International Atomic Energy Agency

Compilation of Nuclear Resonance Fluorescence (NRF) Data

(see also WP2011-14 = Memo CP-D/703)

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Nuclear Resonance Fluorescence (NRF) in Actinides

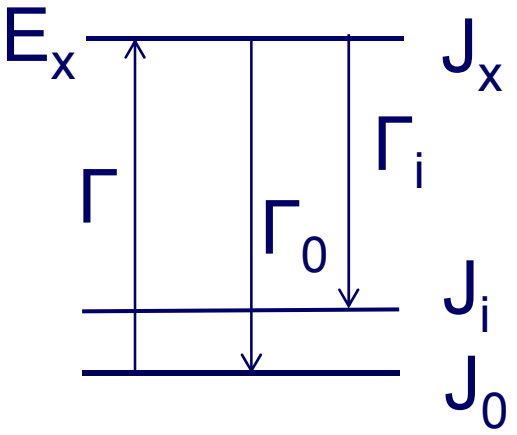
- What is NRF = excitation by photons of a specific resonance in nucleus
  (so called scissor M1 and E1 dipole mode in deformed nuclei)
  and consequent decay by prompt γ-ray emission
  to the ground or excited states = (γ,γ) and (γ,γ')
- First time observed – in 238U and 232Th by R.D. Heil et al., NP A476(1988)39
- Practical importance – non-destructive assay of clandestine **nuclear**, toxic and explosive materials (safeguards of nuclear materials is IAEA mission)
- NRF is being added to ENDF photon library and MCNPX (generate search of exp.data)
- So far 10 experiments performed with Bremsstrahlung and Laser-Compton Scattering:

Target	γ-src	E resonance MeV		Lab.	Author	Journal	Vol	Page	Year	Data	Entry	Remarks
U238	BRST	2.043	2.468	2GERIFS	R.D. Heil+	J,NP/A	476	39	1988	Table	G0028.002	in compil.
U236	BRST	1.791	3.143	2GERIFS	J. Margraf+	J,PR/C	42	771	1990	Table	G0027.002	in compil.
U238	BRST	1.782	1.846	2GERIFS	A. Zilges+	J,PR/C	52	468	1995	Table	G0026.002	in compil.
U235	BRST	1.687	1.862	2GERTHD	O. Yevetska+	J,PR/C	81	044309	2010	Table	G0024.002	prelim.g022
U235	BRST	1.656	2.006	1USAMIT	W. Bertozzi+	J,PR/C	78	041601	2008	Table	L0139.002	prelim.l015
Pu239	BRST	2.040	2.471	1USAMIT	W. Bertozzi+	J,PR/C	78	041601	2008	Table	L0139.003	prelim.l015
Mn55	*BRST*	*1.884*		*1USAMIT*	*W. Bertozzi+*	*J,PR/C*	*78*	*041601*	*2008*	*Number*	*L0139.004*	*prelim.l015*
Np237	BRST	1.698	2.506	1USAMIT	C.T. Angell+	J,PR/C	82	054310	2010	Table	L0155.002	prelim.l015
Th232	LCS	2.044	4.002	1USATNL	A.S. Adekola+	J,PR/C	83	034615	2011	Table	L0159.002	prelim.l015
U235	LCS	1.656	2.755	1USATNL	E. Kwan+	J,PR/C	83	041601	2011	Table	NNDC	

Nuclear Resonance Fluorescence – basic physics

- What is measured – energy integrated cross sections [eV-b]:

$$\sigma\left(E_x, E_i\right) = 2\left(\frac{\pi\hbar c}{E_x}\right)^2 g\,\frac{\Gamma_0\Gamma_i}{\Gamma^2}$$



where $g = \dfrac{2J_x + 1}{2(2J_0 + 1)}$ - statistical factor

J_0 and J_i - spins of the ground and excited states,

Γ_o and Γ_i: - gamma decay widths to ground and excited states (meV)

Γ - sum of all them,

E_x, J_x - resonance (incident gamma) energy and spin,

$E_i = E_x - E_{lvl}(i)$ – energy of decay γ-ray populating the i-th level

Nuclear Resonance Fluorescence Data – example BRST

W. Bertozzi et al. “Nuclear resonance fluorescence excitations near 2 MeV in 235U and 239Pu”, Phys.Rev. C 78, 041601(R) (2008)

INC-Source - Bremsstrahlung photons ,e-beam on Au target, smooth spectrum up to End-point energy 2.2 MeV

Normalization – to 1884-keV resonant line of 55Mn
(which in turn was normalised to well known 2211kev 27Al)

