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Benchmarking the External Surrogate Ratio Method using the $(\alpha, \alpha' f)$ reaction at STARS

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Abstract.
We measured the ratio of the fission probabilities of ^{234}U* relative to ^{236}U* formed via an (α,α') direct reactions using the STARS array at the 88-inch cyclotron at the Lawrence Berkeley National Laboratory. This ratio has a shape similar to the ratio of neutron capture probabilities from ^{233}U(n, f) and ^{235}U(n, f), indicating the alpha reactions likely formed a compound nucleus. This result indicates that the ratios of fission exit channel probabilities for two actinide nuclei populated via (α, α') can be used to determine an unknown fission cross section relative to a known one. The validity of the External Surrogate Ratio Method (ESRM) is tested and the results support the conclusions of Burke *et al.* [1].

Keywords: surrogate reactions, fission reactions
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INTRODUCTION

The direct determination of neutron-induced cross-sections can be challenging, especially with difficult to obtain or short-lived targets. This was addressed by Cramer and Britt in 1970 [2, 3] by using the Absolute Surrogate Method (ASM). They used a direct reaction (t, pf) on a variety of actinide targets to measure the absolute decay probability (P^{CN}_{abs}) of the compound nucleus to deduce the neutron-induced cross-section with success in the actinide region. The absolute decay probability is defined as $P^{CN}_{abs} = N_{\chi f}/N_{\chi}$ where $N_{\chi f}$ is the number of particle-fission coincidence events and N_{χ} is the number of particle single events recorded. The ASM requires clean particle singles data which is challenging because of contaminates in the target, especially carbon and oxygen. Experiments were designed to overcome this problem by placing charged particle detectors at backward angles, thus pushing the contaminates to over E_n=11–12 MeV. However, they encountered a 10–20% experimental uncertainty as they were not free of all the contaminates and furthermore, the spin distribution in neutron induced compound nucleus was different than the spin distribution in the direct reaction used to populate the compound nuclei. Younes and Britt [4, 5] de-convoluted J^{π} from the previous experimental work and weighted the $P_{fission}$ contribution correctly. Plettner and Burke [1, 6] circumvented the problem of contaminates by taking a ratio of two identical reactions on similar targets to cancel out the particle singles data and so for the two nuclei:

$$\frac{P^{CN1}_{abs}}{P^{CN2}_{abs}} = \frac{N^1_{\chi f}}{N^2_{\chi f}} \times \mathrm{A} \tag{1}$$

The correction factor (A) takes account of the differences in target thicknesses, the time beam was on target, the live time of the data acquisition system of the two experiments, and the efficiencies of the detectors. The charged particle detectors were placed at forward angles to better match the spin distribution of the direct and neutron induced reactions. The exit probabilities can be used to to determine an unknown neutron-induced cross section relative to the known cross section. In this External Surrogate Ratio Method (ESRM), the relative probability of ^{236}U(d, pf) to ^{238}U(d, pf) was compared to that of ^{236}U(n, f) to ^{238}U(n, f) from ENDF and the two ratios were found to be in good agreement over an excitation energy range of 6 to 20 MeV [6].

By multiplying the known ^{235}U(n, f) cross section by the ratio of the measured surrogate ^{238}U$(\alpha, \alpha' f)$ / ^{236}U$(\alpha, \alpha' f)$ reaction probabilities, Burke *et al.* [1] inferred the ^{237}U(n, f) cross section for neutron energies between 0 – 20 MeV. Subsequently, extensive experimental [7, 8] and theoretical [9, 10] research has been

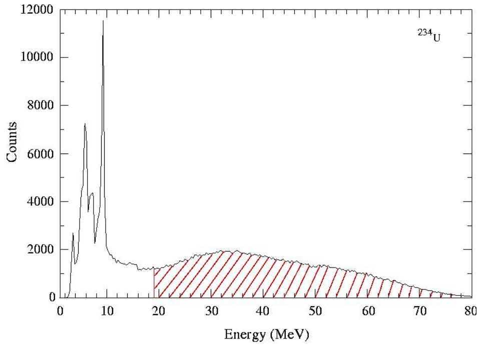

FIGURE 1. (color on-line) Total energy fission spectrum for ^{234}U($\alpha,\alpha' f$) as a function of channel number. The dashed lines represent the fission events considered clean and used for the data analysis.

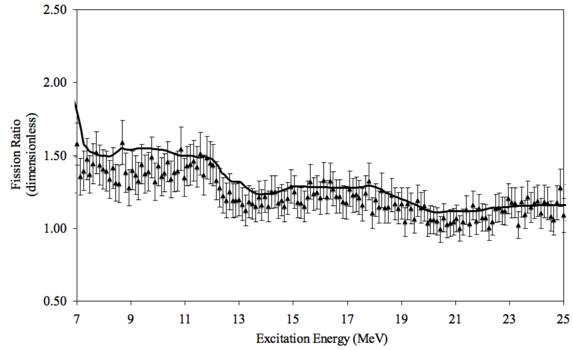

FIGURE 2. The surrogate ratio ($\frac{^{234}U(\alpha,\alpha' f)}{^{236}U(\alpha,\alpha' f)}$) is shown in the solid black points as obtained from this experiment. The solid line is the ENDF-B7 data for the $\frac{^{233}U(n,f)}{^{235}U(n,f)}$ ratio. The error bars represent statistical error only. Please note the suppressed ordinate axis.

focused in this area[1]. In this paper, the ESRM is benchmarked for the $(\alpha, \alpha' f)$ reaction over a wide range ($7 \leq$ E$_x$ (MeV) ≤ 25) of excitation energies.

