Evaluated Gamma-ray Activation File (EGAF)

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EGAF Collaboration

Isotopes Project (LBNL) - R.B. Firestone, A. Hurst, S. Basunia

LLNL Nuclear Data Library – B. Sleaford, N. Summers

Budapest Reactor – Zs. Revay, T. Belgya, L. Szentmiklosi

NIF STARS + LiBerACE Collaboration –

L. Bernstein, D. Bleuel, J.A. Caggiano, D.H.G. Schneider, W. Stoeffl (LLNL)

M. Wiedeking (iThemba Labs, South Africa)

M. Krticka, F. Becvar (Charles University, Prague)

S. Siem, A. Goergen, M. Guttormsen, A.C. Larsen (U. Oslo)

IAEA Nuclear Data Section –D. Abriola, R. Capote, M. Kellett, V. Zerkin

EGAF Database

Prompt thermal (n,γ) data

- Gamma-ray energies E_γ (ENSDF, Budapest)
- Gamma-ray cross sections σ_γ (Budapest)
- PGAA k_0 factors
- Recommended I_γ per 100 neutron captures
- Neutron separation energies S_N (AME mass evaluation)
- RIPL nuclear structure data
  - Recommended J^π values from experiment and theory
  - New J^π values from statistical model calculations
  - Improved level γ-ray branching intensities

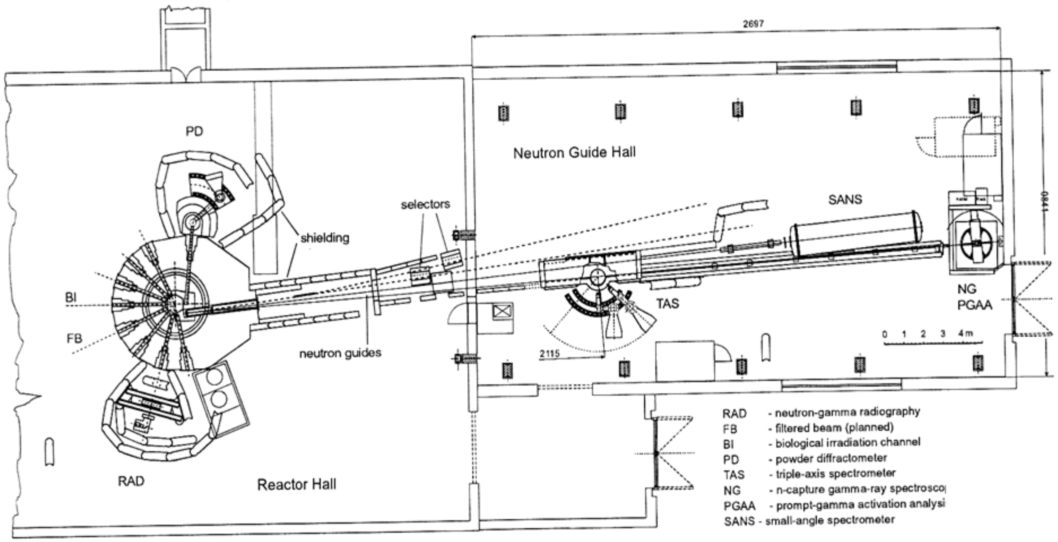
Activation thermal (n,γ) data

- E_γ, P_γ (from DDEP/ENSDF)
- Normalization to γ-ray cross sections, σ_γ
- NAA k_0 factors calculated from σ_γ and P_γ

Total radiative cross sections σ_0

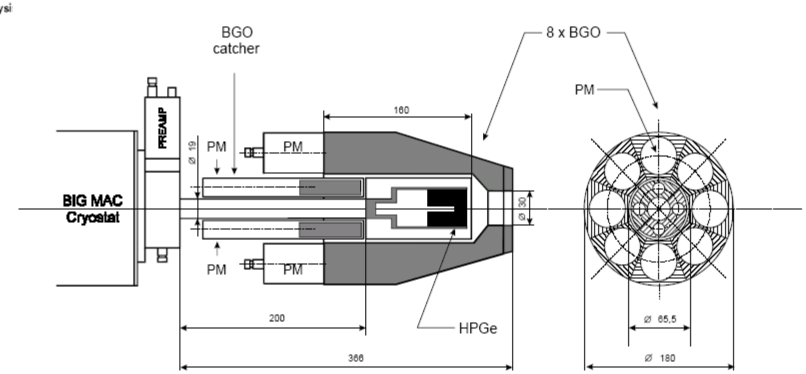
- Compilation measured values (corrected for new standard data)
- New values derived from prompt (n,γ) data and statistical model calculations
- Recommended values from all data

Neutron beam measurements - Budapest



Reactor and neutron guide hall. The PGAA (capture gamma) station is located ≈30 m from the reactor wall.