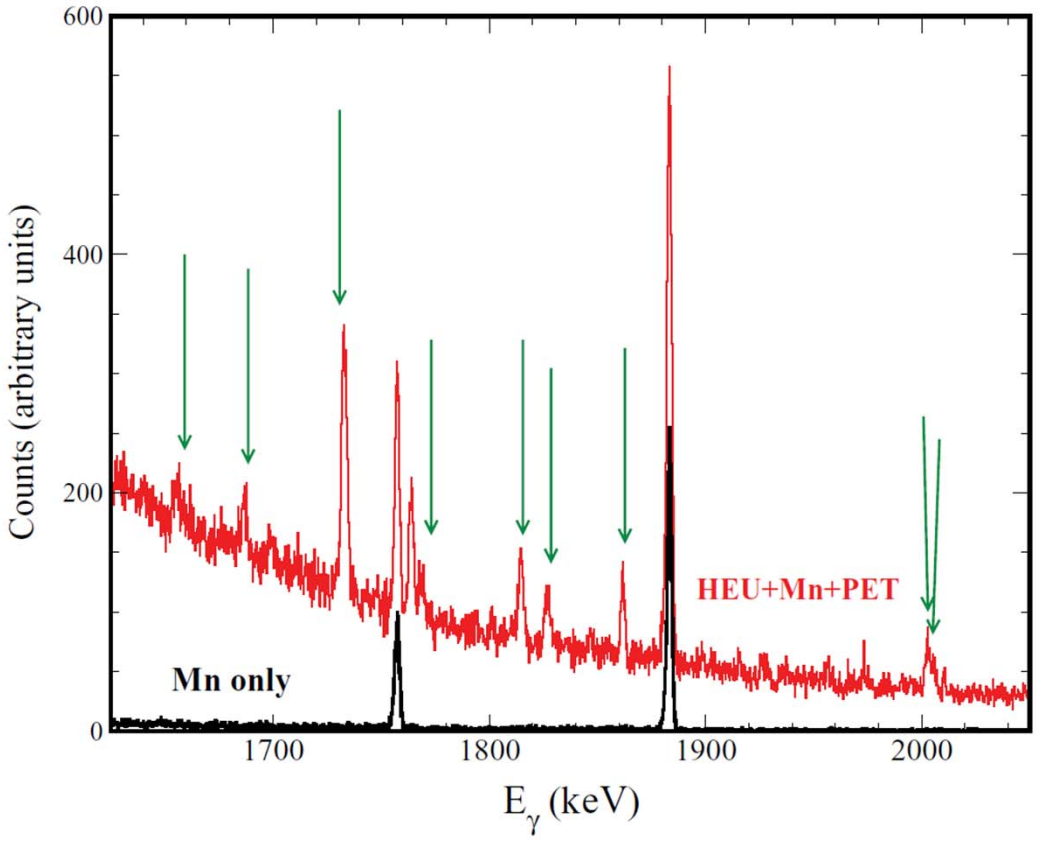


TABLE I. Results from significant γ-ray transitions associated with ^{235}U and ^{239}Pu. Given in the table are isotope, transition energies, statistical significance, and cross sections. The daggers and asterisks are explained in the text.

Isotope	Transition (keV)	Statistical significance	Cross section (eV·b)
^{235}U	1656.23(80)	5.8	4.1(13)
	1687.26(33)†	10.2	6.1(11)
	1733.60(22)†	56.4	29.8(39)
	1769.16(28)‡	9.3	4.4(10)
	1815.31(22)‡	19.9	9.7(17)
	1827.54(23)	13.3	6.7(12)
	1862.31(20)	20.1	9.6(17)
	2003.32(25)	14.5	9.7(17)
	2006.19(31)	7.2	4.7(16)
^{239}Pu	2040.25(21)	5.8	8(2)
	2046.89(31)	4.2	5(2)
	2135.00(37)*	3.5	4(2)
	2143.56(13)*	9.7	13(2)
	2150.98(31)*	4.2	5(2)
	2289.02(25)	6.2	8(2)
	2423.48(22)**	7.2	10(2)
	2431.66(25)**	6.3	9(3)
	2454.37(26)	6.2	9(3)
	2460.46(37)	4.7	6(4)
	2464.60(30)	5.7	8(4)
	2471.07(34)	4.6	6(2)

Nuclear Resonance Fluorescence – example LCS

E.Kwan, "Discrete de-excitations in ^{235}U below 3 MeV from NRF", Phys.Rev C83,041601(2011):
free electron laser light scattered on e-beam – varying photons energy 1.6-3.0MeV with spread 3%
Incident g-flux (after Compton scattering on Cu plate) - was measured by HPGe

