Inelastic Neutron Scattering: from Baghdad to Berkeley (aka Lee's talk)

L.A. Bernstein

5^{th} Workshop on Nuclear Level Density and Gamma Strength

University of Oslo, Norway

May 19, 2015

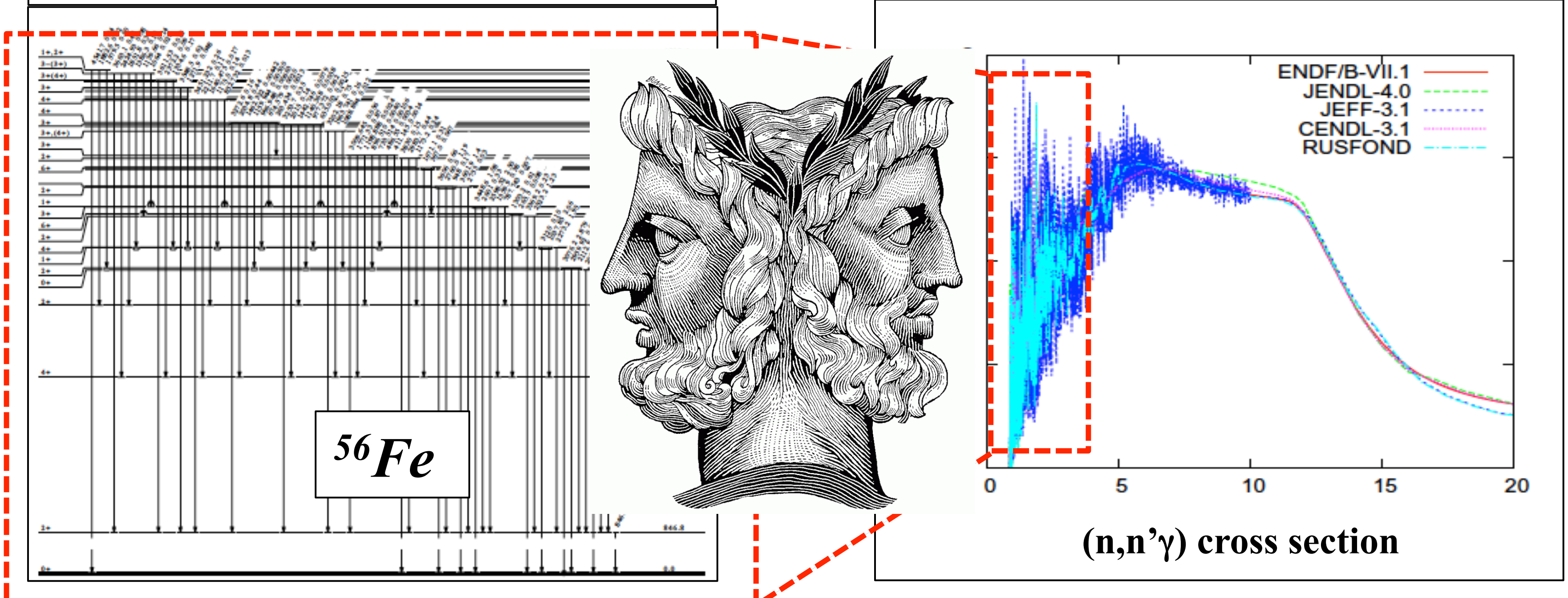
LLNL-PRES-pending

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 and Lawrence Berkeley National Laboratory under contract # DE-AC02-05CH11231.

(n,n'γ), like RSF, sits at the intersection of structure and reactions

Atlas (n,n'γ) data compilation

Evaluated (n,n'γ) cross sections

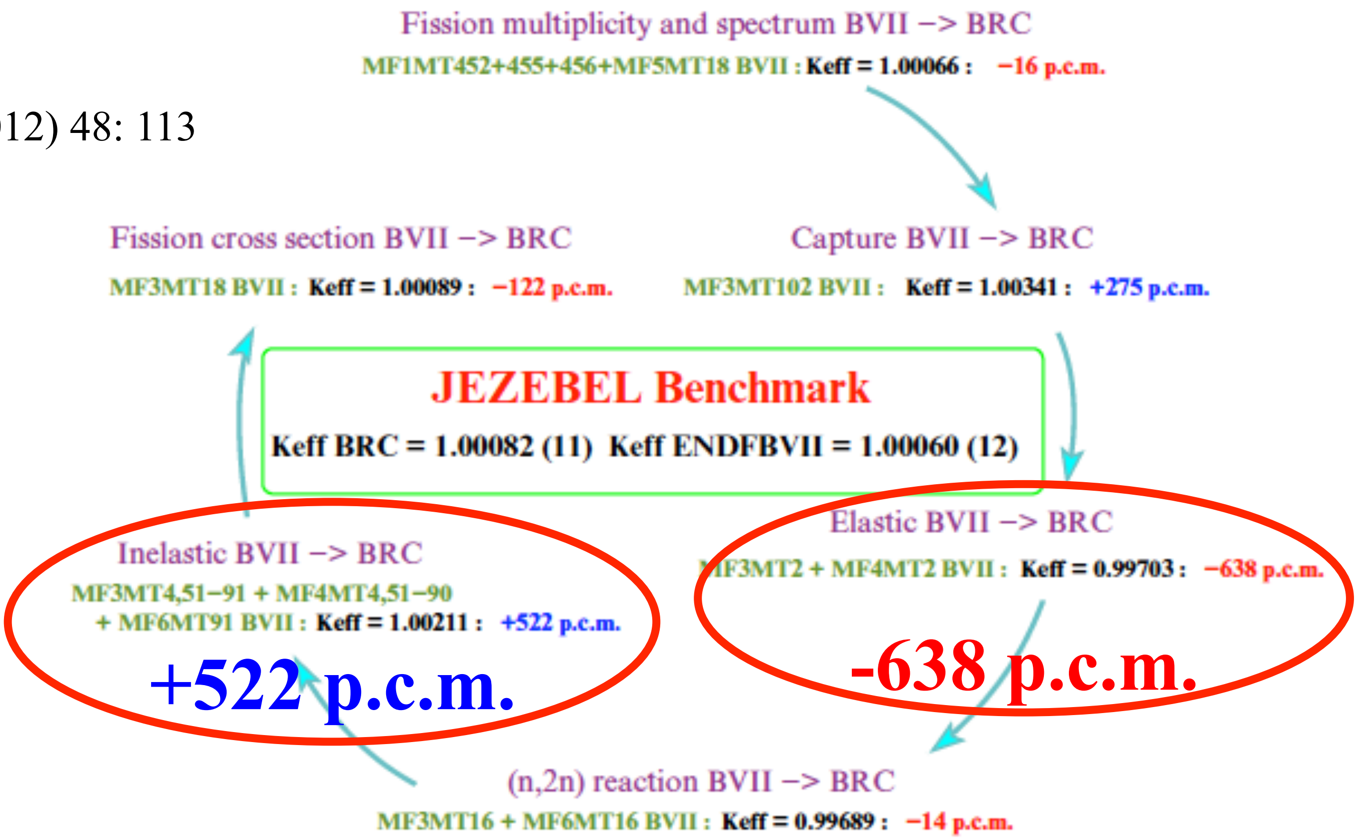


M.B. Chadwick** ***et al. NDS 118 (2014) 1-25

(n,n') for E_n < 10 MeV is very sensitive to low-lying nuclear structure and most of these cross sections remain unmeasured!

Bauge* highlighted the uncertainty in reaction databases for (n,n_{el}) and (n,n’) in a prompt fission neutron spectrum