BUDAPEST COMPTON-SUPPRESSED / PAIR-MODE GAMMA SPECTROMETER

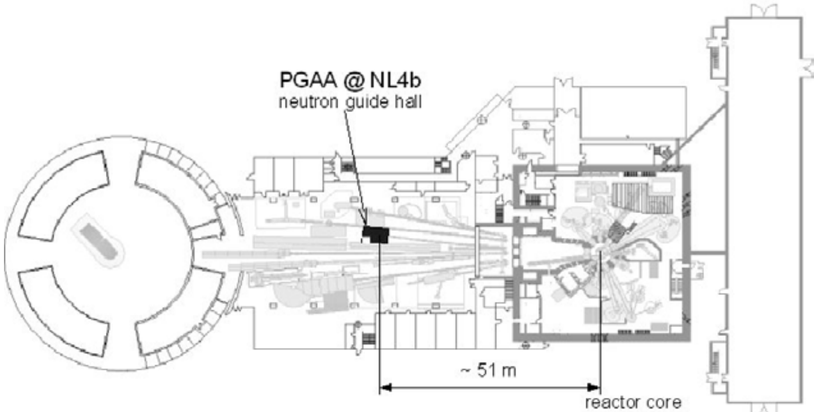


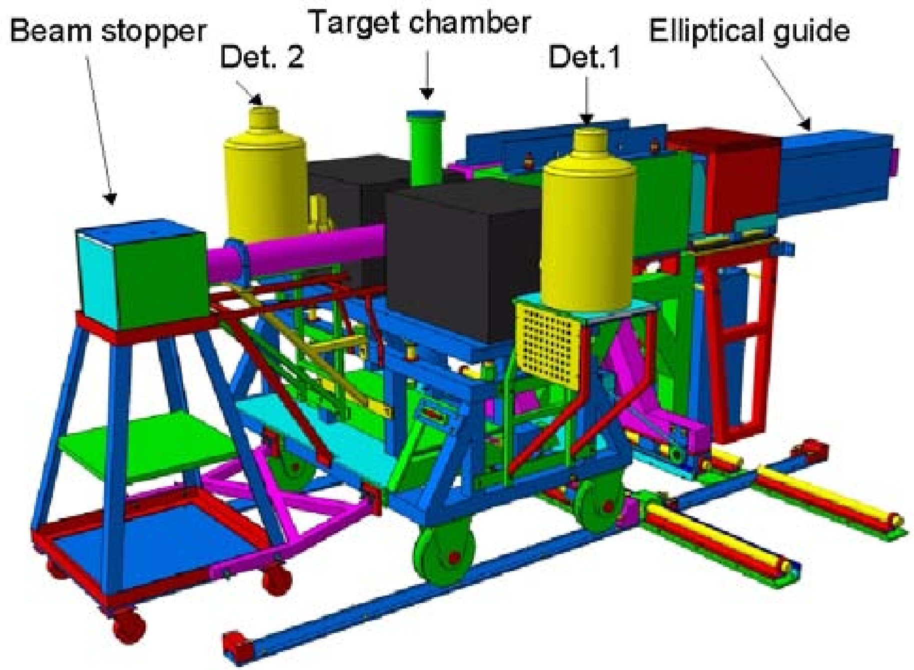
Compton suppression: ≈5 (1332 keV) to ≈40 (7000 keV)

HPGe efficiency curve precision <1% for E=0.5-6 MeV, <3% 0.05-0.5 MeV and >6 MeV.

