



Investigation of the surrogate-reaction method via the simultaneous measurement of gamma-emission and fission probabilities

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Need for neutron-induced cross sections on short-lived nuclei : reactor physics

		Bk 238 144 s		Bk 240 5 m	Bk 241 4.6 m	Bk 242	Bk 243	Bk 244 4.35 h	Bk 245	Bk 246 1.80 d	Bk 247 1380 a	Bk 248	Bk 249 320 d
		e βsf		e Bst	€ γ 262; 152; 211	st v	SI * 6.575 6.543 7 755,945 9	Sf a 8.662; 6.620 y 892; 218; 922 9	SI * a 5.888.6.150 y 253; 381 e g	ε γ 799; 1081; 834; 1124 e	α 5.531; 5.710; 5.688 γ 84; 265 9	μ=0.9 γ551 α? φ=? 4.?	$\begin{array}{c} \beta^{-} \ 0.1; \alpha \ 5.419; \\ 5.391 \dots; \ sf \\ \gamma \ (327; \ 308 \dots) \\ \sigma \ 700; \ \sigma_{I} \sim 0.1 \end{array}$
		Cm 237	Cm 238 2.4 h	Cm 239 3 h	Cm 240	Cm 241 32.8 d	Cm 242 162.94 d	Cm 243	Cm 244 18.10 a	Cm 245 8500 a	Cm 246 4730 a	Cm 247 1.56 · 10 ⁷ a	Cm 248 3.40 · 10 a
		α 6.656	€ α 6.558; 6.503 γ 55	κ γ 188 9	Sf a 6.291; 6.248 sf g	Sf 4 # 5 939 9 472; 431; 132 9" 9	Sf a 6.113; 6.069 sf; g \(\frac{44}{9}; e^- \(\sigma - 20\) \(\sigma_r \sigma 5\)	Sf a 5.765; 5.742 c. sf; g y 278; 228; 210; e o 130; o ₁ 620	ST a 5.805; 5.762 st; g y (43); e ⁻ a 15; a ₁ 1.1	ST α 5.361; 5.304 sf; g γ 175; 133 α 350; α; 2100.	α 5.386; 5.343 sf; g γ (45); e σ 1.2; σι 0.16	α 4.870; 5.267 γ 402; 278 g σ 60; σι 82	α 5.078: 5.035 st. γ. e ⁻ . g g [*] 2.6: m 0.36
Am 234 2.32 m	Am 235 10.3 m	Am 236	Am 237 73.0 m	Am 238	Am 239	Am 240 50.8 h	Am 241 432.2 a	Am 242	Am 243 7370 a	Am 244	Am 245 2.05 h	Am 246	Am 247 22 m
e βst	ε α 6.457 γ 291; 224; 270; 739; 749	* * * * * * * * * * * * * * * * * * *	Sf 4 α 6.042 γ 280; 438; 474; 909 0	Sf * + 5.94 + 963: 919: 561; - 605 - 9	Sf 4 # 5.774 7.278.228 9 9	ST 4 5.378 9 988, 689 9	Sf a 5.486; 5.443 sf; y 60; 26 s ⁻¹ ; g; a 60 + 640 ay 3.15	ST hy (49), e ⁻ α 5.208 st; γ (49) e ⁻ ; g σ 1700 = 330 σγ 5900 σγ 2100	SI a 5.275; 5.233 st; y 75; 44 o 75 + 5 a; 0.079	ST p ⁺ 1.5 p ⁺ 0.4 y (1084) 858 6 ⁺ ; g nj 1600 nj 2200	Sf 7 253: (241: 296) • 7 9	β ⁺ 1.2; β ⁺ 2.2, γ 679; γ 1079; 205; 799; 154; 1060; 756;	β γ 285; 226 e
Pu 233 20.9 m	Pu 234 8.8 h	Pu 235	Pu 236 2.858 a	Pu 237 45.2 d	Pu 238	Pu 239	Pu 240 6563 a	Pu 241	Pu 242 3.750 - 10 ⁵ a	Pu 243 4.956 h	Pu 244 8.00 - 10 ⁷ a	Pu 245	Pu 246 10.85 d
ε α 6.31 γ 235; 535	ε α 6.202; 6.151 γ; e ⁻	Sf 4 5.85 7.49; (750; 34) #*	ST st; Mg 26 y (46; 109); e ⁻ of 160	st 4 5.334 7 60 e ⁻ 9, 2300	ST #5.499; 5.456 #; Si; Mg 7 (43; 100); e ⁻ o 510; o ₁ 17	Sf o 5.157; 5.144 sf; y (52) o"; m o 270; o ₁ 752	ST α 5.168; 5.124 st; γ (45) e ⁻ ; g σ 290; σ ₁ ~0.059	Sf g ⁺ 0.02/g a 4.896 y (149); e ⁺ a 370; aj 1010	ST α 4.901; 4.856 δ[: γ (45) σ"; g σ 19; σ ₁ <0.2	ST β ⁺ 0.8 γ 84g σ<100, σ ₁ 200	ST x 4.589; 4.546 st; 7 e ⁻ o 1.7	ST y 327; 560; 3089 # 150	β ⁺ 0.2; 0.3 γ 44; 224; 180 m ₁
