 150 ns isomer based on our published data.

3.5 Neutrino-less double beta decay backgrounds

Recent advances in understanding the nature of neutrinos has led to proposals to establish their masses and particle nature (whether they are Majorana or Dirac in nature, that is whether the neutrino is its own antiparticle or not) and has led to a number of collaborations undertaking efforts to search for and study the neutrino-less double beta decay ($0\nu\beta\beta$) process. The $0\nu\beta\beta$ process can only occur if neutrinos are Majorana particles, and if it does occur, albeit with a very low probability and hence a long lifetime of $\sim 10^{25}$ years, a peak is expected at the beta decay endpoint. To observe such a peak requires a very sensitive detector and a very low background environment. Thus, these experiments usually are conducted in deep underground laboratories and use low-activation materials for detectors and shielding.

A background contribution that is of concern, in part because it is not well understood is due to the production of γ rays by the interaction of energetic neutrons produced by cosmic rays [17]. GEANIE at LANSCE provides perhaps the best place to establish what backgrounds occur in the $0\nu\beta\beta$ detectors due to high-energy neutrons.

Both the Majorana collaboration [18] and the CUORE collaboration [19] are now studying γ-ray production with GEANIE to better understand high-energy neutron produced backgrounds in ^{nat}Te and ^{76}Ge (detector materials) as well as in Cu and Pb (shielding materials). The presence of a γ ray line from neutron-induced reactions in the detectors or shielding, with an energy equal to the beta-decay endpoint energy can severely limit the ultimate sensitivity of these experiments. Thus knowledge of the backgrounds is essential for interpreting results from these experiments.

Data have been obtained for ^{130}Te, ^{nat}Te, and ^{nat}Pb, with data acquisition on Cu and ^{76}Ge planned for the summer of 2007.

4 Summary

An overview of some of the results from GEANIE was given including lifetime measurements for levels in ^{190}Ir and ^{202}Tl, cross section measurements for ^{48}Ti and ^{197}Au, new nuclear structure information for ^{197}Au, and measurements to better understand the cosmic-ray-neutron-induced backgrounds encountered in neutrino-less double beta decay experiments using Cu, Pb, Te, and ^{76}Ge. Measurements of neutron-induced reaction cross sections on Xe and Kr gas samples are being started in collaboration with staff from the CEA, Bruyères-le-Châtel, France, with initial data on ^{136}Xe already acquired. These new measurements are aimed at improving the cross section and structure information on fission product nuclides.

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