LLNL-PROC-406206

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Using 171,173Yb(d,p) to benchmark a surrogate reaction for neutron capture

R. Hatarik, L.A. Bersntein, J.T. Burke, J.A. Cizewski, J. Gibelin, S.R. Lesher, P.D. O'Malley, L.W. Phair, T. Swan

August 11, 2008

CAARI 20th International Conference on the Application of Accelerators in Research and Industry
Fort Worth, TX, United States
August 10, 2008 through August 15, 2008

Using ^{171,173}Yb(d,pγ) to benchmark a surrogate reaction for neutron capture

R. Hatarik[1], L. A. Bernstein[2], J. T. Burke[2], J. A. Cizewski[1], J. Gibelin[3], S. R. Lesher[2], P. D. O'Malley[1], L. W. Phair[3], T. Swan[1,4]

(1)Rutgers University, New Brunswick NJ 08901, United States
(2)Lawrence Livermore National Laboratory, Livermore CA 94550, United States
(3)Lawrence Berkeley National Laboratory, Berkeley CA 94720, United States
(4)University of Surrey, Guildford GU2 7XH, Surrey, United Kingdom

Abstract

Neutron capture cross sections on unstable nuclei are important for many applications in nuclear structure and astrophysics. Measuring these cross sections directly is a major challenge and often impossible. An indirect approach for measuring these cross sections is the surrogate reaction method, which makes it possible to relate the desired cross section to a cross section of an alternate reaction that proceeds through the same compound nucleus. To benchmark the validity of using the (d,pγ) reaction as a surrogate for (n,γ), the ^{171,173}Yb(d,pγ) reactions were measured with the goal to reproduce the known [1] neutron capture cross section ratios of these nuclei.

PACS: 24.87.+y, 25.40.Lw, 25.60.Je, 27.70.+q

Keywords: Surrogate reaction, neutron capture

Corresponding Author:
Robert Hatarik
Rutgers University
c/o Building 6025, MS6354
Oak Ridge National Laboratory
PO Box 2008
Oak Ridge, TN 37831-6354
Tel: (865) 576-6598
FAX:(865) 576-8746

Introduction

Measuring neutron capture cross sections on unstable nuclei directly with radioactive targets and neutron beam is a major challenge due to target related activity. Such measurements are completely impossible if the half live of the target is short enough so that the background from target activity far outweighs the γ–emission from the reaction. Theoretical calculations of these cross sections usually lack the required accuracy needed for most applications like s- and r-process nucleosynthesis, reactor physics and stockpile stewardship science. An indirect way to measure these cross sections is the surrogate reaction technique, where a different cross section that proceeds through the same compound nucleus is measured. Based on the assumption that formation and decay of the compound nucleus are independent of each other, the cross section of a desired reaction can be expressed as a product of the cross section for the formation of the compound nucleus and its probability to decay into the exit channel of interest. Additional to that it has to be considered that spin and parity are conserved throughout the two step reaction, so the product of formation cross section and decay probability has to be evaluated for each spin and parity separately. This leads to the following equation [2,3]:

$$\sigma_{\alpha\chi}(E_x) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_x, J, \pi) P_{\chi}^{CN}(E_x, J, \pi) \qquad (1)$$

Here $\sigma_{\alpha\chi}$ is the cross section for the entrance channel α into the exit channel χ, σ_{α}^{CN} stands for the formation cross section of the compound nucleus from the entrance channel α and P_{χ}^{CN} is the decay probability into the exit channel χ. The formation cross section of the compound nucleus can usually be determined from theory using optical model parameters, whereas the decay probability is much less understood. In a surrogate experiment one attempts therefore to produce the same compound nucleus via a different “surrogate” reaction with the goal to measure the decay probabilities in the experiment. Most experiments rely on the Weisskopf-Ewing limit [4,5] were the decay probabilities become independent of spin and parity, so that the sum over J and π in equation (1) is no longer necessary.

