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L. A. Bernstein, D. E. Archer, J. A. Becker, D. Drake, P. E. Garrett,
G. D. Johns, R. O. Nelson, W. S. Wilburn, S. W. Yates, W. Younes

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Probing the ^{196}Pt(n,xnγ) reactions using GEANIE at LANSCE/WNR

L.A. BERNSTEIN[1], D.E. ARCHER[1], J.A. BECKER[1], D. DRAKE[2], P.E. GARRETT[3], G.D. JOHNS[2], R.O. NELSON[2], W.S. WILBURN, S.W. YATES[3], W. YOUNES[1]

[1] LLNL, Livermore, USA, [2] LANL, Los Alamos, USA, [3] University of Kentucky, USA

Accelerators coupled to large multi-detector spectrometers have created an explosion of nuclear data on intermediate and high-spin states near the yrast line. Heavy- and light-ion beam induced reactions were used to populate these states and high-fold γ-ray spectroscopy employed to build the level schemes. Although this information has lead to the discovery of a wealth of new phenomena including superdeformation and other exotic structures, it does not provide information regarding off-yrast states, which are extremely sensitive tests of nuclear structure models. Smaller arrays of γ-ray detectors have been used to probe off-yrast low-spin states in stable nuclei following neutron-capture reactions. In 1994 Gill and coworkers [1] pioneered a new approach by assembling a 20 detector spectrometer at the Brookhaven National Laboratory research reactor and studied the ^{168}Er(n, γ) reaction. Although ^{168}Er is one of the most well-studied nuclei, this experiment discovered over 200 new γ-γ coincidences and showcased the new capabilities presented by the combination of a low-energy neutron beam with a high-fold γ-ray spectrometer. However, these techniques can only probe states with the lowest spin (typically $J < 6\ \hbar$). There is a lack of an experimental tool to allow for the study of off-yrast states at moderate ($J > 6\ \hbar$) angular momentum. The GEANIE spectrometer and LANSCE/WNR fills this void. In this paper we will present the results from an experiment studying the ^{196}Pt(n,xn) reactions for $n < 14$ at moderate to high angular momentum using the combination of the LANSCE/WNR spallation neutron source and the multi-Ge detector spectrometer, GEANIE.

GEANIE (GErmanium Array for Neutron Induced Excitations) currently includes 13 Compton suppressed coaxial Ge detectors which have approximately 25% of the efficiency of a 3" X 3" NaI crystal and 7 Compton suppressed LEPS (low energy photon spectrometers) intrinsic Ge detectors. However, the results presented here were obtained with an early partial implementation of the array consisting of 7 coaxial and 4 planar detectors. GEANIE is located 20.3 m from the spallation target at the 60°

right (60R) beam line at the WNR (Weapons Neutron Research) facility at the Los Alamos Neutron Scattering Center (LANSCE). WNR is a 800 MeV spallation neutron source. Beam bursts for this experiment consist of 625 μs "macropulses" which are in turn comprised of 1.8 μs "miropulses". The beam impinges on the W spallation target with a frequency of 100 Hz, leading to an overall duty cycle of 6%. WNR thus produces a "white" spectrum of neutrons with energies from less than 1 MeV to greater than 250 MeV at the GEANIE site. Two 0.54 gm/cm^2 highly-enriched (97.4%) ^{196}Pt targets were placed at the focal volume of the spectrometer and γ-rays from 40 keV to 4 MeV were observed. Energy and timing information from the array was recorded using a specially modified version of the VME-based Michigan State University data acquisition system [2]. Ge detector gains were monitored during the experiment and aligned using a ^{152}Eu calibration source. The Time-of-Flight technique was used to obtain the energy of the neutrons. Data was taken for 44 hours and recorded on magnetic tape.

Data was sorted off-line into γ-ray energy vs. time-of-flight matrices and time-of-flight gated γ-γ matrices. An additional constraint that the γ-γ TAC be no greater than 30 ns insured that γ-γ coincidences were from the same nuclear event. A generalized Palameta-Waddington type background subtraction [3] was applied to the γ-γ matrices. Figure 1a shows a sum spectrum from the coaxial detectors that is TOF-gated to emphasize the (n,n') reaction channel ($0 < E_n < 8$ MeV) and γ-ray gated on the 356 keV ^{196}Pt $2^+ \rightarrow 0^+$ transition. The lack of the 356 keV transition in the spectrum shows the cleanliness of the γ-γ data, indicating the ability to use GEANIE for coincident γ-ray spectroscopy. The lack of any detectors at 90° made assignment of the γ-ray multipolarities impossible. Although this short run was done with approximately half of the full complement of detectors and far larger dead time than the current implementation of the array, we were still able to identify several new transitions in ^{196}Pt.