1.2×10^8 n/cm^2 at target

Neutron beam measurements - Munich





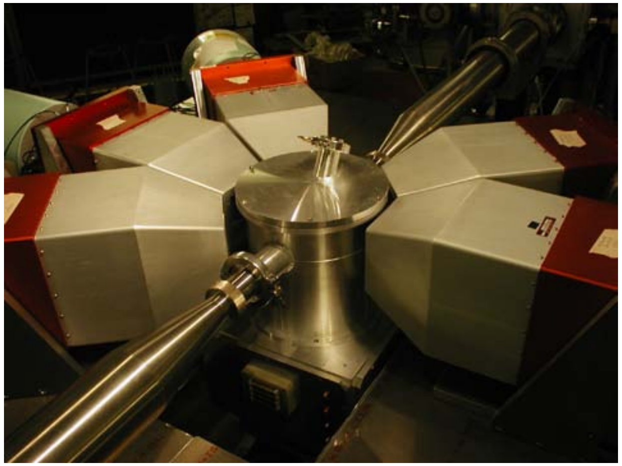
New experiments planned for 2011

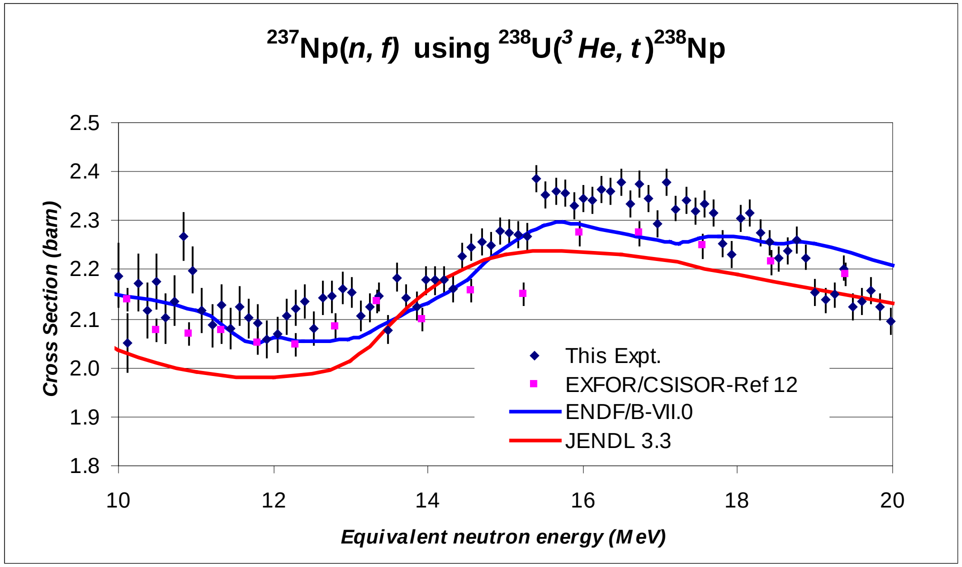
7.3×10^9 n/cm^2 at target position (14 mm×38 mm beam)

2×10^{10} n/cm^2 at He gas-flushed elliptical guide (4 mm×10 mm beam)

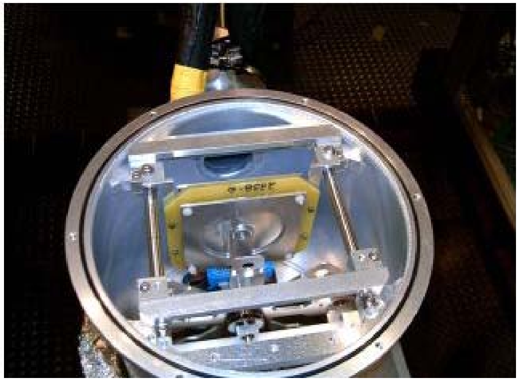
Surrogate reactions - STARS+LiBerACE

Target Chamber+6 “Clover” Ge





Interior w/S2 Si detectors



^{238}U(^{3}He,*t*)^{238}Np surrogate reaction to determine the ^{237}Np(n,f) cross section (S. Basunia - LBNL)

Isotopes Project is LBNL lead group in STARS + LiBerACE collaboration

- Surrogate reaction cross section studies
- Statistical model studies
- NIF nuclear reaction studies

Reaction Input Parameter Library (RIPL)*

BERKELEY LAB

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106Pd
  number of levels:                                 133
  number of gamma-rays:                             212
  number of levels in a complete level scheme:      30
  number of levels with assigned spin and parity:   8
  neutron separation energy:                        9.561510 [MeV]
  proton separation energy:                         9.345901 [MeV]