Np 232 14.7 m	Np 233 36.2 m	Np 234 4.4 d	Np 235 396.1 d	Np 236 225h 1.54-10 ⁵ a	Np 237	Np 238 2.117 d	Np 239 2.355 d	Np 240 7.22 m 65 m	Np 241 13.9 m	Np 242	Np 243 1.85 m	Np 244 2.29 m	
ε γ 327; 820; 867; 864; 282 e	ε α 5.54 γ(312; 299; 547)	ε; β ⁺ γ 1559; 1528; 1602 σt-900	ε; α 5.025; 5.007 γ(26; 84); e g; σ 160 + ?	ε: β ⁺⁺ 0.5, ε: β ⁺⁻ , α γ (642; γ 160; 688); e ⁺⁻ 104; e ⁺⁻ g; α ₁ 2700 g; σ ₁ 3000	S1 α 4.790; 4.774 γ 29; 87; e ⁻ σ 170; σ ₁ 0.020	β ⁻ 1.2 γ 984; 1029; 1026; 924; e ⁻ g; σ; 2600	$\begin{array}{c} \beta^{-} \ 0.4; \ 0.7 \\ \gamma \ 106; \ 278; \\ 228; \ e^{-}; \ g \\ \sigma \ 32 + 19; \ \sigma_1 < 1 \end{array}$	β ⁻ 2.2 β ⁻ 0.9 γ 555; γ 566; 597 974; e ⁻ 601; h ₇ ;g 448;g	β 1.3 γ 175; (133) 9	8 2.7	β γ 288 9	β γ 217; 681; 163; 111 9	152
U 231 4.2 d	U 232 68.9 a	U 233 1.592 · 10 ⁵ a	U 234 0.0054	U 235 0.7204	U 236	U 237 6.75 d	U 238 99.2742	U 239 23.5 m	U 240 14.1 h		U 242 16.8 m		
ε; α 5.456; 5.471; 5.404 γ 26; 84; 102 ε ⁻ ; σ ₁ -250	α 5.320; 5.262 Ne 24; γ (58; 129); e σ 73; σ; 74	α 4.824; 4.783 Ne 25; γ (42; 97); e ⁻ σ 47; σ; 530	2.455 · 10 ⁵ a a 4.775 4.723, sl Mg 28. Ne; y (53, 121) e ⁻ , a 96; og 0.07	26 m 7.038-10 ⁸ a 1 y (0.07) e ⁻ x 185 st e ⁻ x 55. m 586	4.494; 4.445; 542 51; γ (49; 542 113) e ⁻ ; σ 5.3	β 0.2 γ 60; 208 e σ ~100; σ ₁ <0.35	298 ns hy 2514 a 4.198 st 1505 257 y 50 e 27; y 50	β 1.2; 1.3 γ 75; 44 σ 22; σ ₁ 15	β ⁻ 0.4 γ 44; (190) e ⁻ m		β γ 68; 58; 585; 573 m		
Pa 230	Pa 231 3.276 · 10 ⁴ a	Pa 232	Pa 233 27.0 d	Pa 234	Pa 235 24.2 m	Pa 236 9.1 m	Pa 237 8.7 m	Pa 238 2.3 m	Pa 239 1.8 h				
ε; β ⁺⁻ 0.5 o 5.345; 5.326 y 952; 919; 455: 899; 444; σj 1500	a 5.014; 4.952; 5.026; Ne 24; F 237 y27; 300; 303; e a 200; m 0.020	β 0.3, 1.3,; « γ 969; 894; 150,; e σ 460; σ; 1500	β 0.3; 0.6 γ 312; 300; 341; e ⁻ σ 20 + 19; σ < 0.1	β ⁺ 23 β ⁺ 0.5; γ(1001; 1.2; γ(767,) γ(131; 881; h ₁ (74,), s ⁺ 683,s ⁺ η<500	β 1.4 γ 128 - 659 m	β 2.0; 3.1 γ 642; 687; 1763; g βsf ?	β 1.4; 2.3 γ 854; 865; 529; 541	β 1.7; 2.9 γ 1015; 635; 448; 680 9	β γ 522-681		150		
Th 229 7880 a	Th 230 7.54 · 10 ⁴ a	Th 231 25.5 h	Th 232	Th 233 22.3 m	Th 234 24,10 d	Th 235 7.1 m	Th 236 37.5 m	Th 237 5.0 m	Th 238 9.4 m				
α 4.845; 4.901; 4.815; γ 194; 211; 86; 31; e ⁻	α 4.687; 4.621 γ (68; 144); e Ne 24; σ 23.4	β 0.3; 0.4 γ 26; 84	1.405 · 10 ¹⁰ a ~ 4.013; 3.950; st ~ (64); e ⁻	β 1.2 γ 87: 29: 459, e ⁻	β ⁺ 0.2 γ 63; 92; 93 e ⁻ ; m	β 1.4 γ 417; 727;	β 1.0 γ 111; (647;	97	β ⁻ 				

