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Title: Experimental and Theoretical Understanding of Neutron Capture on Uranium Isotopes

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Report

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I. BACKGROUND

Neutron capture cross sections on uranium isotopes are important quantities needed to model nuclear explosion performance, nuclear reactor design, nuclear test diagnostics, and nuclear forensics. It has been difficult to calculate capture accurately, and factors of 2 or more between calculation and measurements are not uncommon, although normalization to measurements of the average capture width and nuclear level density can improve the result. The calculations of capture for ^{233,235,237,239}U are further complicated by the need to accurately include the fission channel.

Many measurements of capture cross sections have been made, yet discrepencies between the data have remained, even in the well-studied nuclide ^{235}U. Measurements are complicated by the radioactive decay of the sample, which both produces a detector background and limits the amount of material that can be measured. Direct measurements ofcapture for the very short-lived isotopes ^{237}U ($T_{1/2}$= 7 day) and ^{239}U ($T_{1/2}$= 23 min) cannot be made with current techniques.

A series of measurements on $^{234,235,236,238}U(n,\gamma)$ using the DANCE detector at LANSCE, coupled with advances in the theoretical understanding of capture, have resolved some measurement discrepencies and improved our ability to calculate the capture cross sections. This physical understanding may enable accurate calculations for ^{237,239}U capture.

II. MEASUREMENTS

DANCE (Detector for Advanced Neutron Capture Experiments) is located on Flight Path 14 at the Lujan Center at LANSCE. Neutrons from thermal to several hundred kilovolts are produced in a room-temperature water moderator. DANCE is an array of 160 barium fluoride scintillators, designed to make measurements on small samples of rare or radioactive nuclei. The high segmentation coupled with high efficiency enables measurements on a wide range of nuclides. For the odd-mass U isotopes where fission is important below an MeV, such as ^{235}U, a fission-tagging detector containing the nuclide was used. Fig. 1 shows the DANCE detector.

A recent measurement of the $^{235}U(n,\gamma)$ cross section resolved a discrepency between different data evaluations in the 1 to 5 keV energy region. New measurements of $^{236}U(n,\gamma)$ and $^{238}U(n,\gamma)$ have also been published, while a new measurement of $^{234}U(n,\gamma)$ is being analyzed.

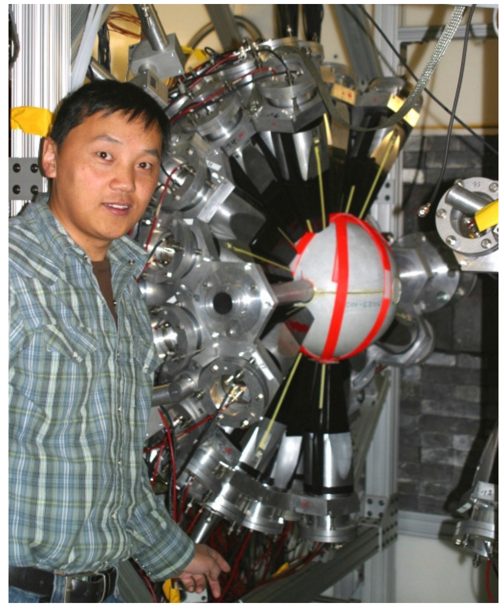

FIG. 1. The DANCE detector, opened to show the individual crystals. In the center is a ^{6}Li-hydride sphere to attenuate neutrons scattered from the sample. The sample is inserted into the center of the detector.

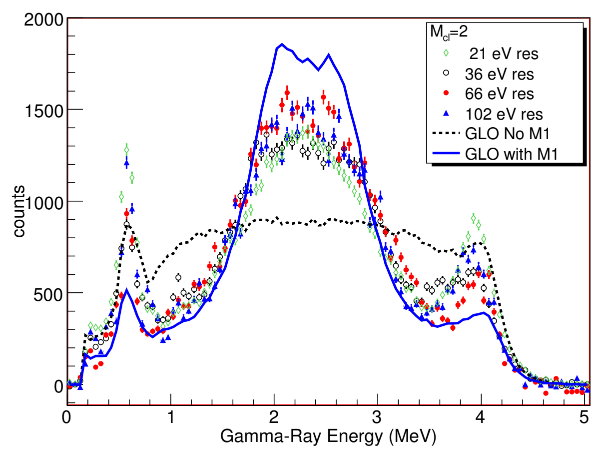

FIG. 2. Gamma-ray spectrum from the two-gamma ray decay of four $1/2^{+}$ neutron resonances in $^{238}U(n,\gamma)$ compared with calculations with and without the SM ("M1") mode.