-------------------------------------------------------------------------------------
 NL   EL[MeV]    S/P   F    T1/2[s]  Ng s unc             s-info  nd m        p        mode
                                          Nf     Eg[MeV]     Pg          Pe          Icc
-------------------------------------------------------------------------------------
  1   0.000000   0.0   1  -1.00E+00   0 u                  0+   0
  2   0.511851   2.0   1   1.21E-11   1 u                  2+   0
                                          1      0.512  9.946E-01  1.000E+00  5.455E-03
  3   1.128010   2.0   1   3.12E-12   2 u                  2+   0
                                          2      0.616  6.461E-01  6.482E-01  3.252E-03
                                          1      1.128  3.515E-01  3.518E-01  7.525E-04
  4   1.133770   0.0   1   6.80E-12   2 u                  0+   0
                                          2      0.622  9.968E-01  1.000E+00  3.171E-03
                                          1      1.134  0.000E+00  0.000E+00  0.000E+00
  5   1.229250   4.0   1   1.34E-12   1 u                  4+   0
                                          2      0.717  9.978E-01  1.000E+00  2.183E-03
```

Jπ are adopted from ENSDF. For calculations if uniquely assigned no problem. Otherwise?

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```
33   2.591200  -1.0   0               1                (2,3)+   0
                                         11      0.659  1.000E+00  1.000E+00  0.000E+00
34   2.624400   0.0   1               3 u                   0+   0
                                          7      1.062  3.608E-01  3.611E-01  8.584E-04
                                          3      1.496  2.505E-01  2.506E-01  4.201E-04
                                          2      2.113  3.883E-01  3.883E-01  0.000E+00
35   2.626870  -1.0   0               3                (2,3)+   0
                                          7      1.065  7.453E-02  7.453E-02  0.000E+00
                                          3      1.499  6.211E-01  6.211E-01  0.000E+00
                                          2      2.115  3.043E-01  3.043E-01  0.000E+00
```

Jπ uncertain

* R. Capote et al, Nucl. Data Sheets 110, 3107 (2009).

Cross section standardization methods

1. **Stoichiometric compounds containing elements with well-known cross sections: H, N, Cl, S, Na, Ti, Au**

   KCl, $(CH_2)_n$, $Pb(NO_3)_2$, Tl_2SO_4

2. **Homogenous mixtures**

   Aqueous (H_2O) or acid (20% HCl) solutions
   Mixed powders (TiO_2)

3. **Activation products with well-known P_γ**

   ^{19}F, ^{28}Al, ^{100}Tc, ^{235}U

Measurements have been completed on all elemental targets

Z=1-83, 92 except for He and Pm

and on the radioactive targets

^{99}Tc, and ^{129}I

The k_0 PGAA/NAA Method

$$(k_{0,H})_\gamma = \frac{M_H \theta_x \sigma_{0,x} P_\gamma}{M_x \theta_H \sigma_{0,H} P_H}$$

$x = \text{PGAA analyte H}(2223.25\gamma)\text{ comparator}$

$\quad = \text{NAA analyte Au}(411.802\gamma)\text{ comparator}$

$M = \text{atomic mass } (M_H = 1.00794, M_{Au} = 196.9655)$

$\theta = \text{isotopic abundance } (\theta_H = 99.9985,\ \theta_{\text{Au}} = 100)$

$\sigma_{0,x} = \text{thermal neutron cross section } (\sigma_{0,H} = 0.3326\text{ b}, \sigma_{0,\text{Au}} = 98.65\text{ b})$

$\text{P}_\gamma = \gamma - \text{ray transition probability } (\text{P}_{2223}(\text{H}) = 1.0, \text{P}_{411}(\text{Au}) = 0.9558)$