Very difficult or even impossible to measure!



"The fundamental role of fission during r-process nucleosynthesis in neutron star mergers", S. Goriely, Eur. Phys. J. A (2015) 51: 22

Surrogate-reaction method

Cramer and Britt (Los Alamos 1970...!)



Validity of the surrogate method

$$\boldsymbol{\sigma}_{n,decay}^{A}(E^{*}) = \boldsymbol{\sigma}_{CN}^{A+1}(E^{*}) \cdot P_{decay}^{surro}(E^{*})$$

Neutron-induced and surrogate reaction must lead to the formation of a compound nucleus : Decay only depends on E^* , J and π !!

$$P_{decay}^{surro}(E^*) = P_{decay}^n(E^*)$$

Populated J and π distributions are equal

Decay independent of J and π (Only valid at high E* in the Weisskopf-Ewing limit)

Not possible to say a priori if a reaction meets these conditions. Data obtained with the surrogate method need to be compared to neutron-induced data!

Results for fission



Results for radiative capture



The cross sections obtained with surrogate method are in clear disagreement with ninduced data for capture!

G. Boutoux et al., Phys. Lett. B 712 (2012) 319

Why do we obtain such discrepancies?



Strong sensitivity of neutron emission to $J\pi$

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Preliminary results!

3He + 208Pb-> 4He + 207Pb↔ n + 206Pb



Can we apply the statistical model to try to reproduce our gamma-emission probability?