*E. Bauge *et al.*,
Eur. Phys. J. A (2012) 48: 113

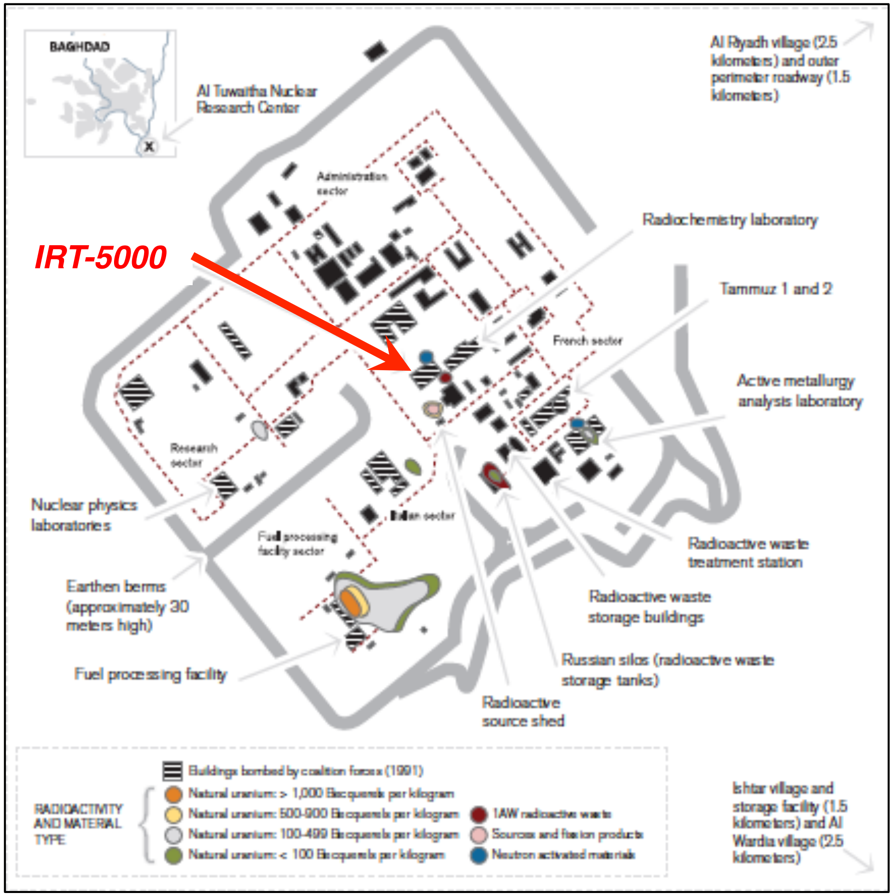


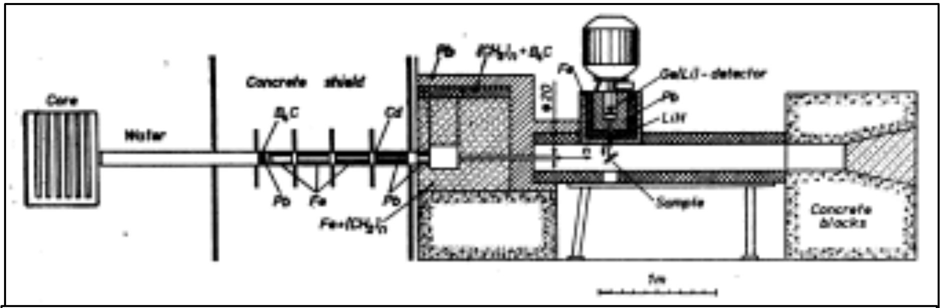
Other calls for (n,n’γ) data:
*“Below 2 MeV differences in ^{56}Fe(n,n’γ) are 28%”**
“New measurements (in ^{56}Fe) have been requested between 0.5-20 MeV” **

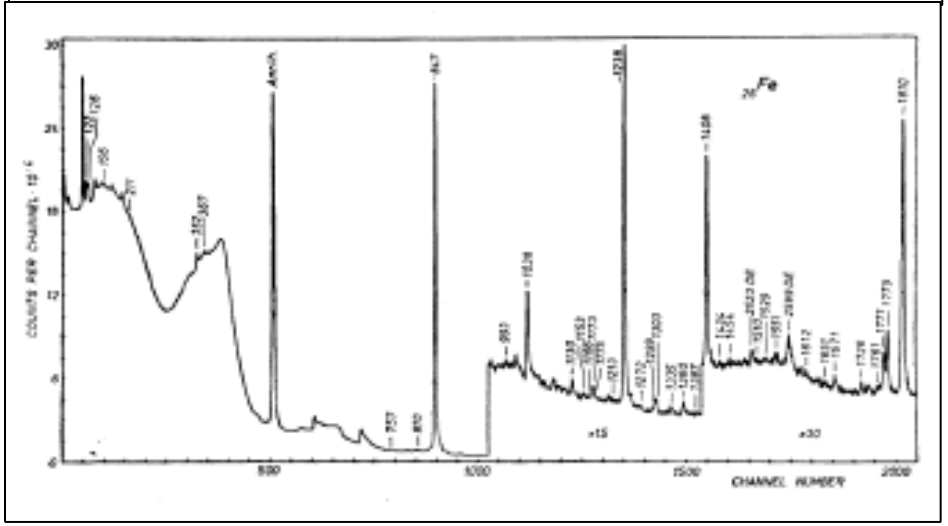
M.B. Chadwick *et al. NDS 118 (2014) 1-25
****http://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=454**

The most comprehensive collection of (n,n'γ) data was taken at the IRT-5000 reactor at the Al-Tuwaitha Nuclear Research Facility

Baghdad Nuclear Research Facility (Al-Tuwaitha)







The same set-up was used for all measurements ➔ *consistency*

Unfortunately, the facility was "decommissioned" by the US Air Force in 1991…

…and the IAEA is cleaning up the mess…

Fortunately, Andrej Trkov had a copy…

…that he sent to Rick…

…that he sent on to Brad Sleaford, Aaron Hurst and me

The data was released in the "Baghdad Atlas" (1978DE41) by *Demidov, Govor, Ahmed et al.,*

ATLAS
OF GAMMA-RAY SPECTRA FROM THE INELASTIC SCATTERING OF REACTOR FAST NEUTRONS

Atlas Specifics

- **7090 γ-rays**
- **105 targets, 75 elements**
  - **Separated Isotopes: Mo, Pd, Cd, Sn, Te, Sm, Dy, W**
- **Absolute γ-ray yields normalized to the ^{56}Fe 2 → 0 @ 847 keV**

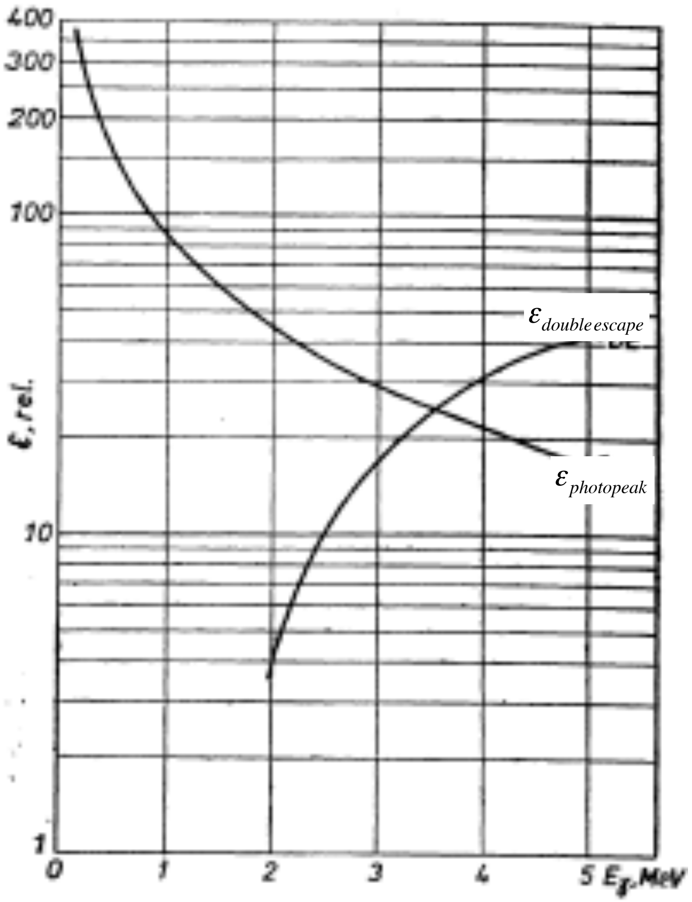
Level scheme of ^{56}Fe [68Gu, 70Ra5, 74La, 74Ti]

E_i	E_γ^0	J_i^π	E_γ	I_γ	E_f	J_f^π	P_x
846.79	846.8	2+	846.78	100	0	0+	68
2085.1(3)	2085.1	4+	1238.3	10.5	846.8	2+	5.3
2657.5(2)	2657.6	2+	2658.3	0.14	0	0+	6.4
			1810.5	6.9	846.8	2+	
2941.4(2)	2941.7	0+	2094.6	1.08	846.8	2+	1.1
2959.7(2)	2960.0	2+	2959.6	—	0	0+	3.3*
			2112.9	3.2	846.8	2+	
3120.0(2)	3120.0	1+	2273.2	2.03	846.8	2+	2.0
3122.9(3)	3123.0	4+	1037.85	2.15	2085.1	4+	1.8
3370.0(2)	3370.2	2+	3369.2	0.24	0	0+	1.5
			2523.2	1.28	846.8	2+	
3388.3(4)	3388.1	6+	1303.2	0.64	2085.1	4+	0.64
3445.37	3445.4	3+	2598.52	2.6	846.8	2+	3.0
			1359.9	0.40	2085.1	4+	
3448.7(4)	3449.3	1+	3448.6	1.13	0	0+	1.1
3602.0(3)	3601.9	2+	3601.9	1.5	0	0+	1.5
3606.9(3)	3607.0	0+	2760.0	1.24	846.8	2+	1.2
3756.2(6)	3755	6+	1671.1	0.32	2085.1	4+	0.32