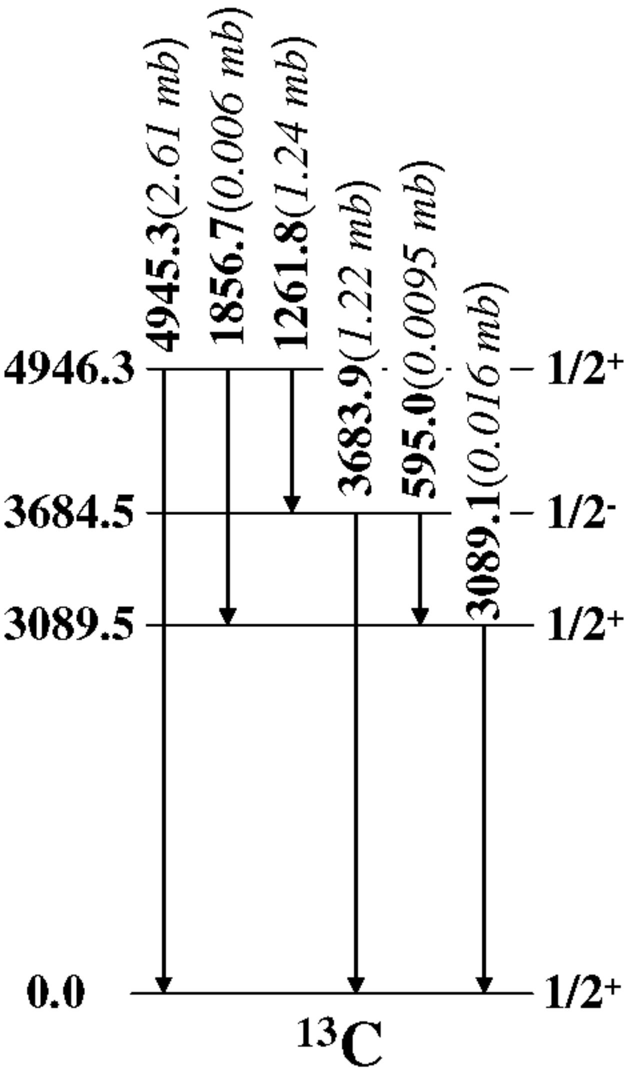
$\sigma_\gamma = \sigma_{0,\text{x}} \text{P}_\gamma$

Relative γ-ray intensities measured in PGAA/NAA from different elements can be converted to relative masses using the γ-ray k_0 factors.

Compilation/Evaluation of σ_0 values

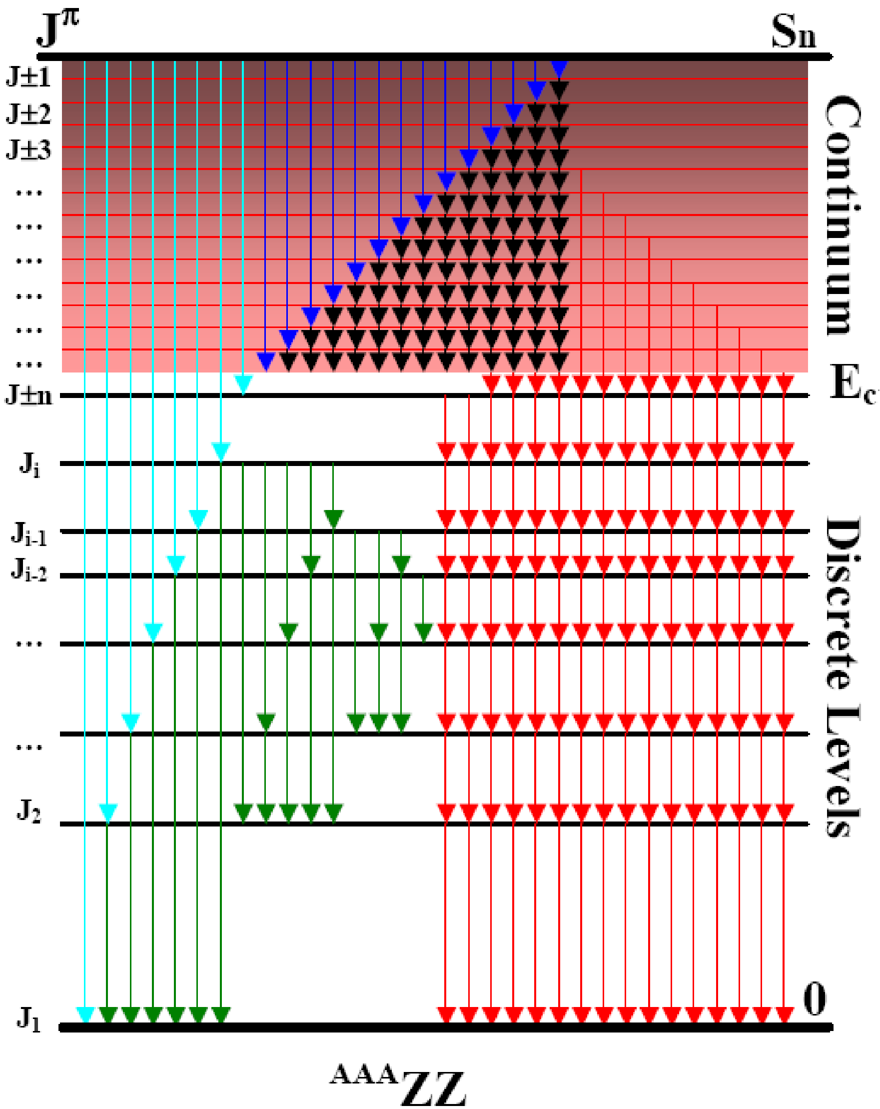
For simple, low-Z level schemes σ_0 can be determined from