PhD Thesis of R. Perez, University of Bordeaux

Fission seems to be much less sensitive to spin/parity differences, why?



The region near the fission Barrier is also a region of low density of states!

The suppression of neutron emission should also affect the fission probability! First step to understand: Simultaneous measurement of fission and gamma-decay probabilities! Never done before!

Setup for simultaneous measurement of fission and gamma-decay probabilities



Challenge: removal of gamma rays emitted by the fission fragments !

$$N_{ejec-\gamma}^{coin}(E^*) = N_{ejec-\gamma}^{coin,tot}(E^*) - \frac{N_{ejec-f-\gamma}^{coin}(E^*)}{\mathcal{E}_f(E^*)}$$

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Setup used for experiment at the Orsay tandem



Fission efficiency ~ 65% Gamma detection efficiency ~ 6%

Preliminary results!

3He + 238U-> d + 239Np ↔ n + 238Np (2,1d)

P. Marini et al., to be published

Preliminary results!

3He + 238U-> 4He + 237U ↔ n + 236U

P. Marini et al., to be published

The fission probability is much less sensitive to the entrance channel than the gamma-decay probability!

P. Marini et al., to be published

d + 238U-> p + 239U ↔ n + 238U

→ Problem: deuteron breakup, corrected with method based on CDCC and DWBA
by J. Lei and A. Moro Phys. Rev. C 92(2015) 044616
Breakup fusion contribution :Imaginary part of the n-238U optical potential was
divided into two , one part corresponding to CN formation

Q. Ducasse et al., Phys. Rev. C 94 (2016) 024614

Can we explain these results within the framework of the statistical model?

$$P_{surro,decay}(E^*) = \sum_{J^{\pi}} P_{surro}^{form}(E^*, J^{\pi}) \cdot G_{decay}(E^*, J^{\pi})$$

Interpretation of results: 238U(3He,4He)237U

Preliminary calculations based on extended R-Matrix theory

Preliminary results!

3He + 238U-> 4He + 237U

O. Bouland, contribution to ND2016

Surrogate data can be used to tune model parameters in order to infer n-induced cross sections.

Perspectives

4He+240Pu 4He + 240Pu-> 4He' + 240Pu* ↔ n + 239Pu

240Pu: Even-even fissioning nucleus expected to be more sensitive to spin/parity differences!

Good-quality n-induced data available!

Experiment expected in April 2017 at the Tandem of the IPN Orsay

Perspectives

Measurements in direct kinematics are limited by the availability and the quality of the targets!

Experiments in inverse kinematics with RIBs!

But, RIBs have low quality: large dispersion in energy (few MeV) and size (few mm)

Decay-probability measurements inside a storage ring

Experimental Storage Ring (ESR) at GSI

•Excellent beam –energy definition, beam-energy resolution of few hundreds keV at 10 A MeV, beam size 1 mm!! •In-ring measurements with gas-jet targets (H2, D2, 3He, 4He) with **10¹⁴/cm².** Effective target thickness increased by ~10⁶ due to revolution frequency •Pure beams, pure targets (no contaminants, no backing)! •Pure isomeric beams! •Measurements possible at the ESR at GSI in the near future

First reaction cross-section measurement at the ESR! B. Mei et al., Phys. Rev. C 92 (2015) 035803

Decay-probability measurements inside a storage ring

Conclusions and questions...

- First simultaneous measurement of gamma-decay and fission probabilities for surrogate reactions
- The fission probability is much less sensitive to the populated angular momentum than the gamma-decay probability
- Can we use the surrogate method to infer neutron-induced fission cross sections in regions where no data are available?
- How well can we predict n-induced CN formation cross sections far from stability?
- γ & particle-emission prob. are useful to constrain statisticalmodel calculations, provided that the populated J^π distributions are known. What information do we need to calculate them?
- Very promising perspectives open up for decay probability measurements in inverse kinematics with RIBs at storage rings to help answering these questions.

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