Iron $_{26}$Fe

E_γ	I_γ	A_Z	E_i	E_γ	I_γ	A_Z	E_i
122.1(2)	2.2(2)	^{57}Fe	122.1	1165.9(6)	0.08(3)		
126.0(2)	1.6(2)	^{55}Mn	126.0	1173.?(8)	0.25(10)	^{56}Fe	3830.6
156.5(2)	0.40(10)	^{54}Mn	156.5	1175.0(8)	0.15(10)	^{56}Fe	4297.4
211.0(3)	0.22(3)	^{56}Mn	211.0	1213.0(7)	0.06(3)		
352.5c	1.6(2)	^{57}Fe	367.0	1238.3(2)	10.5(5)	^{56}Fe	2085.1
367.1(2)	0.54(5)	^{57}Fe	367.0	1271.9(10)	0.05(2)	^{56}Fe	4395.4
757.3(4)	0.10(3)	^{56}Fe	757.3	1298.9(4)	0.12(4)		
810.3(2)	0.43(3)	^{58}Fe	810.3	1303.2(3)	0.64(10)	^{56}Fe	3388.3
846.78c	100	^{56}Fe	846.8	1334.6(4)	0.18(3)	^{56}Fe	4457.6
992.8(4)	0.10(3)			1359.9(3)	0.40(4)	^{56}Fe	3445.4
1037.85c	2.15(10)	^{56}Fe	3122.9	1386.6(10)	0.06(3)		
1130.0(3)	0.39(4)	^{56}Fe	2538.2	1408.2(2)	3.5(2)	^{54}Fe	1408.2
1152.8(4)	0.14(3)	^{56}Fe	2561.0	1434.2(10)	0.05(2)		

The "Baghdad Atlas" included information about the target irradiation time and sample sizes to provide



Element	Sample	Mass, g	Exposition, h	E_γ	^{A}Z	I_γ(Fe), %
O	$Y(NO_3)_3 \cdot 6H_2O$	28.3	22.0	1983	^{16}O	0.11 (4)
F	^{6}LiF	11.1	22.6	1236	^{19}F	5.9 (7)
Na	NaOH	22.5	22.0	440	^{23}Na	139 (28)
Mg	Mg	7.9	24.7	1369	^{24}Mg	28 (3)
Al	Al	11.0	14.1	1014	^{27}Al	28 (3)
Si	Si	13.0	37.2	1779	^{28}Si	27.0 (25)
P	P_2O_5	13.2	21.3	1266	^{31}P	21 (3)
S	S	23.7	14.3	2230	^{32}S	15.1 (20)
Cl	C_6Cl_6	7.0	22.0	1220	^{35}Cl	5.2 (5)
K	KOH	24.0	25.5	2814	^{39}K	2.6 (4)
Ca	Ca	11.3	24.2	3904	^{40}Ca	2.2 (4)
Sc	$Sc + Sc_2O_3$	6.4+6.0	24.0	364	^{45}Sc	28 (4)
Ti	Ti	24.5	13.5	983	^{48}Ti	77 (8)
V	V_2O_5	14.2	22.9	320	^{51}V	115 (16)
Cr	Cr	23.5	24.8	1434	^{52}Cr	52 (6)
Mn	MnO_2	32.8	24.7	858	^{55}Mn	16.8 (18)
Fe	Fe_2O_3	17.4	8.0	847	^{56}Fe	100

ε_{det} and target thickness info was provided to allow γ-yield normalization to the ^{56}Fe 2 → 0 @ 847 keV

The non-proliferation community at LLNL started the process of compiling the Atlas

The Atlas was scanned and OCR-ed (Sleaford)

$E\gamma$	$I\gamma$	Az	Ei	Az	Ei	Eai	$J\pi i$	$E\gamma$	$I\gamma$	Ef	$J\pi f$	Ps
Boron			**5B**	**Level schemes of 10B [66La] and 11B [68Aj, 71Br]**								
477.7 (2)	1048 (50)	7Li	478	10B	718.21 (15)	717	1+	718	38	0	3+	27
718.18 (15)	38 (8)	10B	718		1739.6 (4)	1740	0+	1021	5	718	1+	1.6*
1021.4 (3)	4.7 (7)	10B	1740		2154.9 (6)	2154	1+	2155	1	0	3+	4.3*
1436.5 (5)	1.6 (4)	10B	2155					1437	2	718	1+	
2124.0 (3)	100	11B	2124		3585.9 (10)	3585	2+	2867	4	718	1+	7.4*
2155.0 (6)	1.1 (4)	10B	2155	11B	2124.3 (3)	2124	1/2-	2124	100	0	3/2-	95
2867.3 (8)	4.2 (8)	10B	3586		4443.2 (9)	4444	5/2-	4442	38	0	3/2-	38
2895.1 (8)	4.6 (8)	11B	5020		5019.8 (11)	5021	3/2-	5018	18	0	3/2-	23
4442.2 (9)	38 (8)	11B	4443					2895	5	2124	1/2-	
5018.4 (12)	18 (3)	11B	5020									

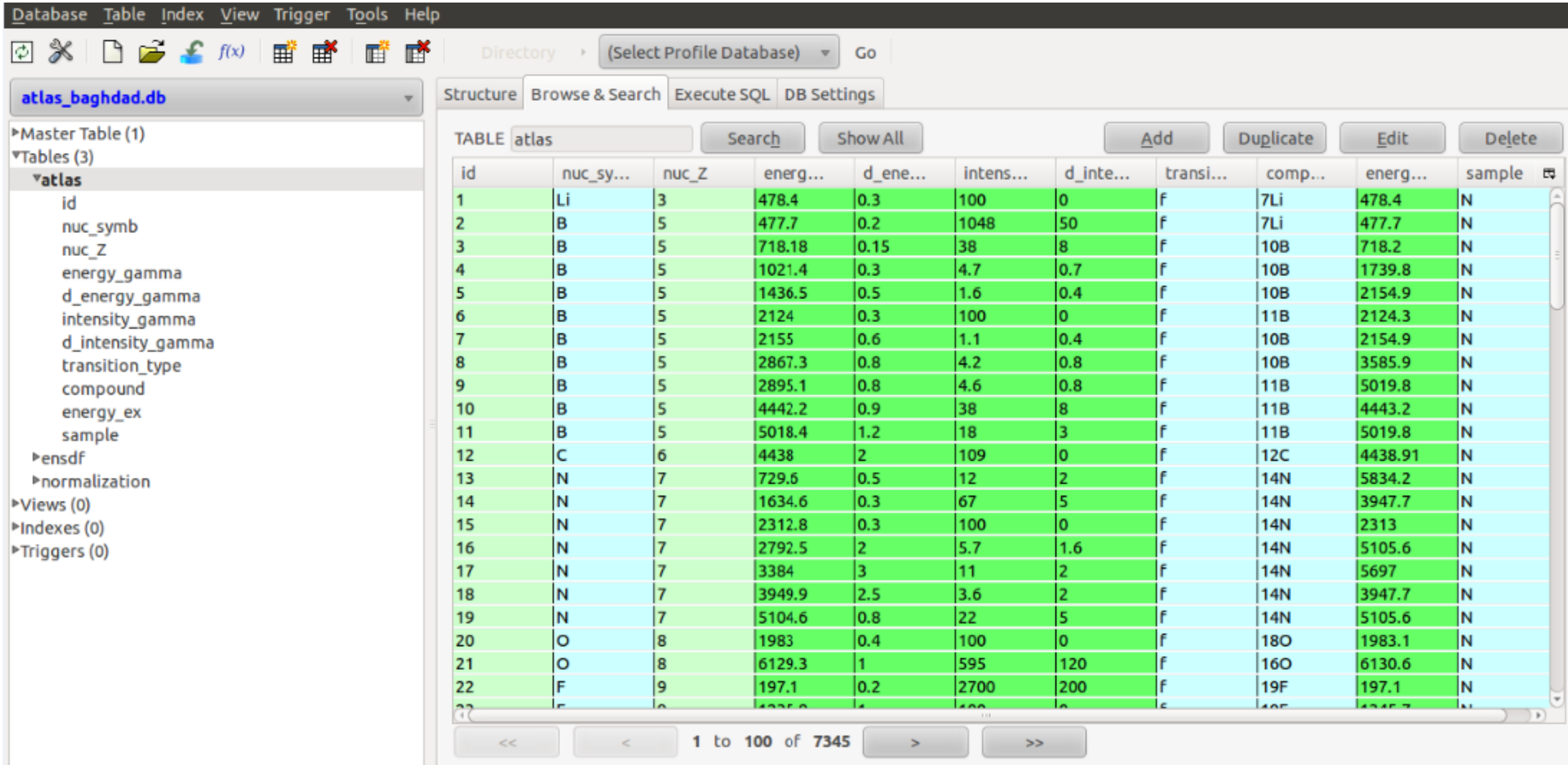
Data was converted into an excel spreadsheet and normalized to the 847 keV ^{56}Fe line (Walston)

```
=IF((LEN(I636)>0),$P$3*I636*0.01*$M$634*0.01,"")
```