$$\sigma_0 = \sum \sigma_\gamma(\text{primary}) = \sum \sigma_\gamma(\text{GS})$$

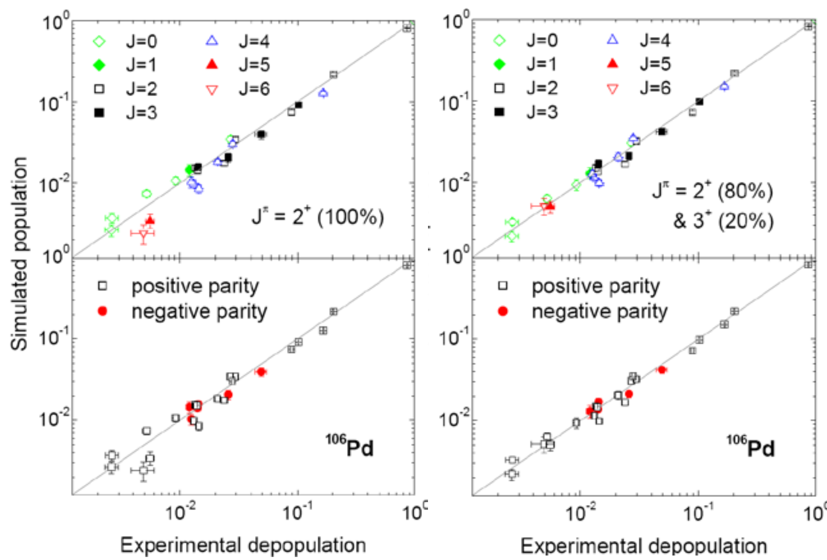


σ(in)	σ(out)	σ(in-out)
0.0	3.86	3.86 mb
1.24	1.22	0.02
0.016	0.016	0.00
3.85	0.0	3.85 mb

