Lawrence Livermore National Laboratory

USNDP – CSWEG update of LLNL experimental activities Brookhaven National Laboratory Long Island, New York November 4, 2009



Jason T. Burke

for LLNL and STARS/LIBERACE Collaboration

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The ⁴⁸Ca + ²⁴⁹Bk reaction is running at JINR now to attempt to produce element 117 - Courtesy Mark Stoyer



A Dubna/LLNL/GSI collaboration is forming to at<u>tempt confirmation of elements 115 & 116_at GSI</u>



LLNL Fission chamber at LANL – Ching-Yen Wu

- 1. Experiment to measure the fission neutron spectrum using the newly developed fission chamber in conjunction with FIGARO, has been fielded at LANL/LANSCE from August 6 to 15, 2009 and extended for at least a week.
- 2. Fission chamber performed extremely well with the initial indication of huge success.





LLNL fission chamber at FIGARO

S&T Principal Directorate - Physical Science / N Division

Surrogate reactions using the ratio technique

"Surrogate" reactions



Ratio of ²³³U(n,f)/²³⁵U(n,f) compared to ²³⁴U($\alpha,\alpha'f$)/²³⁶U($\alpha,\alpha'f$) Courtesy Shelly Lesher (LLNL)





²³⁶U(n,f) Cross Section from ratio of ²³⁸U(³He, α 'f)/²³⁵U(³He, α 'f) x σ [²³³U(n,f)] Courtesy B.F. Lyles U.C.B.



²³⁷Np(n,f) cross section from ²³⁸U(³He,tf) surrogate reaction Courtesy S. Basunia (LBNL)



Ref. 15. O. Shcherbakov *et al.*, J. Nucl. Sci. and Tech., Supp. 2, 230, 2002 Ref. 16. F. Tovesson and T. S. Hill, Phys. Rev. C 75, 034610, 2007.

239 U(n,f) ($\tau_{1/2}$ =24minutes) determined from 238 U(18 O, 16 O) 240 U J.T. Burke to be submitted to PRC fall 2009



Physical Sciences

Option:UCRL#

Surrogate nuclear reaction method using inelastic scattering



"Surrogate" reaction



Hauser-Feshbach theory describes the "desired" reaction as a product of entrance channels (σ_{α}^{CN} – can be calculated reliably) and exit channel branching ratios (G_{γ}^{CN} – can't be calculated reliably)

Alternative ("surrogate") reaction can be used to form the same compound-nucleus of interest and determine G_{γ}^{CN}

We measure this ratio



s-process branch-point nucleus ¹⁵³Gd Courtesy Nick Scielzo (Lawrence Fellow/LLNL)



^{152,154}Gd cannot be produced by the *r*-process and therefore these isotopes can be used to understand the *s*-process

 (n,γ) cross sections for branch-point nuclei (n capture and β -decay rates are comparable) such as ¹⁵³Gd are needed

¹⁵³Gd is radioactive ($t_{1/2}$ =240 days) \rightarrow direct measurements very difficult

Well-suited for surrogate techniques because many stable Gd isotopes can be used for measurement and benchmarks. Compound nucleus created through inelastic (p,p') scattering



Determining the compound nucleus spin-parity Nick Scielzo and Jutta Escher



The measured γ -ray yields compared to calculated yields for different spin distributions (error bars not shown).

Extract most likely J^{π} distribution from a comparison of data and calculations...



¹⁵⁵Gd(n, γ) cross section from a Weisskopf-Ewing analysis

Cross section (purple dots) obtained by using Weisskopf-Ewing approximation

 $\sigma_{\alpha\chi} \mathbf{E} = \sigma_{\chi}^{CN} \mathbf{E} \mathbf{G}_{\chi}^{CN} \mathbf{E}$

compared to cross sections obtained using simulated surrogate analysis with different compound nucleus spin-parity distributions

Distributions 2-6 are closest to reproducing γ -ray cascade and are also closest to extracted cross section results





Experimental Set-up with STARS-LiBerACE

Enriched, self-supporting, metal 154,156,158 Gd targets bombarded with 22-MeV protons from the 88-Inch Cyclotron at LBNL to create the same compound nuclei as 153,155,157 Gd(n, γ) reactions

Detect scattered *p* in segmented silicon detector array

Coincident detection of characteristic γ rays using an array of Comptonsuppressed "clover" HPGe detectors



New experimental hall – Cave 2 @ 88 Inch Cyclotron \$150k investment in equipment by LLNL



Hydra New scattering chamber for precision studies.