	A	B	C	D	E	G	I	M	R	S
	E_γ (keV)	I_γ	A_Z	E_i (keV)	E_γ (keV)	E_γ error (keV)	I_γ (%)	I_γ (Fe) (%)	$\sigma_{n,n'\gamma}$ (mb)	Error on $\sigma_{n,n'\gamma}$ (mb)
625	**Iron**			**26Fe**	Iron					
626	122.1(2)	2.2(2)	57Fe	122.1	122.1	0.2	2.2		10.296	0.936
627	126.0(2)	1.6(2)	55Mn	126	126.0	0.2	1.6		7.488	0.936
628	156.5(2)	0.40(10)	54Mn	156.5	156.5	0.2	0.40		1.872	0.468
629	211.0(3)	0.22(3)	56Mn	211	211.0	0.3	0.22		1.0296	0.1404
630	352.5c	1.6(2)	57Fe	367	352.5		1.6		7.488	0.936
631	367.1(2)	0.54(5)	57Fe	367	367.1	0.2	0.54		2.5272	0.234
632	757.3(4)	0.10(3)	53Fe	757.3	757.3	0.4	0.10		0.468	0.1404
633	810.3(2)	0.43(3)	58Fe	810.3	810.3	0.2	0.43		2.0124	0.1404
634	**846.78c**	**100**	**56Fe**	**846.8**	**846.78**		**100**	100	**468**	
635	992.8(4)	0.10(3)			992.8	0.4	0.10		0.468	0.1404
636	**1037.85c**	**2.15(10)**	**56Fe**	**3122.9**	**1037.85**		2.15		**0.01,"")**	**0.468**
637	1130.0(3)	0.39(4)	54Fe	2538.2	1130.0	0.3	0.39		1.8252	0.1872
638	1152.8(4)	0.14(3)	54Fe	2561	1152.8	0.4	0.14		0.6552	0.1404

The data can be easily converted to ENSDF format using xls2ens

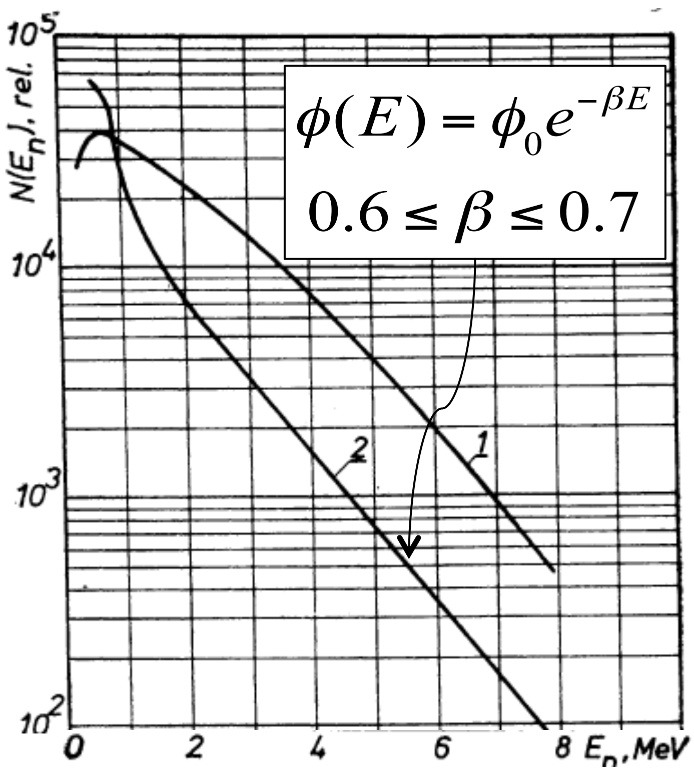
Aaron Hurst translated the Atlas into an SQL database



id	nuc_sy...	nuc_Z	energ...	d_ene...	intens...	d_inte...	transi...	comp...	energ...	sample
1	Li	3	478.4	0.3	100	0	f	7Li	478.4	N
2	B	5	477.7	0.2	1048	50	f	7Li	477.7	N
3	B	5	718.18	0.15	38	8	f	10B	718.2	N
4	B	5	1021.4	0.3	4.7	0.7	f	10B	1739.8	N
5	B	5	1436.5	0.5	1.6	0.4	f	10B	2154.9	N
6	B	5	2124	0.3	100	0	f	11B	2124.3	N
7	B	5	2155	0.6	1.1	0.4	f	10B	2154.9	N
8	B	5	2867.3	0.8	4.2	0.8	f	10B	3585.9	N
9	B	5	2895.1	0.8	4.6	0.8	f	11B	5019.8	N
10	B	5	4442.2	0.9	38	8	f	11B	4443.2	N
11	B	5	5018.4	1.2	18	3	f	11B	5019.8	N
12	C	6	4438	2	109	0	f	12C	4438.91	N
13	N	7	729.6	0.5	12	2	f	14N	5834.2	N
14	N	7	1634.6	0.3	67	5	f	14N	3947.7	N
15	N	7	2312.8	0.3	100	0	f	14N	2313	N
16	N	7	2792.5	2	5.7	1.6	f	14N	5105.6	N
17	N	7	3384	3	11	2	f	14N	5697	N
18	N	7	3949.9	2.5	3.6	2	f	14N	3947.7	N
19	N	7	5104.6	0.8	22	5	f	14N	5105.6	N
20	O	8	1983	0.4	100	0	f	18O	1983.1	N
21	O	8	6129.3	1	595	120	f	16O	6130.6	N
22	F	9	197.1	0.2	2700	200	f	19F	197.1	N

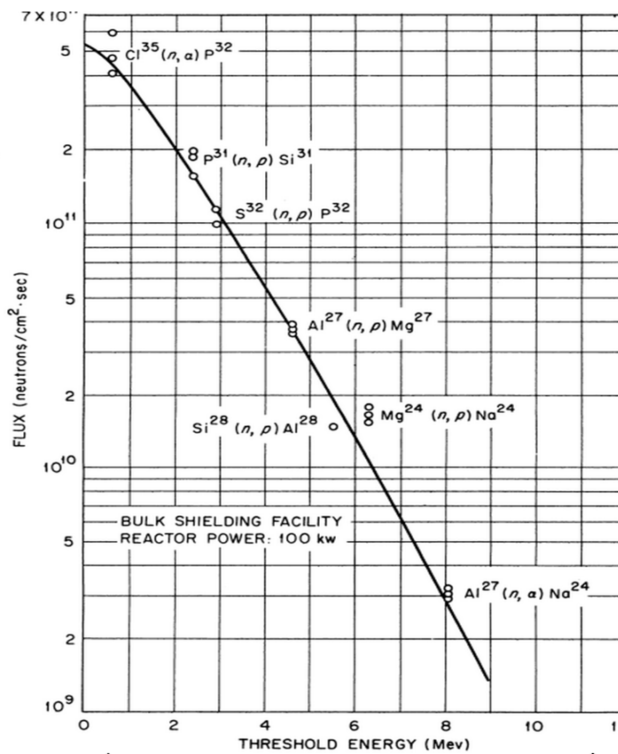
- GUI can be used to manipulate data or execute SQL code
- All γ-ray information from the ATLAS entered.

The energy dependence of the reactor neutron flux ($\Phi_\nu(E_\nu)$) is based on a set of activation measurements