Determining σ_0 for complex level schemes



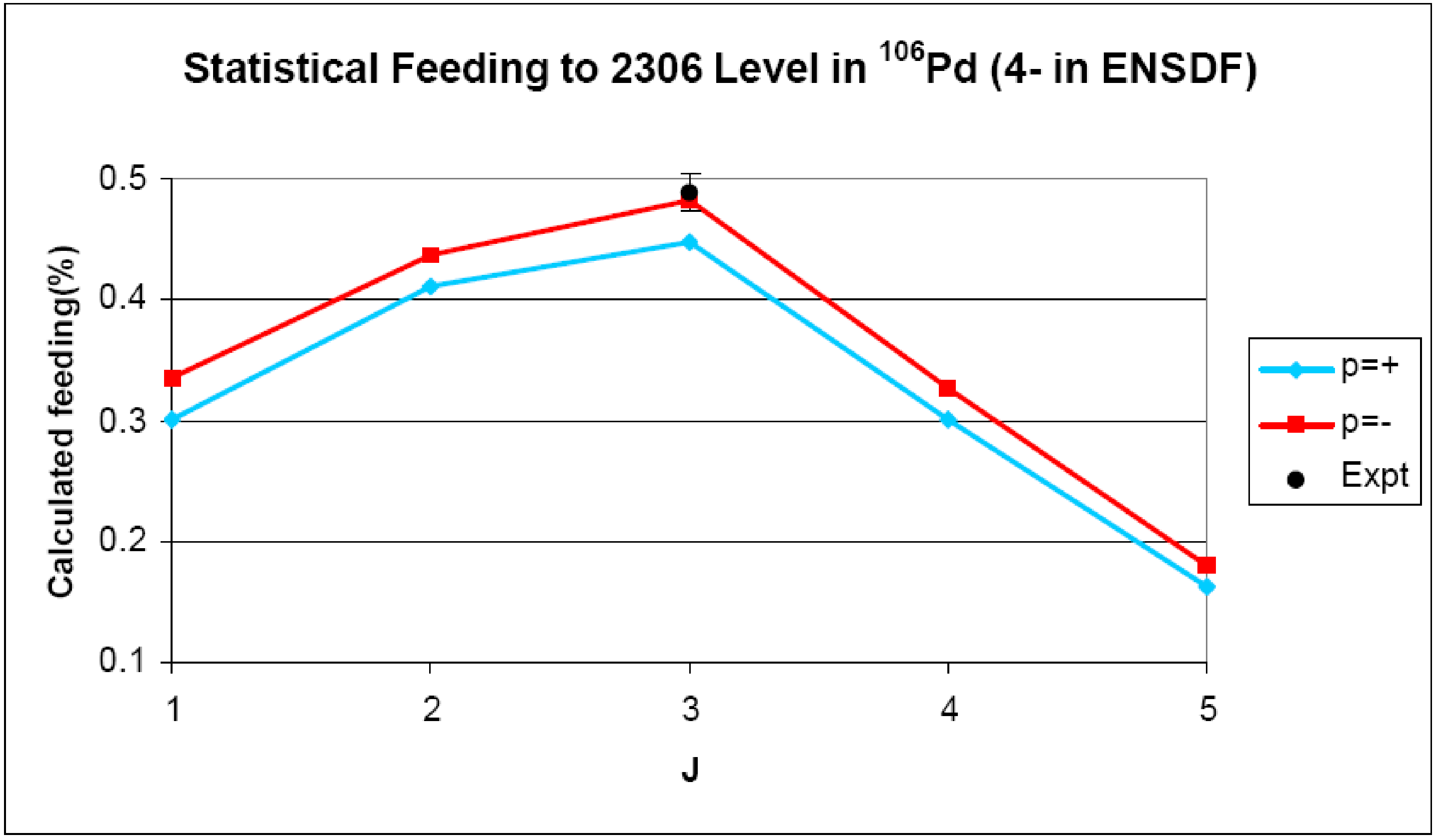
- Below E_{crit} all nuclear structure is known (RIPL)
- All primary γ-ray to levels below E_{crit} are measured (Budapest)
- The rest of the levels and γ-rays can be calculated with DICEBOX
- $\sigma_0 = \sigma_0(GS)_{obs} + \sigma_0(GS)_{stat}$



Population/Depopulation plot

Improved J^{π} Assignments

Significant deviations of the measured depopulation from the calculated are always due to mistakes in the RIPL data.



Palladium Isotopes Results*

Isotope	σ_0(literature) (b)	σ_0(this work) (b)
$^{102}Pd(n,\gamma)^{103}Pd$	1.6 0.2	1.1 0.4
$^{104}Pd(n,\gamma)^{105}Pd$	0.65 0.30	0.75 0.26
$^{105}Pd(n,\gamma)^{106}Pd$	21.0 1.5	21.7 0.5
$^{106}Pd(n,\gamma)^{107}Pd$	0.30 0.03	0.36 0.10
$^{108}Pd(n,\gamma)^{109g}Pd$	7.6 0.5	8.6 0.6
$^{108}Pd(n,\gamma)^{109m}Pd$	0.185 0.011	0.185 0.010
$^{110}Pd(n,\gamma)^{111}Pd$	0.70 0.17	0.34 0.10

* M. Krticka, R.B. Firestone, D.P. McNabb, B. Sleaford, U. Agvaanluvsan, T. Belgya, and Z.S. Revay, Phys. Rev. C 77, 054615 (2008).