The neutron transfer reaction (d,pγ) has the advantage over direct neutron capture measurements that it can be performed in inverse kinematics with radioactive ion beams and deuterated plastic targets, as was demonstrated in Ref. [6]. A surrogate experiment using this technique would allow the determination of cross sections on short lived species, which could otherwise not be measured. The described experiment served as a benchmark test, to investigate the feasibility of using (d,pγ) as a surrogate reaction for (n,γ).

In a (d,pγ) surrogate experiment the γ-ray decay probability of the compound nucleus is experimentally determined via

$$P_{\gamma}^{CN} = \frac{N_{(d,p\gamma)}}{\varepsilon N_{(d,p)}} \qquad (2)$$

where $N_{(d,p\gamma)}$ is the number of proton-γ coincidences, $N_{(d,p)}$ is the number of total protons detected and ε is the detection efficiency of γ-ray detection. The largest systematical uncertainty comes hereby from $N_{(d,p)}$, due to background from (d,p) reaction on target contaminants and deuteron breakup. It is therefore more reliable to measure to different nuclei and attempt to determine the cross section ratio of those instead; this is called the surrogate ratio method. In this approach the cross section ratio is given by:

$$\frac{\sigma_{n\gamma}^{(1)}(E_x)}{\sigma_{n\gamma}^{(2)}(E_x)} = \frac{\sigma_{n}^{CN(1)}(E_x)P_{\gamma}^{CN(1)}(E_x)}{\sigma_{n}^{CN(2)}(E_x)P_{\gamma}^{CN(2)}(E_x)} \approx \frac{\varepsilon^{(1)}N_{(d,p\gamma)}^{(1)}}{\varepsilon^{(2)}N_{(d,p\gamma)}^{(2)}} \qquad (3)$$

This approximation is valid since in many cases the formation cross sections can be assumed to be equal. The surrogate ratio method was successfully applied to fission surrogate measurements in Ref. [7,8].

Experimental setup

Since this was a benchmark test using stable nuclei (with known neutron capture cross sections [1]), the experiment was performed in direct kinematics using an 18.5 MeV deuteron beam of the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory. The experimental setup used the silicon detector array STARS (Silicon Telescope Array for Reaction Studies [9]) to detect reaction protons; coincident γ–rays were detected using an array of 6 HPGe Clover detectors [10,11], called the Livermore Berkeley Array for Collaborative Experiments (LiBerACE). The two targets used were both self supporting metallic foils of isotopically enriched ytterbium. A total of 4 days of beam time were used; the beam intensity varied between 2 and 3 nA.

The STARS arrangement consisted of three double-sided silicon detectors from Micron Semiconductor, which were located downstream of the target. The detectors were in a ΔE-E configuration for particle identification: the first detector (looking downstream from the target) had a thickness of 500 μm and was followed by two 1000 μm thick stopping detectors ($E1$ and $E2$). This allows for particle identification by looking at the energy loss in the ΔE detector relative to the total particle energy (see Fig. 1). The ΔE and $E1$ detectors were of the Micron S2 type, whereas the $E2$ was of S1 type. The S1 and S2 type detectors have a CD shaped active area with an outer radius of 35 mm for the S2 and 48 mm for the S1. The inner radius is 11 mm for the S2 and 24 mm for the S1 detector. The ΔE detector was placed 12.5 mm downstream of the target. The $E1$ detector was 1 mm behind the ΔE, followed by the $E2$ detector, which was 13 mm behind the $E1$ detector. This arrangement covered the forward angular range from 44˚ to 77˚. Each detector is separated into rings in front and wedge shaped sectors on the back side, which allows the angle relative to the beam axis as well as the azimuthal angle to be determined. The

S2 detectors are separated into 48 rings and 16 wedges, but due to limited channels of electronics two neighboring rings and sectors of the *E1* detector were coupled giving it effectively 24 rings and 8 wedges. The S1 type *E2* detector had 16 rings and 16 wedges. The determination of the angles by each detector separately has the advantage that the detected particle can be ray-traced back to the target. Between the target and the silicon detectors was placed a 4.44 mg/cm^2 aluminum foil to shield the detectors from δ-electrons. A target wheel was employed to switch between targets.