$$\phi(E) = \phi_0 e^{-\beta E}$$

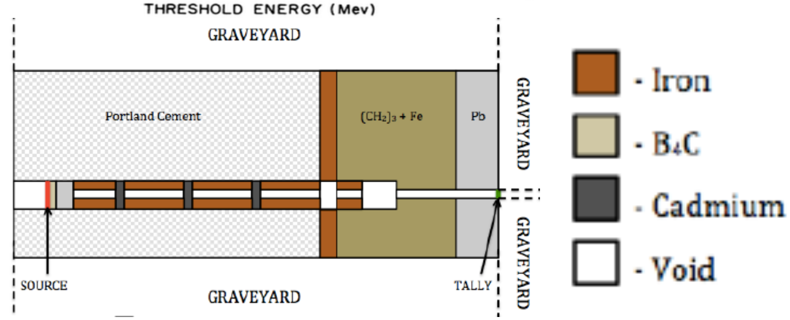
$$0.6 \le \beta \le 0.7$$



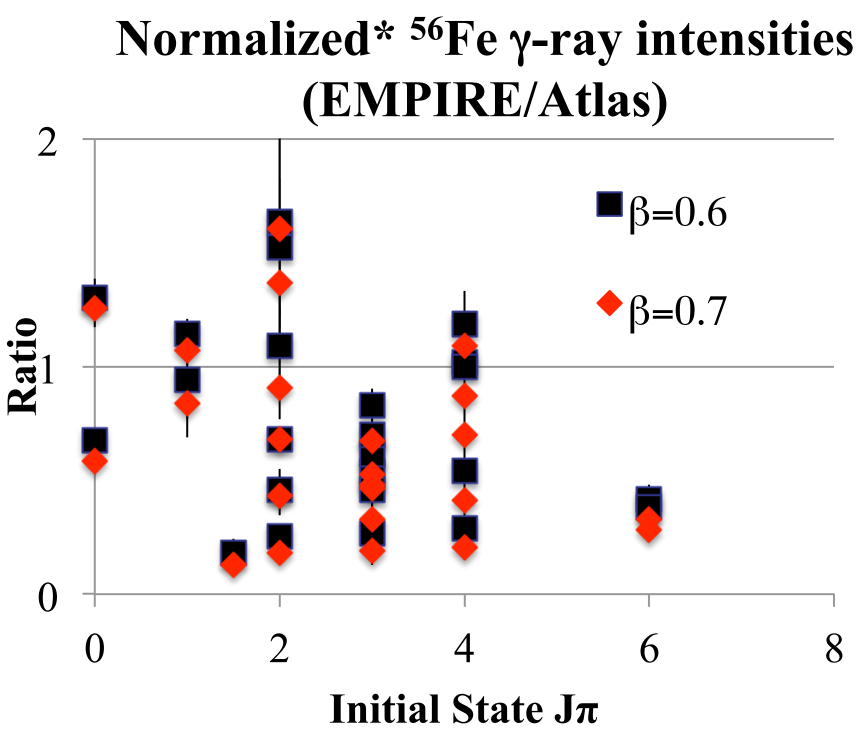
Inelastic neutron scattering in the region A=11-40 ,
L. Nichol and T. j. Kennet

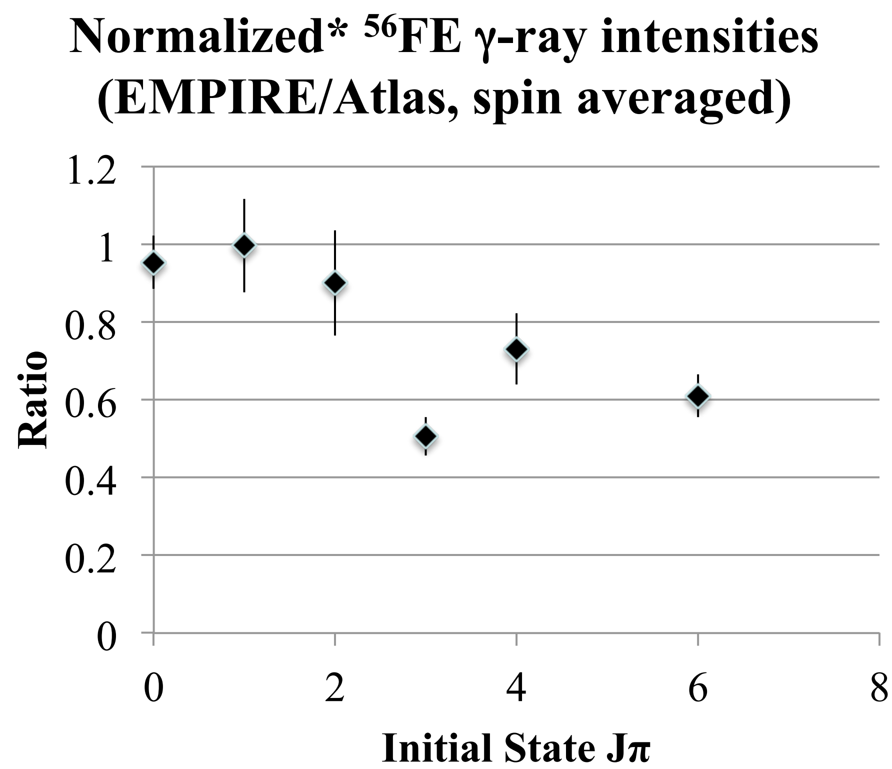
NUCLEAR REACTION	THRESHOLD ENERGY (Mev)
$S^{32}(n,p)P^{32}$	2.9
$P^{31}(n,p)Si^{31}$	2.4
$Cl^{35}(n,\alpha)P^{32}$	0.5**
$Al^{27}(n,p)Mg^{27}$	4.6
$Al^{27}(n,\alpha)Na^{24}$	8.1
$P^{31}(n,\alpha)Al^{28}$	
$Si^{28}(n,p)Al^{28}$	5.5

Neutron transport is being modeled by R. Slaybaugh and students @ UC



Modeling of the partial γ-ray cross sections using EMPIRE and TALYS (I. Abramovic) show little sensitivity to $\Phi_\nu(E_\nu)$





Deviations between the Atlas and EMPIRE can be used to point to deficiencies in the low-lying off-yrast structure, *ρ(J)* etc.

*All γ-rays normalized to the yrast $2^+ \rightarrow 0^+$

Demidov *et al.*, recognized the value of (n,n'γ) as a tool for nuclear structure studies (2004DE49)

Physics of Atomic Nuclei, Vol. 67, No. 10, 2004, pp. 1884–1891. Translated from Yadernaya Fizika, Vol. 67, No. 10, 2004, pp. 1908–1915.

NUCLEI

PHYSICAL REVIEW C **81**, 037304 (2010)

Employi… Intr… …neously …^{6}Fe

First 3^- excited state of ^{56}Fe

N. Fotiades,* R. O. Nelson, and M. Devlin

Russian R… Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA …32 Russia

(Received 4 February 2010; published 31 March 2010)

Abstract—Reactions of the (n,nγ) type proceed through a compound-nucleus stage; therefore, the excitation cross section is usually independent of the level nature. Accordingly, all of the excited states must manifest themselves in such reactions through γ transitions (with allowance for their internal conversion). ***In comparing the energy-level and γ-transition diagrams obtained in investigating γ rays from the inelastic scattering of fast reactor neutrons with the diagrams published in the last issues of Nuclear Data Sheets, it was found that 120 levels in 34 nuclei must be excluded from compiled data because the γ transitions expected from them were not observed.*** The case of the questionable first 3^- level in ^{56}Fe at 3076 keV is considered by way of example. It is concluded that there is no such level in ^{56}Fe.

Let's examine one of these cases – ^{110}Cd

Table 1. List of excluded levels

Isotope	Level, keV (from NDS)	J^π (from NDS)	References $(n, n'\gamma)$	References NDS
^{104}Pd	1941.2(5)		[6]	[7]
	1999.1(4)	(1, 2)		
	2125.5(1)			
^{106}Pd	1904.31(10)	$2^-, 3^-$	[6]	[8]
^{106}Cd	2338.55(21)	(4^+)	[9]	[8]
	2521.9(3)	$(4, 5^+)$		
^{110}Cd	1809.484(18)	(2^+)	[10]	[11]
	2000			
	2184(2)	(1^-)		
	2198(2)	$2^+, 3^+$		
	2365(2)	2^+		
	2377(2)	4^+		
	2381(2)			
	2385(2)	(2^+)		
	2405(2)	$(0^+, 2^-)$		
	2432(2)	2^+		
	2451(2)			

E(level)ⁿ	Jπᵒᵖᑫ	XREF
2332.08 20	(0+)	A C FG IJK O
2355.81 5	(1+,2+)	BC F IJK O
2365 2	2+	O
2377 2	4+	J
2381 2		O
2385 2	(2+)	J
2405 2	(0+,2−)	J
2432 2	2+	J O
2433.25 3	3+	B F I
2451 2		J