The neutron flux at WNR drops by approximately one order of magnitude from 10 MeV to 20 MeV. Coincident γ-γ spectroscopy beyond $E_n > 10$ MeV was therefore not possible in a run of such short duration. However, singles γ-rays can still be used to identify the reaction channels populated by higher energy neutrons. The ability to observe states resulting from high-energy neutron-induced reactions using γ-ray spectroscopy was shown in an earlier experiment by Vonach et. al, [4] which observed ^{200}Pb using the ^{208}Pb(n,9n) reaction with a single Ge detector during a one-month run. The capabilities of the GEANIE spectrometer vastly exceed those of this earlier experimental set-up, as can be seen in Time-of-Flight gated spectra obtained from the E_γ-TOF matrices. In order to eliminate γ-rays which were uncorrelated to the beam a "Random-TOF" singles spectrum corresponding to γ-rays that arrived at the detectors prior to the γ-flash from the spallation target was subtracted from the TOF-gated spectra. Figures 1b,c show two of these TOF-gated background subtracted coaxial detector spectra with neutron energy gates between 70 and 80 MeV (b) and 130 and 150 MeV (c). Transitions belonging to the ground state bands in nuclei resulting from (n,xn) reactions with $x < 14$ were observed. Although transitions were observed in the odd-mass Pt nuclei down to ^{185}Pt, the larger number of low-lying states resulting from the breaking of pairing made spectroscopic assignments in these odd-mass nuclei considerably more difficult.

These results have important implications for nuclear structure and reaction studies. We start by examining the low-energy results. The lowest-lying transitions in most nuclei provide sufficient information to allow for a classification of the low-lying structure using the simple tripartite system proposed by Zamfir [5] as single-particle, pre-collective, and collective rotational. However, these states give little insight into the mechanisms by which the structure evolves between the single-particle and collective limits with respect to particle number, energy and spin. In order to study this transition it is necessary to consider the off-yrast states. The Pt isotopic chain studied in this work is a classic example of this paradigm. The lowest ($J < 6\ \hbar$) states in ^{196}Pt nuclei have been admirably described through the observation of branching ratios between yrast and off-yrast states. These results have been described by Cizewski [6] et al. using the O(6) limits of the interacting boson model [7], which has the γ-soft rotor as its geometric analog. However, total Routhian surface calculations [8] indicate that the nucleus undergoes a transition from the γ-soft to the γ-rigid with increasing angular momentum. This transition is predicted to occur near $J = 10\ \hbar$, a region of phase space which is within the reach of GEANIE. Preliminary results studying the ^{196}Pt(n,n') reaction initiated by neutrons with $E < 10$ MeV indicate that states with $J < 14\ \hbar$, are observed. Therefore, with more data, it may be possible to make an unambiguous determination of whether ^{196}Pt undergoes a transition from a γ-soft to a γ-rigid minimum.

The results at higher neutron energy are of great interest for two reasons. First, the observation of the (n,13n) reaction channel with this intensity is an unexpected result. Reaction codes including PACE and CASCADE not only fail to predict the relative magnitude of the ^{196}Pt(n,13n) and ^{196}Pt(n,11n) reactions, but vastly over-predict the charged particle evaporation channels, including ^{196}Pt(n,α11n)^{182}Os. There is no indication whatsoever in this data of any charged particle evaporation channels up to the neutron energy limits set by the timing resolution of the detectors and the electronics ($E_n = 170$ MeV). This deviation may be due to a) the mass formulas used to predict all Pt nuclei lighter than ^{186}Pt (the last measured isotope) and b) the low-angular momentum of the compound system, which would tend to disfavor charged particle channels. GEANIE can address these discrepancies by measuring the absolute cross sections for the different reaction channels. Cross sections can be obtained by measuring γ-ray intensities of low-lying transitions and normalizing using neutron flux information obtained from a ^{235}U/^{238}U fission chamber located on the beam line.

The other compelling feature is the potential of using high (n,xn) reactions to study the low-lying structure of extremely neutron-deficient nuclei. Nuclei near the proton drip line have small formation cross sections, and knowledge of structure for $40 < N, Z < 50$ is sparse. Neutron deficient nuclei are of tremendous interest because of a number of phenomena that are unique to this region, such as proton radioactivity, N=Z and the heaviest mirror nuclei, and the exploration of exotic residual interactions, including proton-neutron pairing. The technique currently employed by the nuclear structure community to study these nuclei at a number of facilities including Michigan State University, Ganil, and Oak Ridge National Laboratory involves a combination of heavy-ion accelerators, mass separators to identify the charge/mass ratio of the evaporation residue, and large γ-ray spectrometers at either the target or catcher position. Although GEANIE does not use evaporation residue tagging the excitation function of a γ-ray transition can be extracted and used to identify the reaction channel. In addition, the LEPS detectors are ideal for detecting coincident X-rays which can in turn be used to identify the Z of the evaporation residue.