- 17 inch diameter
- 9 inch deep
- dome roof for out of plane studies of fission
- Delta E E telescope
- Up to 12 or so $\triangle \text{EE pairs}$
- 200 $\mu \textbf{m}$ thick $\Delta \textbf{E}$
- -5000 μm thick E
- -2 degree uncertainty due to acceptance



Digital Electronics Upgrade – VF48 VME \$150k investment from LBNL/U.Richmond/LLNL

- Silicon digital electronics:
 - 528 channels of energy and time with waveform sampling of each channel. 10 bit ADCs which have 12 bit equivalent number of bits resolution (4096 chns).
- Germanium digital electronics:
 - 6 GRETINA 10 channel modules which have 14 enob resolution.



New detectors courtesy NA-22 \$60k investment in new detectors LLNL

Delta E – E telescope

Stops a 33 MeV proton

- Up to 12 or so ΔEE pairs
- 200 μm thick ΔE
- -5000 µm thick E
- -2 degree uncertainty due to acceptance







Upcoming work on CS for FY10

-Continue to develop surrogate method reaction theory Ian Thompson, Jutta Escher, Jason Burke & Nick Scielzo

-Measure (n,gamma) and/or (n,2n) cross sections in Y/Zr region - LLNL

-Measure ²³⁸Pu(n,f) cross section over energy range of 0 to 20 MeV – LLNL/NA-22

-Measure ^{23x}Np(n,f) cross section – UCB/Donuts

-Collaborate with French labs BRC/CENBG to measure ^{17x}Lu(n,gamma) cross sections using surrogate technique

-Start collaboration with JAERI I. Nishinaka – interested in surrogate method

-New People coming to join the Collaboration:

-D. Meyer – Prof., Rhodes College/SSAA

-Tim Ross – GS, University of Surrey

-J. Ressler – Staff, LLNL

-TBD - Post-Doc, University of Richmond/SSAA

-Robert Casperson – Post-Doc, LLNL

Ultimate goal of the Surrogate Program is to be able to measure cross sections in inverse kinematics experiments at FRIB



Really a team effort among institutions







Collaborators (students in red post-docs underlined)

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D. A. Meyer

Rhodes College











Fission chamber performance – Ching-Yen Wu



Option:UCRL#

Option: Additional Information

Weisskopf-Ewing Approximation

Weisskopf-Ewing Approximation: branching ratios G_{χ}^{CN} are independent of spin and parity when many decay channels are open

"Desired" reaction



$$\sigma_{\alpha\chi} \mathbf{E} = \sigma_{\chi}^{CN} \mathbf{E} \mathbf{G}_{\chi}^{CN} \mathbf{E}$$

Hauser-Feshbach theory describes the "desired" reaction as a product of entrance channels (σ_{α}^{CN} – can be calculated reliably) and exit channel branching ratios (G_{χ}^{CN} – can't be calculated reliably)

154Gd p stable $P_{\chi} \bigoplus = G_{\chi}^{CN} \bigoplus = \frac{N_{\bigoplus,p\gamma} \bigoplus}{N_{\bigoplus,p} \bigoplus}$ Alternative ("surrogate") reaction can be used to form the same

"Surrogate" reaction

Ľ

compound-nucleus of interest and

determine G_{γ}^{CN}

²³⁸U(n,f) determined from ²³⁸U(¹⁸O,¹⁷O)²³⁹U/ ²³⁴U(¹⁸O,¹⁷O)²³⁵U J.T. Burke (LLNL)



Option:UCRL#

Electronics Upgrade: Implementation started Burke and Phair

- Silicon detectors:
 - 140 μm, 500 μm, 1000 μm thick silicon S2
 - 48 rings 0.5 mm wide and 16 sectors (64 channels needed)
 - 500 μ m, 1000 μ m thick silicon S1
 - 48 rings 0.5 mm wide and 16 sectors (64 channels needed)
 - 300 $\mu m,\,1000~\mu m$ thick silicon W2
 - 4x16=64 rings 1.5 mm wide and 16 sectors (80 channels needed)

Typical experiment: STARS annular telescope (128 to 144 channels)

STRIPES square telescope (2X(32+32)=128 channels)

Total silicon channels = 256 to 272 channels of energy and time



²³⁹U(n,f)(n,γ), and (n,2n) ($\tau_{1/2}$ =24minutes) determined from the ²³⁸U(¹⁸O,¹⁶O)²⁴⁰U (preliminary data analysis)



Silicon Telescope Array for Reaction Studies (STARS) Livermore Berkeley Array for Collaborative Experiments (LIBERACE)



The Surrogate Nuclear Reactions approach is an indirect method for determining cross sections of compound-nuclear reactions

Used when direct measurements are not possible because of beam and/or target limitations.