EXPERIMENTAL SETUP

In this experiment, the ^{234}U and ^{236}U targets were bombarded with a 55 MeV α-particle beam produced by the 88-inch Cyclotron at the Lawrence Berkeley National Laboratory. The scattered alphas were detected in coincidence with the fission fragments using the Silicon Telescope Array for Reaction Studies (STARS) comprised of two, double-sided S2 type detectors, a 152μm ΔE detector and a 994 μm E detector. The detectors covered a forward angle of 42° to 66° relative to the beam axis and fission fragments were detected in a 140 μm S2 type detector located at back angles of 106° to 131° relative to the beam axis. The master trigger (MT) for the data acquisition required a coincident signal in the ΔE and E detectors. Fission detector energies were recorded if they came within 7 μs of the master trigger. Details of the experimental set up are described in Ref. [1]. The targets, ^{234}U and ^{236}U, were 253 μg/cm^2 and 184 μg/cm^2, respectively and mounted on a thick (2.3 mg/cm^2) piece of ^{nat}Ta foil.

ANALYSIS & RESULTS

In the off line analysis, charged particles ($p, d, t, ^3He$ and α) were identified in a particle identification plot and a 2-d gate was used to select the α-particles. The α-particle energies were reconstructed, taking into account the angular-dependent recoil energy of the target nucleus, energy losses in the uranium and tantalum layers of the target as well as in the thin (4 mg/cm^2) aluminum fission fragment shield and in the dead layers of the silicon detectors. The excitation energy of the uranium nucleus was calculated by subtracting the α-particle energy and calculated uranium recoil energy from the beam energy.

Fig. 1 shows the energy spectrum from the fission detector in coincidence with the prompt time peak for ^{234}U. In both of the targets, events with E$_{fission} \leq 19$ MeV in the fission detector were potentially overlapping with a signal from light-ion contaminants and not used in the data analysis. The particle-fission relative time spectrum was used to determine the prompt events for comparison of the two data sets. A random background subtraction was performed with the required E$_{fission} \geq 19$ MeV gate in order to produce a spectrum of coincident α-fission events or N$_{\alpha f}$(E*) as a function of excitation energy.

In order to extract the desired ratio of cross-sections, the scalar data was recorded and used to account for the differences in the beam flux and the data acquisition system live times for the two data sets as shown in Equ. 1 and explained in Ref. [1].

In Fig. 2, the surrogate ratio ($\frac{^{234}U(\alpha,\alpha' f)}{^{236}U(\alpha,\alpha' f)}$) from this experiment is compared to the $\frac{^{233}U(n,f)}{^{235}U(n,f)}$ cross-section ratio from the ENDF/B7 database [11] and agree within 10%. The plot does not take into account the anisotropy of detecting the fission fragments nor the efficiency of the particle detector, neither of which we anticipate will have a significant effect on the measured curve. From this data we support the conclusions made in Burke *et al.* [1] when extracting the ^{237}U(n, f) cross section using the same technique.

[1] For more on this topic, please see other papers in this proceedings including J.T. Burke, R. Hatarik, M.S. Basunia, and J.E. Escher.

Conclusion

The fission probabilities of $^{234}U^{*}$ relative to $^{236}U^{*}$, formed via an (α,α') direct reaction, have been measured using the STARS array at the 88-inch Cyclotron at the Lawrence Berkeley National Laboratory. Our measurements are in good agreement with the ENDF-B7 data for the $\frac{^{233}U(n,f)}{^{235}U(n,f)}$ cross-section ratio over an excitation energy range of $7 \leq E_x$ (MeV) ≤ 25 and supports the work of Burke *et al.* [1].

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REFERENCES

1. J.T. Burke, L.A. Bernstein, J. Escher, L. Ahle, J.A. Church, F.S. Dietrich, K.J. Moody, E.B. Norman, L. Phair, *et al.*, *Phys. Rev. C* **73**, 054604 (2006).
2. J.D. Cramer, and H.C. Britt, *Nucl. Sci. Eng.* **41**, 177 (1970).
3. J.D. Cramer, and H.C. Britt, *Phys. Rev. C* **2**, 2350 (1970).
4. W. Younes, and H.C. Britt, *Phys. Rev. C* **67**, 024610 (2003).
5. W. Younes, and H.C. Britt, *Phys. Rev. C* **68**, 034610 (2003).
6. C. Plettner, H. Ai, C.W. Beausang, L.A. Bernstein, L. Ahle, H. Amro, M. Babilon, J.T. Burke, *et al.*, *Phys. Rev. C* **71**, 051602(R) (2005).
7. B.F. Lyles, L.A. Bernstein, J.T. Burke, F.A. Dietrich, J. Escher, I. Thompson, D.L. Bleuel, R.M. Clark, P. Fallon, *et al.*, *Phys. Rev. C* **76**, 014606 (2007).
8. M.A. Basunia, R.M. Clark, L. Phair, D.L. Bleuel, P. Fallon, J. Gibelin, M.A. McMahan, E. Rodriguez-Vieitez, *et al.*, *Phys. Rev. C* **submitted** (2007).
9. J. Escher, L.Ahle, L. Bernstein, J. Church, F. Dietrich, C. Forssén, and R. Hoffman, *Nucl. Phys. A* **758**, 86c (2005).
10. J. E. Escher, and F. S. Dietrich, *Phys. Rev. C* **74**, 054601 (2006).
11. M.B. Chadwick, P. Obložinský, M. Herman, N.M. Greene, R.D. McKnight, D.L. Smith, P.G. Young, *et al.*, *Nucl. Data Sheets* **107**, 2931 (2006).