The GEANIE spectrometer offers a unique combination of high-resolution coincident and singles γ-ray spectroscopy of neutron-induced reaction products. The low-energy (n,n') and (n,2n) reactions in particular can be used to access yrast and off-yrast states in nuclei which are inaccessible using any other reactions due to the lack of a Coulomb barrier between the target and beam particles. These states are of particular interest to theory since they provide stringent tests of nuclear structure models. High energy reactions ($E_n > 100$ MeV) offer the opportunity to study exotic nuclei near the proton drip line and to probe reaction theory in a limit which has been inaccessible until now due to accelerator energy limits.

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Figure 1

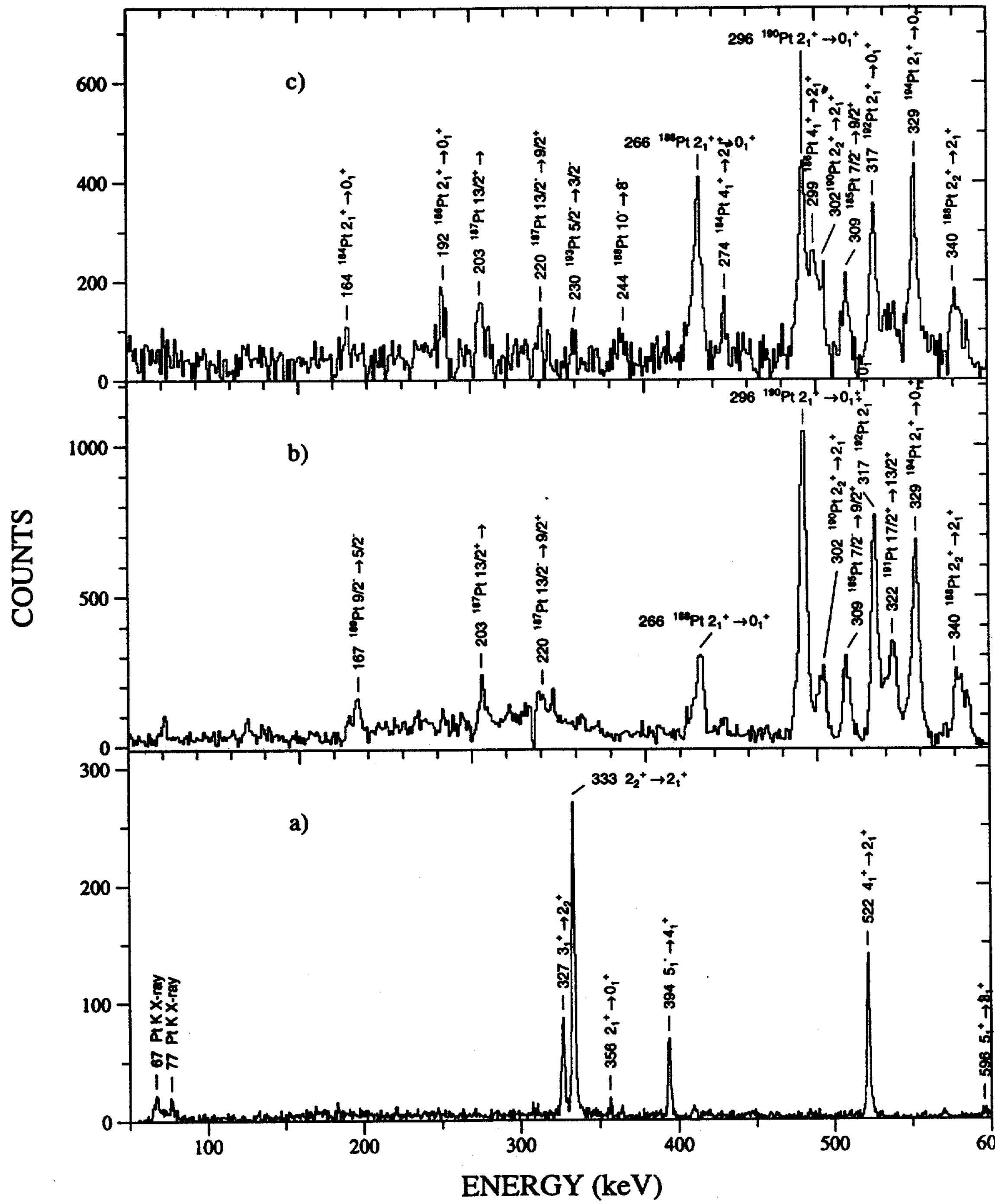

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Figure 1: GEANIE coaxial detector spectra. a) Gated on 356 keV ^{196}Pt $2^+ \rightarrow 0^+$ and 1 MeV $\leq E_n \leq$ 8 MeV, b) TOF gated - 70 MeV $< E_n <$ 80 MeV, c) TOF gated - 130 MeV $< E_n <$ 150 MeV.

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University of California • Livermore, California 94551