The data were recorded in two different trigger modes: either a particle-γ coincidence trigger or a particle-singles trigger, which triggers on each silicon detector event alone. To determine the surrogate cross section using the approximation from equation (3), only proton-γ coincidences are needed. Since a coincidence trigger greatly reduces the data rate, which increases the live time of the data acquisition system, most data were recorded using this trigger. However to verify the approximation made in equation (3) a part of the beam time was used to record data with a particle-singles trigger. Table 1 shows the distribution of the beam time for each target and trigger mode.

Data analysis and results

A compound nucleus produced in a neutron induced reaction is excited above the neutron separation energy; therefore a surrogate experiment needs to provide the same excitation energy. Since higher proton energy implies lower excitation energy, only protons with an energy low enough not to reach the third detector are of interest. Hence the third detector was used as a veto only. The data were analyzed on an event by event basis: first each event is calibrated; then the addback for adjacent leaves of the clover detectors is done. Afterwards it is checked that *ΔE* and

E1 have exactly one hit and *E2* has not been hit (the above mentioned veto). Depending on the rings hit in the two detectors only events that ray-trace back to the target position were used. The obtained proton energy from the silicon detectors has to be corrected for energy losses in the target, the aluminum δ-electron shield and the 3000 Å thick gold layer on the silicon detectors. To convert the obtained proton energy into the excitation energy of the compound nucleus it is transformed into the center of system, the energy of the recoiling nucleus is added and the result is subtracted from the reaction q-value. An equivalent neutron energy is obtained by subtracting the neutron separation energy from the excitation energy. For each equivalent neutron energy bin a coincident γ-ray spectrum is obtained. To get the number of proton-γ coincidences the number of events from a characteristic transition of the compound nucleus were used. The strongest γ-line for both targets was the 4^+ to 2^+ yrast transition. The intensity of the line was estimated by integrating the count rate over the peak area and subtracting the background based on the count rate on both sides of the peak. Fig. 2 shows the obtained count rates for both targets. The count rates are proportional to the decay probabilities of interest with the constant of proportionality depending on efficiency of γ-ray detection, beam current and beam time allocated for each target. This constant can be determined from the event rate obtained from gating on events corresponding to an excitation energy right below the neutron separation energy: below the neutron separation energy the compound nucleus can only decay via γ-emission, which implies the probability for γ-ray decay is one. This can be used to normalize the spectrum and obtain the γ-decay probabilities for both nuclei. Using these probabilities the surrogate cross section ratio can be obtained from equation (3). The top of Fig. 3 shows the result of this by gating on the 4^+ to 2^+ transition compared with the neutron capture cross section ratio obtained from Ref. [1], whereas the middle part of Fig. 3 shows the result by gating on the 6^+ to 4^+ transition instead.

The result from gating on the 4^+ to 2^+ transition is about 30% to 35% lower then the neutron capture cross section and by gating on the 6^+ to 4^+ transition this difference increases even more to about 45%. The difference of these two results indicates that the Weisskopf-Ewing limit does not apply. To get more accurate results in this case, the surrogate experiment should imitate the spin distribution of a neutron capture reaction as closely as possible. Neutron capture in the keV region is dominated by s-wave capture and therefore favoring lower spin states in the compound nucleus. In opposite to that, the (d,p) reaction transfers more angular momentum, and by gating on the 6^+ to 4^+ transition the higher spin states are even more favored, which explains why the difference to the neutron capture cross section increases even more. To select a spin distribution closer to the neutron capture case the feeding from the 6^+ state was subtracted from the intensity of the 4^+ to 2^+ line, which selectively disregards components from higher spin states. The result of this approach is shown in the bottom of Fig. 3. Here the surrogate result is within 15% of the neutron capture cross section ratio.

Summary and Conclusions

The (d,pγ) transfer reaction is a good candidate for a surrogate reaction since it can be performed in inverse kinematics. We have carried out a benchmark experiment in order to test how well a (d,pγ) surrogate experiment would reproduce neutron capture cross sections. It was shown that if the J^π mismatch is understood and corrected for, the preliminary surrogate ratio result was within 15% of the neutron capture cross section ratio for the ^{171,173}Yb isotopes.