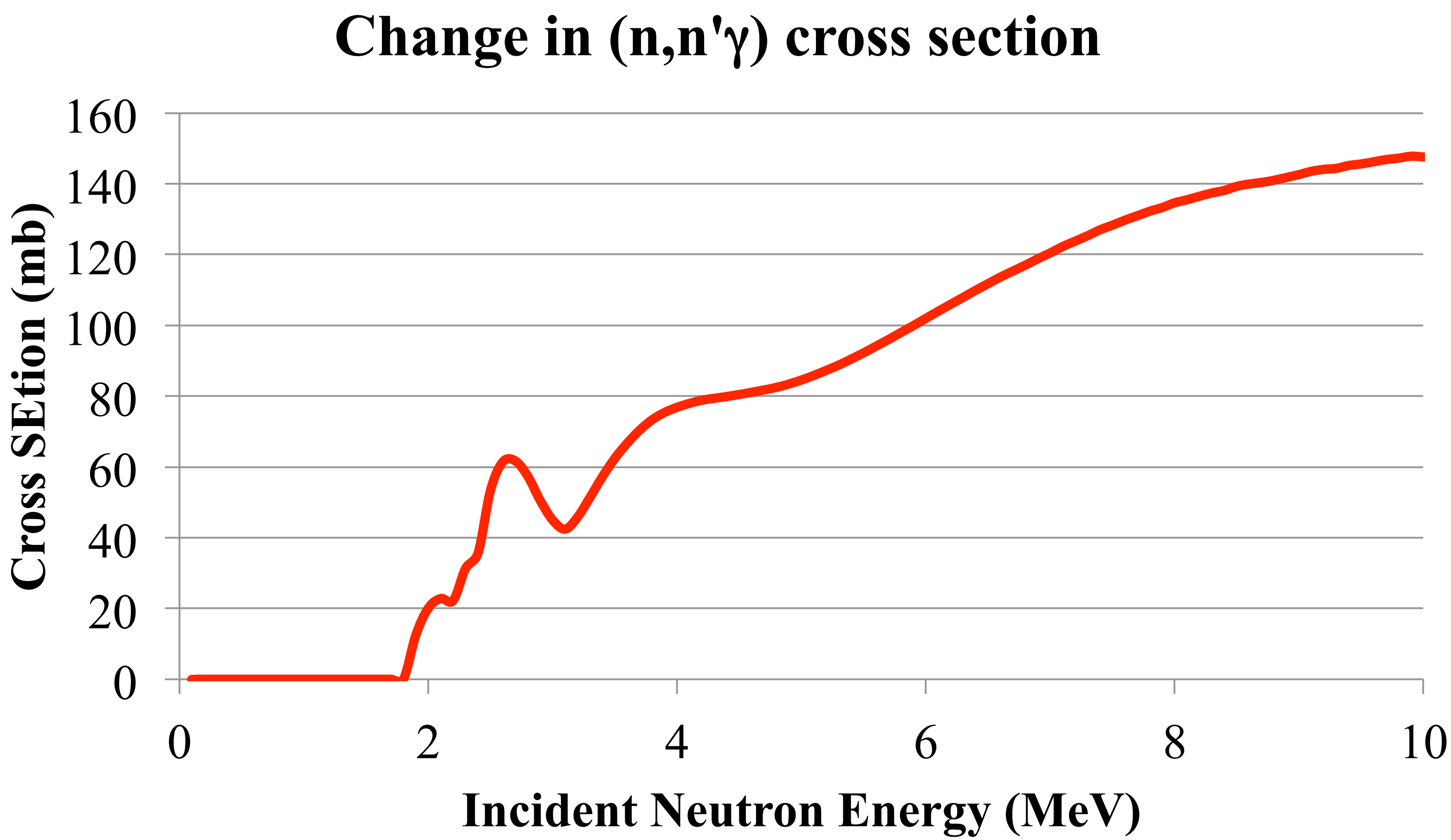
Nuclear Physics A540 (1992) 27–56
North-Holland

NUCLEAR PHYSICS A

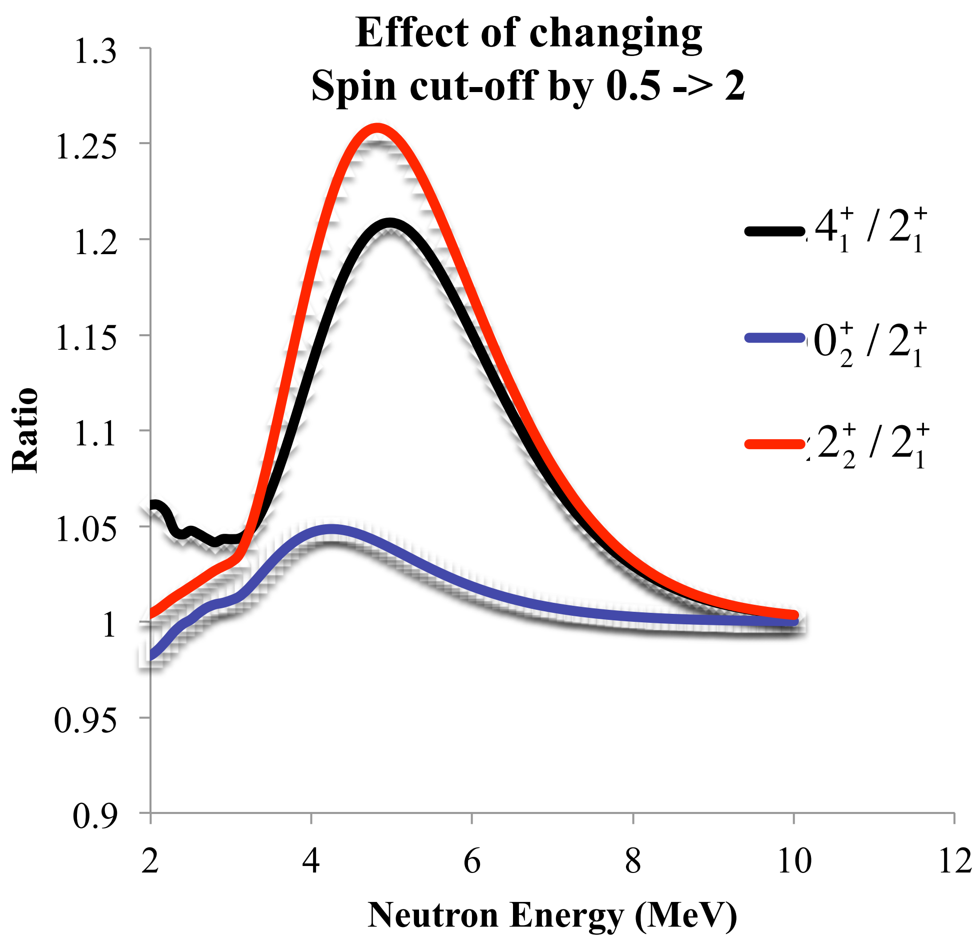
Hexadecapole strength distributions of vibrational nuclei in the $A = 100$ mass region

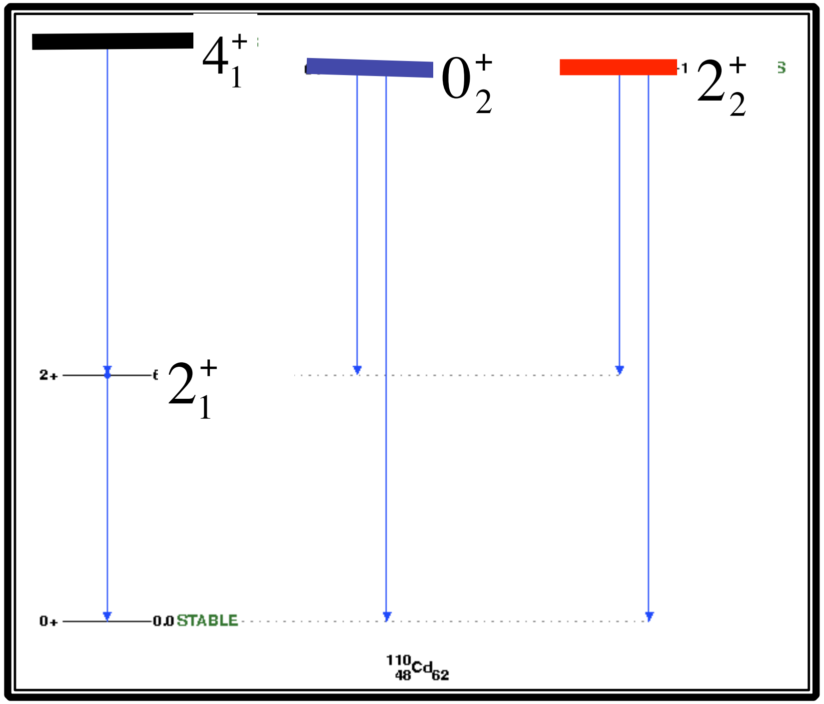
M. Pignanelli, N. Blasi and S. Micheletti
Dipartimento di Fisica dell'Universitá and INFN, sezione di Milano, I-20133 Milan, Italy

What are the effects of removing these levels on the calculated (n,n’) reaction cross section?