For *s*-process branch nuclei, this approach circumvents limitations imposed by low flux of neutron beams and small mass of radioactive targets – create compound nucleus through reaction of light-ion beam on a stable isotope of same element



Surrogate nuclear reaction method using (p,p')

The surrogate nuclear reactions approach is an indirect method for determining cross sections of compound-nuclear reactions that can be used when direct measurements are not possible because of beam and/or target limitations.





Measuring γ -ray decay probabilities

γ -ray decay probability can be measured:

$$P_{\boldsymbol{\varphi},p\gamma}(E_{ex}) = \frac{\boldsymbol{\varepsilon}_{p}(\boldsymbol{\varphi} + \boldsymbol{\alpha}_{IC})}{\boldsymbol{\varepsilon}_{p}\boldsymbol{\varepsilon}_{\gamma}f} \times \frac{N_{\boldsymbol{\varphi},p\gamma}^{obs}(E_{ex})}{N_{\boldsymbol{\varphi},p}^{obs}(E_{ex})}$$

with E_{ex} determined from scattered proton energy:

$$E_{ex} = E_{beam} - E_{p}^{obs} + E_{deadlayer} + E_{recoil}$$

904

$$365$$
 but a fraction of
 539
 278
 261
 4^+
 80
 0
 182
 4^+
 4^+
 0^+
 182
 0^+
 158 Gd
(Energies in keV)

Ground state band

collects majority of

γ-ray strength



γ-ray Detection

As nucleus de-excites, many γ -ray cascades pass through the lowest excited states



All $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$, and $2^+ \rightarrow 0^+$ transition γ -rays observed with good statistics.



Exit Channel Probabilities

$$P_{\boldsymbol{\varphi},p\gamma}(E_{ex}) = \frac{\boldsymbol{\langle} + \alpha_{IC}}{\varepsilon_{\gamma}f} \times \frac{N_{\boldsymbol{\varphi},p\gamma}^{obs}(E_{ex})}{N_{\boldsymbol{\varphi},p\gamma}^{obs}(E_{ex})}$$

With $P_{(p,p\gamma)}$ at hand, next step is to combine these experimental results with reaction modeling to determine (n, γ) cross sections...

...and compare to known ¹⁵⁵Gd and ¹⁵⁷Gd cross sections to determine reliability



Weisskopf-Ewing Approximation



Absolute cross sections obtained using Weisskopf-Ewing approximation (assuming spin-parity of compound nucleus doesn't matter) and absorption cross sections. No surprise this simple strategy doesn't work.

FORSSÉN, DIETRICH, ESCHER, HOFFMAN, AND KELLEY Phys. Rev. C 75 055807 (2007)



FIG. 7. (Color online) Extraction of (n, γ) cross section from a surrogate experiment simulation using the Weisskopf-Ewing approximation; see WE simulation of Table III and discussion in text.



Determining the compound nucleus spin-parity



Conclusions and outlook

- Developing new technique to measure (n,γ) cross sections for radioactive isotopes
- Surrogate nuclear reactions method combines measured exit channel probabilities with reaction modeling
- Exit channel probabilities for ^{153,155,157}Gd(n,γ) surrogate reactions have been measured
- Effort underway to determine J^π sensitivity and incorporate entrance channel to extract cross sections



Collaborators

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University of Richmond

J.M. Allmond, C. Beausang



What about ratios?





(a) 2⁺→0⁺

Approaching the Island of Inversion: ³⁴P

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A 10 nal Laboratory, Berkeley, National Laboratory, Livermore, CA 94551 University of Richmond, VA 23173 ational Laboratory, Livermore, CA 94551 tional Laboratory, Berkeley, California 94720 ineering, University of California, Berkeley, CA 94720 (Dated: March 6, 2009)

ere investigated using the ¹⁸O(¹⁸O,pn) reaction at energies of 20, 24, 25, 30, lorida State University and at Lawrence Berkeley National Laboratory. The level scher expanded, γ -ray angular distributions were measured, and lifetimes were inferred with the Doppler-shift attenuation method by detecting decay protons in coincidence with one or more γ rays. The results provide a clearer picture of the evolution of structure approaching the "Island of Inversion", particularly how the 1 and 2 particle-hole (ph) states fall in energy with increasing neutron number approaching inversion. However, the agreement of the lowest few states with pure sd shell model predictions shows that ³⁴P is not itself inverted. Rather, the accumulated evidence indicates that the 1-ph states start at 2.3 MeV. It also appears that the lowest 2-ph state lies at 6236 keV, just below the neutron separation energy of 6291 keV.