Acknowledgments

The authors thank the operations staff of the 88-Inch Cyclotron. The Rutgers group was supported in part by the U.S. Department of Energy under grant number DE-FG52-03NA00143 and the National Science Foundation. Part of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Support for Lawrence Berkeley National Laboratory was provided by the U.S. Department of Energy under contract No. DE-AC02-05CH11231.

References

[1] K. Wisshak et al., *Phys. Rev. C* **71**, 051602 (2005).

[2] W. Hauser and H. Feshbach, *Phys. Rev.* **87**, 366-373 (1952).

[3] J. Escher et al., *J. Phys. G Nucl. Part. Phys.* **31,** S1687-S1690 (2005).

[4] E. Gadioli and P. E. Hodgson, *Pre-Equilibrium Nuclear Reactions*, Clarendon Press, Oxford (1992).

[5] J. Escher and F. S. Dietrich, *Proceedings of Perspectives on Nuclear Data for the Next Decade*, CEA DIF Bruyères-le-Châtel, France (2005).

[6] J.A. Cizewski et al., *Nucl. Instrum. and Meth. B* **261**, 938 (2007).

[7] C. Plettner et al., *Phys. Rev. C* **71**, 051602 (2005).

[8] J. Burke et al., *Phys. Rev. C* **73**, 054604 (2006).

[9] L. A. Bernstein et al., *Proceedings of Nucl. Data for Science and Technology*, Santa Fe, NM (2004).

[10] G. Duchêne, *Nucl. Instr. and Meth*. A **432**, 90 (1999).

[11] Z. Elekes et al., *Nucl. Instr. and Meth. in Phys. Res. A* **503**, 580 (2003).

[12] F. Becvár, *Nucl. Instr. and Meth. A* **417**, 434 (1998).

Table 1. Beam time allocated for each target and trigger mode.

Target	Trigger	Beam time
^{171}Yb	p-singles	5 h
^{171}Yb	p-γ coincidences	24 h
^{173}Yb	p-singles	8 h
^{173}Yb	p-γ coincidences	47 h

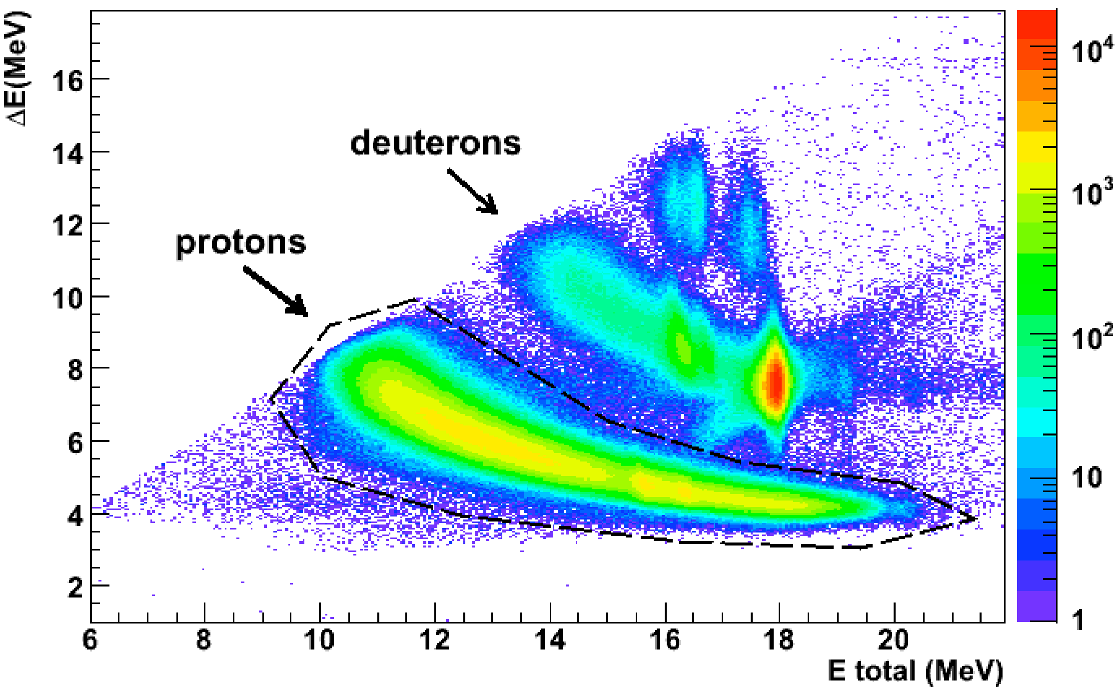

Fig. 1. (Color Online) Energy deposited in the ΔE detector vs the total energy E of the particle. Protons and deuterons are clearly separated.