III. CALCULATIONS

DANCE also can be used to measure the spectrum of gamma-rays following capture, subject to various conditions. Calculating these spectra provides an additional constraint on the theoretical models. Studies of the

DANCE spectra have confirmed that an additional mode of nuclear excitation, the "scissors mode" (SM) that has been observed in measurements of other nuclear rections, is required to reproduce the observed gamma-ray spectra. In addition, the parameters of the SM can be varied to provide the best fit to the gamma-ray spectra. This is illustrated in Fig. 2, which shows the measured spectrum for a two-gamma-ray decay in several neutron resonances observed in $^{238}U(n,\gamma)$ compared to calculations including the SM ("M1"), and without the SM ("No M1").

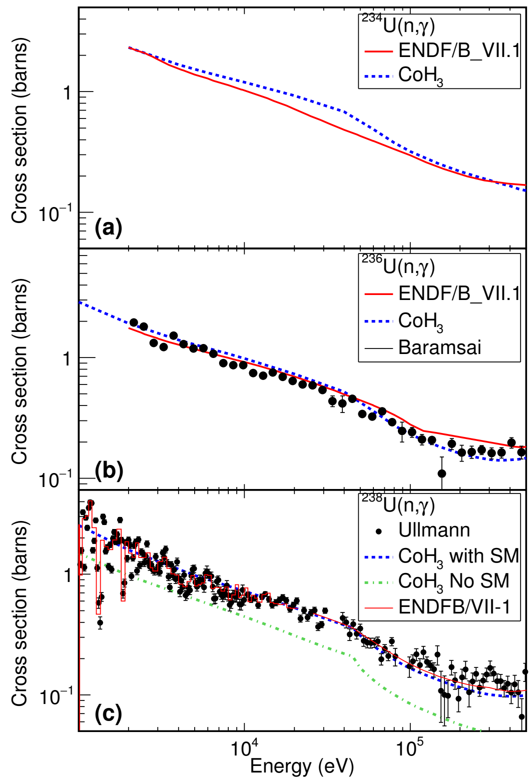

FIG. 3. Calculated cross sections for ^{234,236,238}U(n,γ) compared to the ENDFB/VII-1 evaluation and representative data. For ^{236}U, the recent DANCE measurements of Baramsai (2017) are shown. There are currently no data for ^{234}U tabulated in the National Nuclear Data Center experimental data base. For ^{236}U, the recent DANCE measurements of Baramsai (2017) are shown. The ^{238}U(n,γ) data are from Ullmann (2014).

Cross-section calculations for $^{234,236,238}U(n,\gamma)$ made with Kawano's CoH$_3$ code using the SM parameters that fit the gamma-ray spectra are shown as the dashed lines in Fig 3. It must be emphasized that these calculations are absolute, and not normalized to other quantities. For reference, the cross section calculated for $^{238}U(n,\gamma)$ without including the SM ("No SM") is also shown. We are currently analyzing the gamma-ray spectra from $^{235}U(n,\gamma)$ in order to extend the analysis to non-spin zero isotopes that also have a fission contribution, with the utimate goal of making accurate capture calculations for ^{237}U and ^{239}U.

This approach to calculating cross sections has been extended by Mumpower and Kawano to a wide range of deformed nuclei. A similar study of capture in Pu isotopes is also underway.

IV. PUBLICATIONS

"New Precision Measurement of the $^{235}U(n,\gamma)$ Cross Section." M. Jandel, et al., Physical Review Letters **109**, 202506 (2012).

"Cross Section and γ-ray spectra for $^{238}U(n,\gamma)$ measured with the DANCE detector array at the Los Alamos Neutron Science Center." J.L. Ullmann, et al., Physical Review C **89**, 034603 (2014).

"Estimation of M1 scissors mode strength for deformed nuclei in the medium to heavy mass region by statistical Hauser-Feshbach model calculations." M.R. Mumpower, et al., Physical Review C **96**, 024612 (2017).

"Radiative neutron capture cross section from ^{236}U." B. Baramsai, et al., Physical Review C **96**, 024619 (2017)..

"Constraining the calculation of $^{234,236,238}U(n,\gamma)$ cross sections with measurements of the γ-ray spectra at the DANCE facility." J. L. Ullmann, et al., Physical Review C **96**, 024627 (2017).

V. PERSONNEL AND FUNDING

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