Status of EGAF

EGAF version 1.0 published and available on Internet

- *Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis*, R.B. Firestone, et al, IAEA STI/PUB/1263, 251 pp(2007)

  Http://www-pub.iaea.org/MTCD/publications/PubDetails.asp?pubId=7030
- IAEA Prompt Gamma-ray Activation Analysis Viewer:

  http://www-nds.iaea.org/pgaa/pgaa7/index.html
- LBNL Capture Gamma-ray Data

  http://ie.lbl.gov/ng.html

EGAF version 2.0 currently in progress

- Updated evaluations – first pass revision complete
- DICEBOX calculations – σ_0 measurements, improved RIPL
- Activation file – $k_0/\sigma_0/P_\gamma$ comparison
- σ_0 measurement compilation – CSISRS plus

Status of EGAF

Publication status

- Pd published
- Z=1-19, 26, 63, 64, 68, 74 publication planned for 2011
- NDS publication planned (see discussion in later talk)

Planned separated isotope measurements at Budapest and Munich Reactors in FY2011

- ^{2}H, ^{3}He, ^{73}Ge, ^{90,91,92,94,96}Zr, ^{153}Eu, ^{155,157}Gd, ^{182,183,184,186}W, ^{167}Er

LBNL LIBERACE/STARS measurements in FY2011

- ^{167}Er(d,p) – search for collective nuclear structure contribution to statistical decay.
- ^{106,108,110}Pd(p,p') – ^{107}Pd s-process waiting point nucleus surrogate reaction cross section study (proposed).
- ^{73}Ge(d,p) – surrrogate cross section measurement, preliminary NIF experiment.

Comparison of IUPAC(k_0), Atlas(σ_0), and EGAF(σ_γ) PGAA/NAA data

$\sigma_0(^{24g}Na)_{NAA}$ = 542(3) mb
$\sigma_0(^{24g}Na)_{PGAA}$ = 540(4) mb
$\sigma_0(^{24g}Na)_{Atlas}$ = 517(4) mb

$\sigma_0(^{24}Na^{m})_{PGAA}$ = 478(4) mb
$\sigma_0(^{24m}Na)_{Atlas}$ = 400(3) mb

$k_0(^{36}S)_{IUPAC} = 1.96(4)\times10^{-6}$
$k_0(^{36}S)_{EGAF} = 3.05(10)\times10^{-6}$

$\sigma_0(^{39}K)_{PGAA}$ = 2.21(3) b
$\sigma_0(^{39}K)_{Atlas}$ = 2.1(2) b
$\sigma_0(^{40}K)_{PGAA}$ = 90(3) b
$\sigma_0(^{40}K)_{Atlas}$ = 30(8) b
$\sigma_0(^{41}K)_{PGAA}$ = 1.522(22) b
$\sigma_0(^{41}K)_{Atlas}$ = 1.46(3) b

$^{30}Si(n,\gamma)$

$P_\gamma(1266)_{ENSDF}$ = 0.00050(4)
$P_\gamma(1266)_{PGAA}$ = 0.000589(12)

$\sigma_0(^{45m}Sc)_{NAA}$ = 7.77(21) b
$\sigma_0(^{45m}Sc)_{Atlas}$ = 9.9(11) b

$\sigma_0(^{70}Zn)_{NAA}$ = 83(5) mb
$\sigma_0(^{70}Zn)_{Atlas}$ = 22 mb

$\sigma_0(^{127}I)_{k0}$ = 5.48(12) b
$\sigma_0(^{127}I)_{Atlas}$ = 6.15(6) b
or
$P_\gamma(443)_{ENSDF}$ = 0.1261(8)
$P_\gamma(443)_{Atlas}$ = 0.112(3)

$\sigma_0(^{185}W)_{NAA}$ = 34.8(2) b
$\sigma_0(^{185}W)_{Atlas}$ = 38.1(5) b
From new ENSDF P_γ

$^{114m}In(t_{1/2}$=49.51 d)

ENSDF
%IT=96.75(24)
%EC+β^+=3.25(24)
EGAF-NAA
%IT=95.72(7)
%EC+β^+=4.28(7)

$\sigma_0(^{155}Gd(n,\gamma)^{156}Gd)$	
Atlas	60,900(500)
EGAF	66,200(4,100)
$\sigma_0(^{157}Gd(n,\gamma)^{158}Gd)$	
Atlas	254000(815)
EGAF	216000(5000)

Conclusions

- EGAF version 1.0 completed in 2007
- EGAF version 2.0 under development
- Surrogate reaction studies are continuing at the LBNL 88” cyclotron with STARS+LiBerACE
- New neutron beam measurements at Budapest and Munich
- New publications of EGAF data in literature and possible Nuclear Data Sheets