I. INTRODUCTION

The (³He,tf) as a surrogate reaction

The surrogate reaction 238U(3He,tf) is used to d

equivalent neutron energy range from 10 to 20 M

was bombarded with a 42 MeV 3He2+ beam from

Laboratory (LBNL). Outgoing charged particles

Telescope Array for Reaction Studies (STARS) (

type silicon detectors. These results were compar-

measurements, the Evaluated Nuclear Data File

Data Library (JENDL 3.3) and found to closely

surrogate to extract (n,f) cross section in the 10 to

Surrogate two neutron transfer reactions to popu

nuclei present in nu-

had a renewed interest in

enaissance in nuclear power

Jason T. Burke, Nick Scielzo, Steven Sheets and Darren B

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Larry W. Phair[†]

Serkeley National Laboratory

²³⁸U/¹⁸O,¹⁶O)²⁴⁰U to populat

December 30, 2008)

PACS: 24.85 +n: 25.60 +: 25.60 I a

The fission cross sections of nuclei with half lives shorter

than several hundred years are difficult to measure due

to target induced backgrounds. We have measured the ²³⁹U(n.f) cross section indirectly using the two neutron

transfer reaction $^{238}\mathrm{U}(^{18}\mathrm{O},^{16}\mathrm{O})^{240}\mathrm{U}$ and compared it to the $^{234}\mathrm{U}(^{18}\mathrm{O},^{16}\mathrm{O})^{236}\mathrm{U}$ reaction. These two reactions are surrogate reactions for the $^{239}\mathrm{U}(\mathrm{n,f})$ and $^{235}\mathrm{U}(\mathrm{n,f})$

reactions respectively where the $\sigma_{219U}(n, f)$ is unknown

and the $\sigma_{235U}(n, f)$ is known. By taking the ratio of the number of ¹⁶O particles in coincidence with fission frag-

ments for both reactions and multiplying by the known

 $\sigma_{232U}(n, f)$ we can obtain $\sigma_{232U}(n, f)$. The use of the

(¹⁸O, ¹⁶O) reaction is less desirable than a (t,p) reaction

to populate the appropriate nuclei, it was used out of ne

cessity as there were no tritium beams available at the

II. EXPERIMENTAL PROCEDURE

This experiment used a 250 MeV ¹⁸O⁷⁺ hear pro-

duced by the 88 Inch Cyclotron at Lawrence Berkeley

National Laboratory. The ¹⁸O beam, with a beam cur-

rent up to 1 enA, impinged upon a 600 $\frac{\mu g}{cm^2}$ self sup-

porting ²³⁸U target. Scattered particles from the vari-

ous nuclear reactions were detected in the STARS silicon

M. S. Basunia^a, R. M. Clarl

D. L. Bleuel^a, B. Darak

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f Physics and Astronomy, Rutg

A major issue in nuclear structure is how the filling of proton shells affects the neutron shell structure, and vice-versa. One of the best regions to study this effect is among nuclei in the so-called "Island of Inversion" with $Z \sim 10$ and $N \sim 20$. The ground state structures of these nuclei are dominated by intruder configurations involving neutrons in orbitals above N = 20. That is, the level structure is inverted, with the intruder states neutron number exceeds 20 and $\nu f_{7/2}$ configurations be come normal for the ground states. Because the lighter P isotopes are better known, we have investigated N = 19³⁴P in the present work. Another reason to study ³⁴P is that there has been uncertaintity about the assignment of its lowest intruder state, and this state plays a crucial role in the approach to inversion, as described in Ref. [3].

Progress in unraveling the structure of ³⁴P has come slowly over the last four decades. A spin-parity assignment of 1⁺ was made to the ground state from obser-

s in ³⁴S [4].