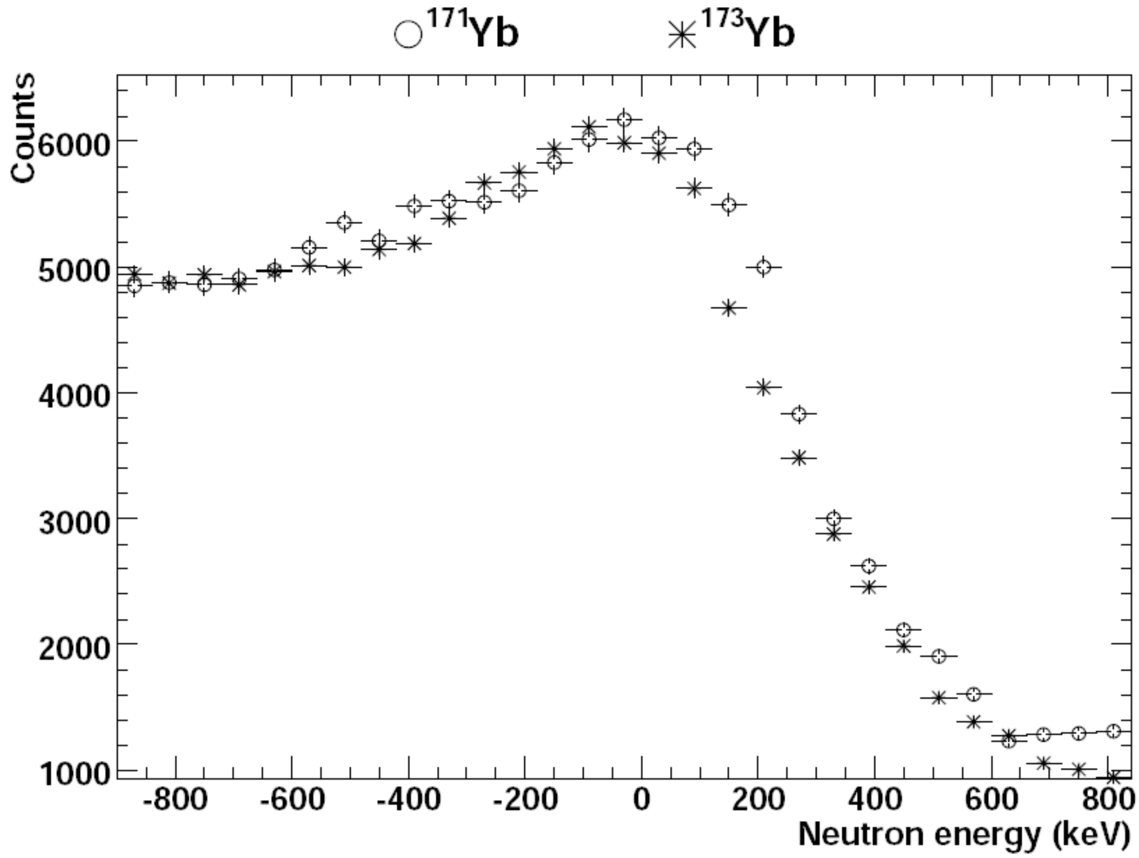

Fig. 2. Count rates of the 4^+ to 2^+ transitions for both targets as a function of equivalent neutron energy.