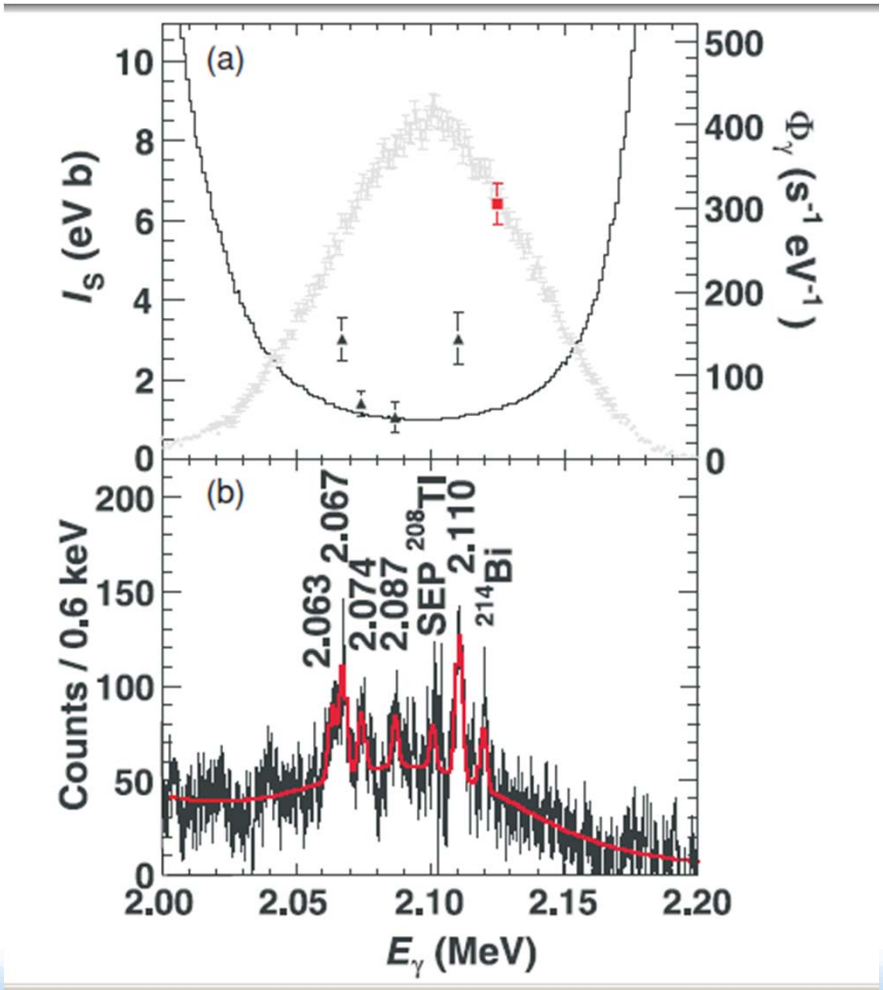


TABLE I. Transitions observed from ^{235}U in the present work. The integrated cross sections, widths, and intensity ratios relative to the intensity of the ground-state transition determined in this work are given.

E_x[a] (keV)	E_γ[b] (keV)	J_f^π[c]	I_S[d] (eVb)	$\frac{g\Gamma_0^2}{\Gamma}$[e] (meV)	R[f]
1656.3(7)	1656.4(7)	7/2$^-$	3.0(11)	2.1(8)	1
1733.6(2)	1687.0(5)	9/2$^-$			0.6(2)
	1733.6(2)	7/2$^-$	22(4)	17(3)	1
1769.3(4)	1769.3(4)[g]	7/2$^-$	6.4(15)	5.2(12)	1
1815.2(2)	1769.3(4)[g]	9/2$^-$			0.62(4)
	1815.2(2)	7/2$^-$	8.9(11)	7.7(9)	1
1827.7(2)	1782.1(6)[h]	9/2$^-$			0.45(18)
	1827.6(2)	7/2$^-$	5.5(13)	4.8(12)	1
1862.4(1)	1862.4(1)	7/2$^-$	9.6(7)	8.7(7)	1
1973.8(3)	1973.8(3)	7/2$^-$	4.6(6)	4.7(6)	1
2003.3(2)	1957.4(2)	9/2$^-$			0.62(13)
	2003.0(3)	7/2$^-$	6.7(12)	7.0(13)	1
2005.9(4)	2005.9(4)	7/2$^-$	4.6(9)	4.8(9)	1
2010.6(3)	2010.6(3)	7/2$^-$	3.0(5)	3.2(6)	1
2067.1(4)	2067.1(4)	7/2$^-$	3.0(5)	3.4(6)	1
2074.2(3)	2074.2(3)	7/2$^-$	1.4(3)	1.5(4)	1
2086.7(6)	2086.7(6)	7/2$^-$	1.1(4)	1.2(4)	1
2110.2(3)	2063.3(6)	9/2$^-$			0.51(13)
	2110.4(3)	7/2$^-$	3.0(7)	3.5(8)	1
2216.1(3)	2216.1(3)	7/2$^-$	2.8(5)	3.6(6)	1
2416.1(3)	2416.1(3)	7/2$^-$	3.6(6)	5.4(9)	1
2555.6(6)	2555.6(6)	7/2$^-$	2.5(6)	4.3(10)	1
2754.7(4)	2754.7(4)	7/2$^-$	3.6(6)	7.2(11)	1

Nuclear Resonance Fluorescence Data – non Actinides

NRF observed in other nuclei:

Ti - Ba and Ce – Pt

J. Enders et al., Phys. Rev. C71, 014306 (2005) (review of measurements and theory)

K. Heyde et al., Rev. Mod. Phys., 82(2010)2365 (review of measurements and theory)

12C, 14N

T. Hayakawa, Rev. Sci. Instr. 80, 045110 2009

Conclusions

To cover NRF data in EXFOR:

Actinides

- **check completeness and correctness (physics and EXFOR rules) of Prelims**

Non Actinides

- **analyze published articles on relevance for EXFOR and ENSDF**
- **prepare list of article for compilation**