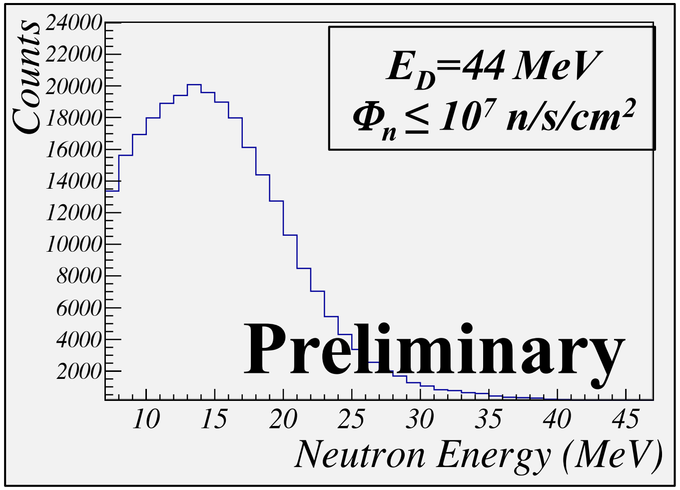


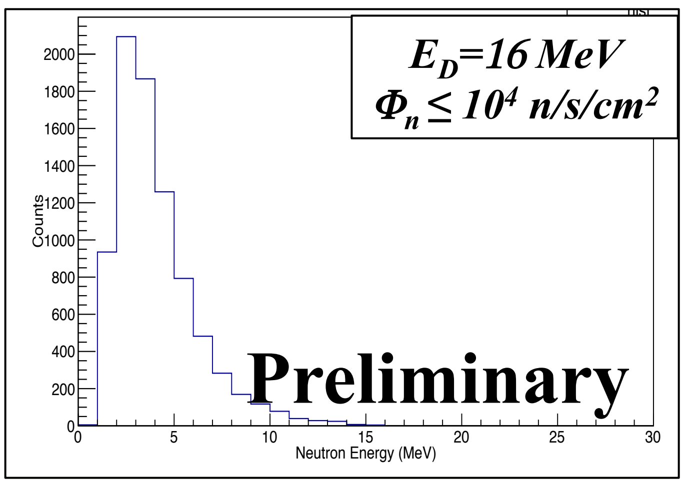
TALYS shows that the discrete state population in (n,n'γ) provides a probe for *ρ(J)*

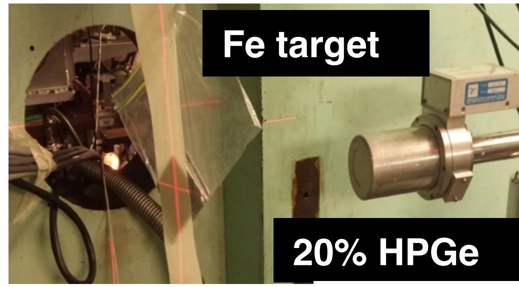




We are performing complementary (n,n'γ) measurements using deuteron breakup at the 88-Inch cyclotron

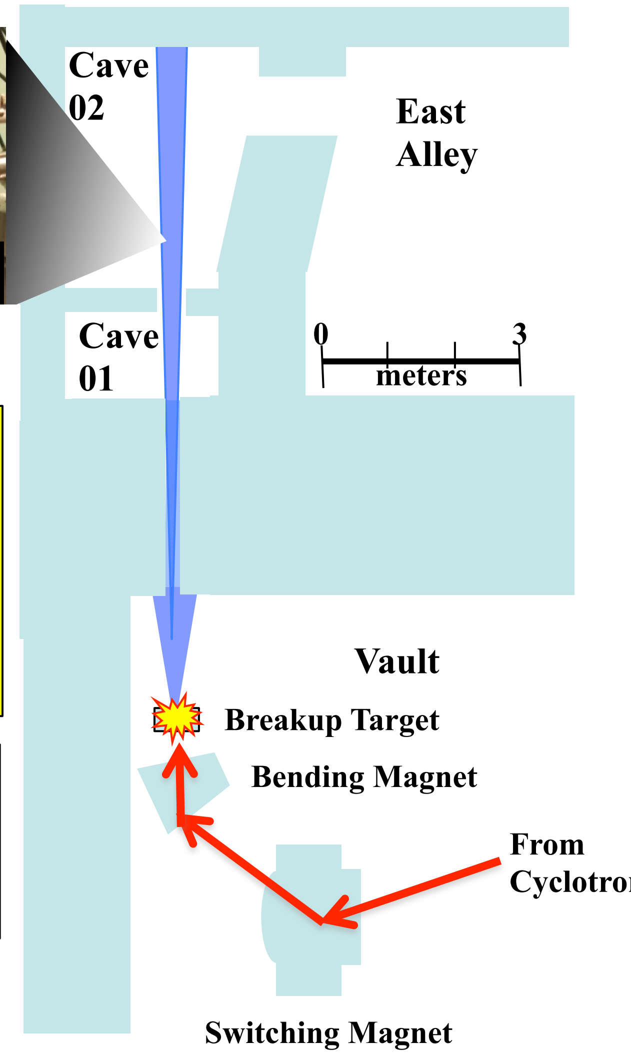






Our student-led experimental program: Josh Brown(G), Leo Kirsch (G) and Keegan Harrig (UG)

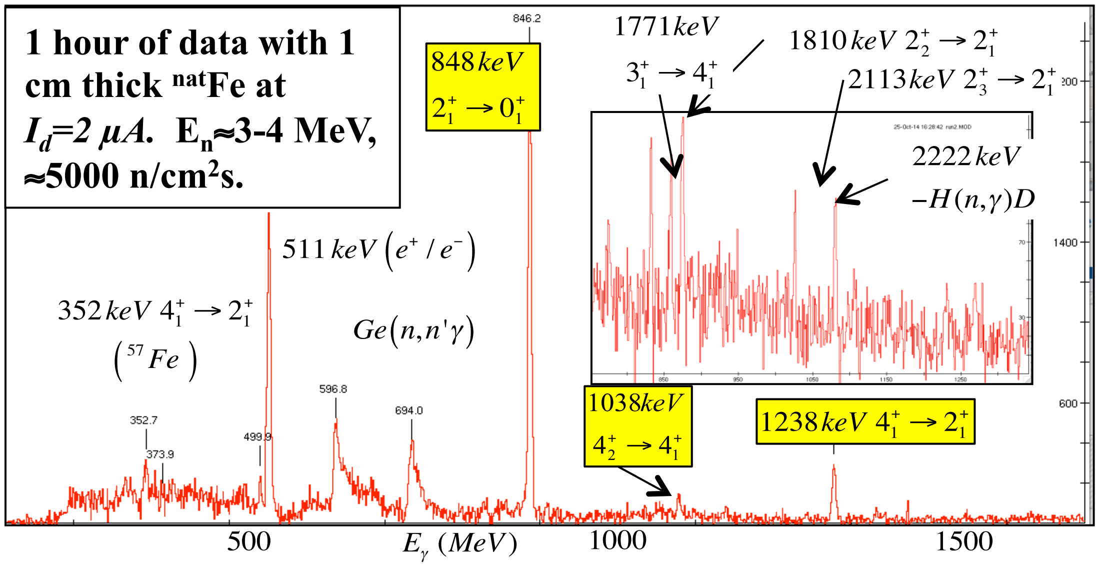
Similar measurements are taking place at HZDR[1] and GELINA[2]

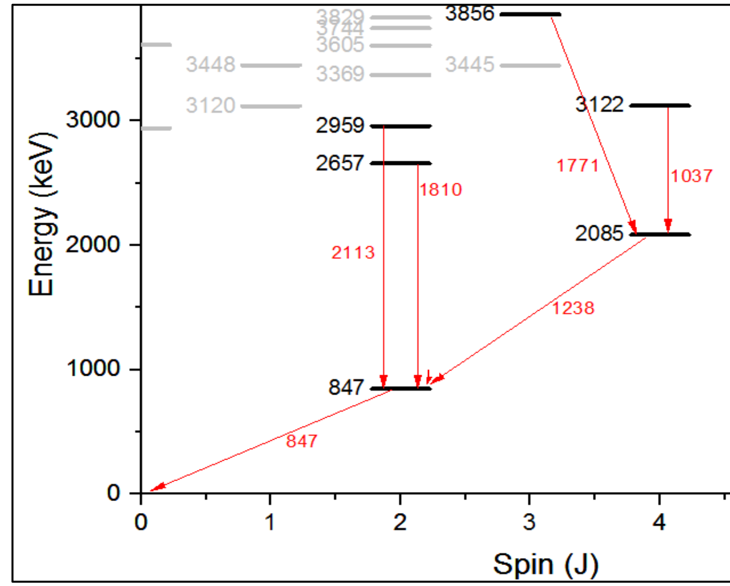


[1] R. Beyer *et al.*, Nucl. Phys. A 927 (2014) 41-52

[2] A. Negret *et al.*, PRC 90, 034602 (2014)

In October 2014 we demonstrated that (n,n'γ) can be studied in a fission-like neutron spectrum @ LBNL