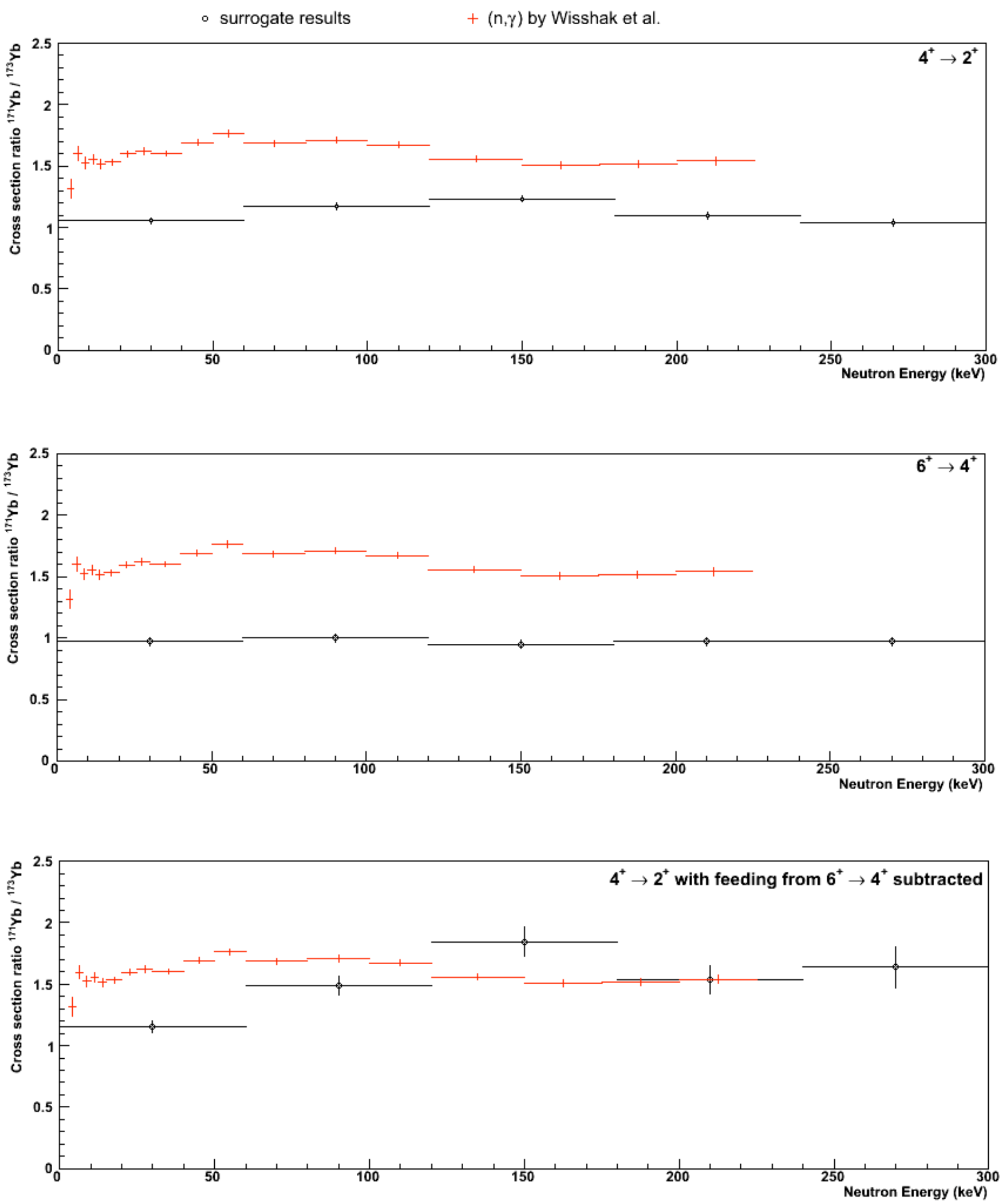

Fig. 3. (Color Online) Comparison of preliminary surrogate ratio results with neutron capture cross section ratio for 3 different cases: at the top by gating on 4^+ to 2^+ yrast transition, at the middle by gating on the 6^+ to 4^+ transition and the bottom shows all decays from the 4^+ state that were not fed by the 6^+ state. The shown error bars include only statistical errors.