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or any reac

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action along er a γ decay

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ity 3⁻ or 4⁻

f short-lived

ation led to

Determination of (n, γ) cross-sections in Gd using surrogate reactions

N. D. Sciakov, L. A. Bernstein, D. L. Bleuel, J. T. Burke, F. S. Dietrich, J. Escher, S. R. Lesher, E. B. Norman, S. A. Sheets, and I. Thompson Lawrence Livermore National Laboratory, Livermone, CA 94551 USA	
 J. M. Allmond and C. W. Beausang University of Nonod, Richmond, VA 20173 USA M. S. Basunia Y. L. Yu, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. A. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. McM'sware and the print, P. Fallon, J. Gibelin, B. L. Goldburn, M. M. McM'sware and M. Wiedeking, M. Gibelin, B. L. Goldburn, M. McM'sware and the print, P. Kataka, M. Kataka, M.	
There is even cannel probabilities for 10,106,105 Ged nuclei were measured up to excitation ener- try for W_{i} (G minimu targets were bonkarded with 22 MV protons and γ -rays were detected in the proton of the state	

Neutron captures on unstable nuclei play an important

FIG. 1: The ovvren isotoper neutron capture and β -decay processes for many nuclei scope. Note that only the or with half-lives ranging from weeks to years. (n, γ) cross

neutron density of these astrophysical environments from silicon detector located 11 observed isotopic abundances []. Evaluations of nuclear The ¹⁸O nuclei that und reactor system designs and fuel cycle concepts require the targets produced part neutron-capture cross sections on short-lived actinides. to neon. The silicon teles In addition, (n, γ) cross sections are needed for many apoxygen isotopes from one plications in nuclear forensics, stockpile stewardship, and band as well as measure t homeland security.

band as were as measure γ nonnearm sections. particle. The excitation i Currently, no direct experimental technique has suc-structed from the known i cessfully measured an (n, γ) cross section for an isotope ticle energy and angle whi with a half-life significantly shorter than 100 years be-methy and the section of the sec

updating deadtime per re trometry to count product nuclei [3] have reached preci-sions of $\sim 10\%$ for isotopes with 100 year half-lives. How-This deadtime setting res ever, these experiments become increasingly difficult as approximately 80%. the nuclear half-lives decrease.

III. DATA REDUC determine neutron-induced cross sections because of target limitations. The surrogate nuclear reaction method

tions using a combination of reaction modeling and ex-

compound nucleus that would result from the neutronevent basis. Valid events induced reaction through a different ("surrogate") reac-

itation of a The subseiserved (429 tion that involves a combination of projectile and target V. The latthat is more accessible in the laboratory. The technique

 $e 2225 \pm 10$ has previously been used to determine (n, f) cross sections at energies $\gtrsim 1$ MeV for actinide nuclei using light rediate lines ion reactions [4-9]. perhaps be-At these energies, theoretical studies [10] indicate gher energy

that limited angular momentum differences between the neutron-induced and surrogate reactions play a small role especially when measurements are made relative to a known cross section. At lower energies, angular momentum considerations must be taken into account to extend the technique down to 0.1 MeV [11, 12].

In this paper, the surrogate nuclear reaction method is applied to determine low-energy (n, γ) cross sections for 57 Gd using data collected up to ≈ 3 MeV from inelas tic proton scattering. Over this energy range, theoretical studies using statistical-reaction models have shown that the differences in angular momentum imparted in the desired (n, γ) and the surrogate reaction must be accounted for to extract an (n, γ) cross section [13]. A simple treatment of the compound-nuclear spin-parity distributions is carried out based on the observed γ -ray yields for the ground-state band transitions. Cross sections resulting from different approaches to angular momentum were compared to direct measurements coving an energy range up to 2.5 MeV [14, 15]. The sensitivity of this technique to spin and parity considerations of the compound nucleus are explored. Simple surrogate analyses that neglect angular momentum considerations have previously been carried out [16] but the results reproduce known cross-sections only approximately.

In addition, the (n, γ) cross section for ${}^{153}Gd(n, \gamma)$, a branch-point nucleus for the astrophysical s-process for which no data currently exists, can be determined. Other efforts have incorporated experimental results from inverse photodisintigration (γ, n) reaction rates with the

The Surrogate Ratio Method in the Actin Benchmarking the Internal Surrogate Ratio

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thod, the measured decay pr

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eds through the same compound nu

gate Ratio Method (SRM), uses a ratio of

section relative to a known one. To test the 5

 ${}^{4}U(\alpha, \alpha' f)$ to ${}^{236}U(\alpha, \alpha' f)$ with the ratio of cross s

were found to be in agreement with a confidence le

PACS numbers: 24.10.-i, 24.75.+i, 24.87.+v, 25.85.Ge

Gamma-Ray Multiplicity Measurement of ²⁵²G

large solid angle γ -ray measurement with a reasonable reconstruction

multiplicity was determined in certain cases by identifying the prompt

HPGe/BGO Detector Array

(Dated: April 24, 2009)