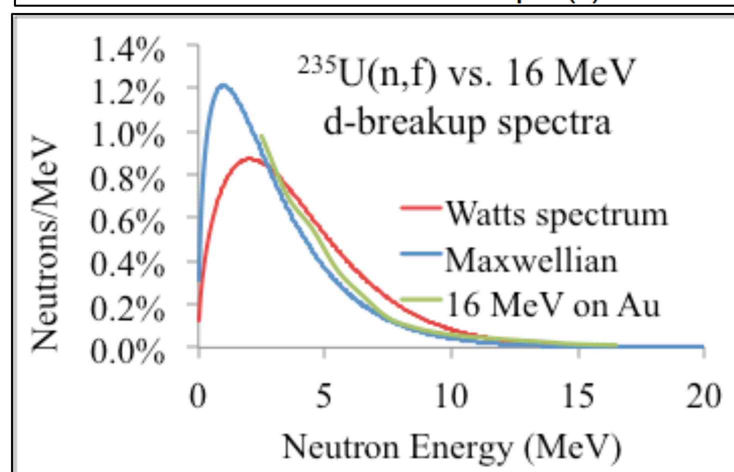


$$R_{exp/endf}\left(847/1238\right)=1.26\pm0.08$$

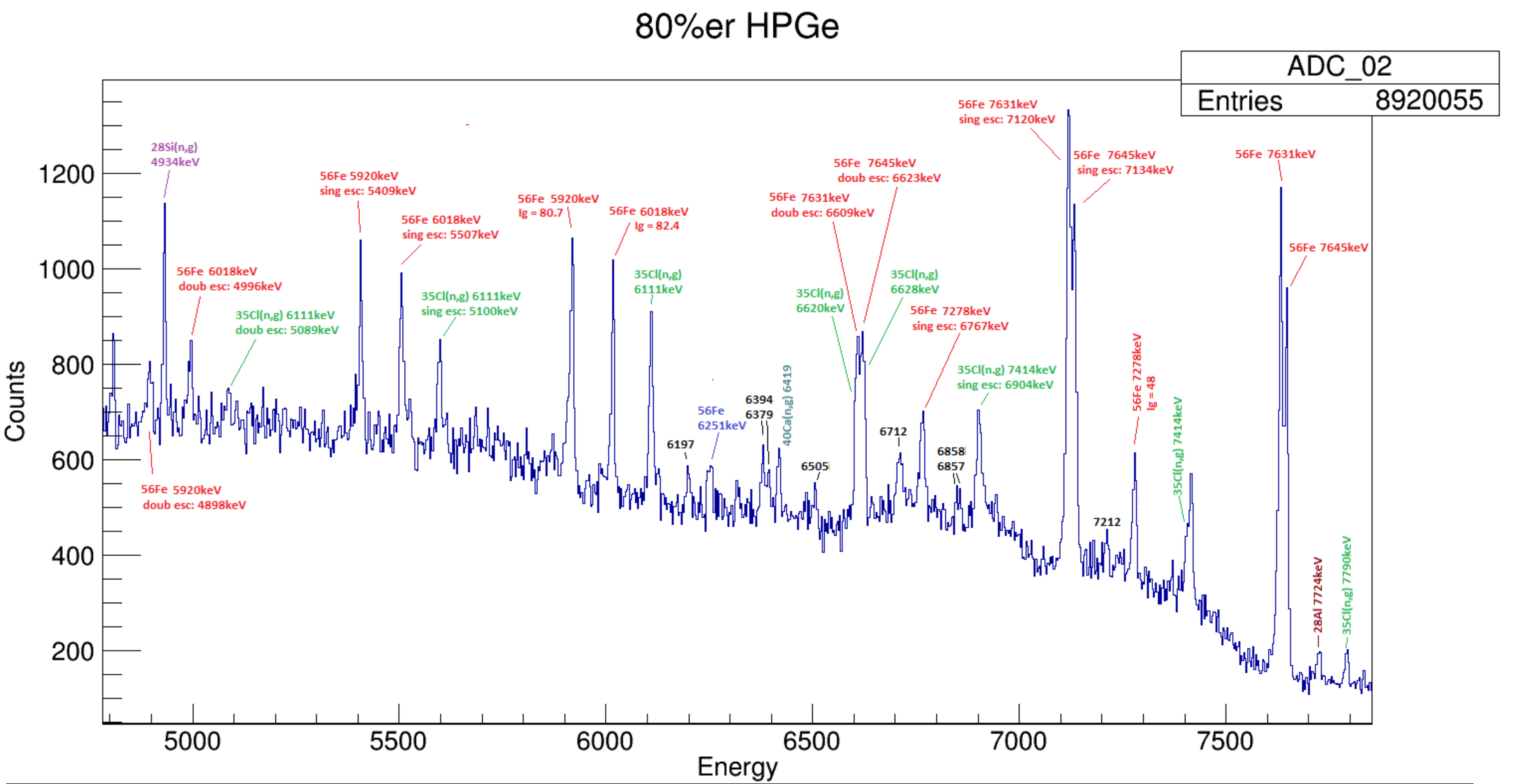
$$R_{exp/endf}\left(847/1037\right)=1.06\pm0.06$$

$$R_{exp/endf}\left(848/1238\right)=1.04\pm0.08$$

$$R_{exp/endf}\left(848/1037\right)=1.06\pm0.06$$

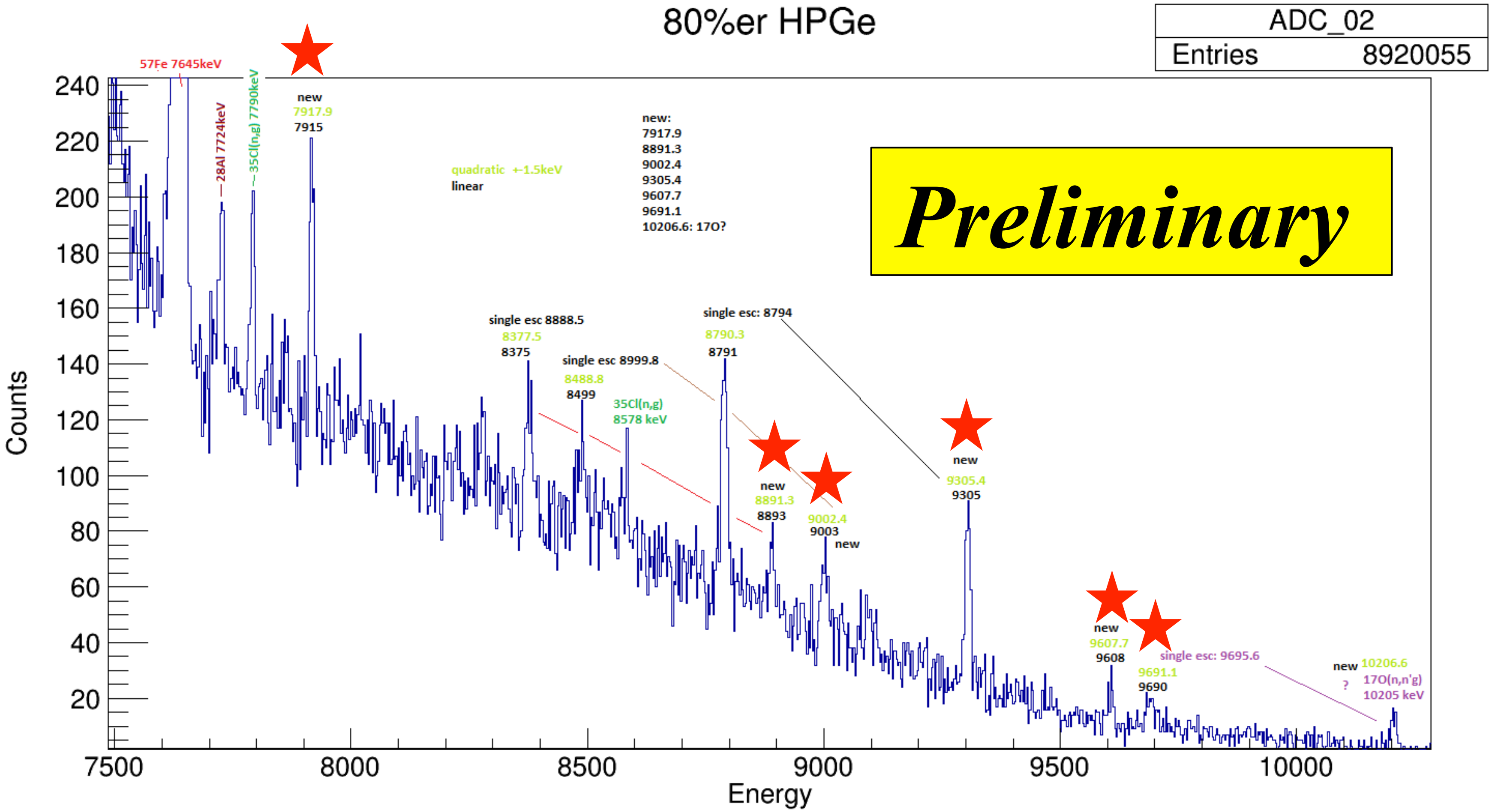


Last month we performed our first (n,n' γγ) coincidence measurements (L. Kirsch)



$^{56}Fe(n_{th},\gamma)$ is used for energy and efficiency calibration

The experiment revealed several new potential transitions at $E_\gamma > 10$ MeV



Next Steps

- Compile "high priority" nuclides in the atlas into ENSDF format
- Model the partial γ-ray production cross sections using EMPIRE and TALYS
- Complete modeling of the neutron beam-line to obtain the Atlas neutron energy spectrum
- Perform targeted (n,n'γγ) measurements

All of this leads to a (n,n'γ) horizontal evaluation

Collaborators on this work

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[2] *Lawrence Berkeley National Laboratory*
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[4] *University of California-Berkeley Dept. of Nuclear Engineering*
[5] *Brookhaven National Laboratory-NNDC*

And now for some blatant advertising

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