Abstract

INTRODUCTION

Neutron-induced reaction cross sections play a role in

many areas of nuclear physics and astrophysics such as

nucleosynthesis [1, 2], stockpile stewardship, and nuclear

energy research [3]. The direct measurement of neutron-

induced cross sections can be a challenge, especially with

difficult to obtain or short-lived targets. The Surrogate

Method, first used by Cramer and Britt in 1970 [4], and

more recently by Petit et al. [5] and Plettner et al. [6]

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M.D. Heffne

PACS numbers: 24.75.+1, 25.85.Ca

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7.6-25 MeV

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Lawrence Nuclear Science Di rkelev ⁴Department o Rutaers Univer usics and A (Dated: Octob tio Method (ISRM) is

gamma and fission decay [same ²³⁶U* compound nucleus $\leq E_n$ < 3.6 MeV. In the experim arget (450µg/cm²) with particle-gamma, p focus is on particle-gated gammas, spins, provide the key information for tagging the gamn method for tagging the gamma channel by analyz particle-gamma coincidence data. This method cane thus avoiding the difficulties and large uncertainties breakup. Sensitivity to tagging the gamma channel Additionally, the method may provide a viable mea

PACS numbers: 23.20.En, 23.20.Lv, 24.10.-i, 24.50.+g, 2 Keywords: surrogate, reaction, compound, weisskopf-ew

I. INTRODUCTION

The surrogate reaction technique, first applied in 1970 [1], has recently been under investigation [2-5] in order to establish its use and accuracy. The surrogate method (absolute [1] and ratio [6]) has been employed to circumvent technical challenges presented by the fabrica-

STARS: A Silicon Tele Reaction Sti

J.T. Burke

ope array for ΔE -E particle ident ng Department, University of California, B_t has been developed for use in light-ion reaction scope Array for Reaction Studies) is made up o detectors with contacts arranged in 24 concent sectors on the reverse side of each detector. The of the array has a maximum range of 30 degree The minimum and maximum scattering angle, the detectors may be varied depending on the in conjunction with Ge clover detectors at Yal lev National Laboratory (LiBerACE (Livermor Experiments)) facilitates the study of incomple The detectors were arranged in a cubic pattern around a 1 µCi ²⁵²Cf | development of the Surrogate Reaction Techniq

Segmented silicon detectors facilitate the st particular, the distinction between exit chan broader than predicted by theory, and no evidence of correlation with and ⁴He. This ability to clearly differentiate bined with gamma-ray counting in high-resc resulted in advancements over a wide variety nuclear physics. Because silicon is relatively arrays in existence throughout the community with CsI detectors and achieve outstanding rp-process nuclei have been studied in invernuclear equation of state with LASSA [?].

Preprint submitted to Elsevier

in.¹ J.T. Burke.¹ J. Phair. ^aLawrence Liverm ^bLawrence Berkele M.A. Stover,¹ and M ational Laboratory, Livermore

ley National Laboratory, Berkeley, C A silicon tele Coincident γ -rays from a ²⁵²Cf source were measured using an array germanium (HPGe) Clover detectors each enclosed by 16 bismuth-g

> Key words PACS

fragment pairs. Multiplicity distributions from previous experiments 1 Introduction convolved with the response function of the array and compared to results suggest a γ -ray multiplicity spectrum slightly broader than pre-

> telescope array previously described in [1]. The silicon telescope array for this experiment consisted of two S1 Micron detectors whose thicknesses were 140 micron and 1000 micron respectively. The silicon detectors had ad-jacent rings and sectors bussed together forming 24 rings and 8 sectors for each detector. The silicon telescop was located 33 mm downstream of the target location and covered an angular range of 19 to 45 degrees. Fis sion fragments were detected with a 140 micron thick

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I. INTRODUCTION

ole in many areas of basic and applied science. The synthesis of heavy elements by the astrophysical s-process [1] is influenced by the competition between radiative

sections are required to uncover the temperature and

correction. Over the five day run, alternately exposed to th alternately exposed to th alternately exposed to that index of the infinctilies associated with target radioactive provide events at rates of activation measurements using accelerator mass spec-undating deadline are run to the second second second second second to the second secon

For many nuclei, indirect methods will the only way to

A. Event can be used to determine compound-nuclear cross sec-

The particle singles da perimental results. The method involves creating the





