236sNp isomer yields in 237Np(n,2n) and 238U(p,3n) reactions.

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Collaboration

- **ADVANCED EVALUATION OF 237Np and 243Am NEUTRON DATA'**
- **COLLABORATION**
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- Neptunium-237 is a major constituent of the spent nuclear fuel. Main chains
- $^{235}U(n, \gamma)\ ^{236}U(n, \gamma)\ ^{237}U(\beta^-)\ ^{237}Np$ and $^{238}U(n, 2n)\ ^{237}U(\beta^-)^{237}Np$.
- The transmutation of the ^{237}Np in VVER is affected by
- $^{237}Np(n,\gamma)\ ^{238}Np(\beta^-)^{238}Pu(n,\gamma)\ ^{239}Pu$.
- $^{236(s)}Np$ - $^{237}Np(n,2n)^{236s}Np(\beta^{-236}Pu(\alpha)^{232}U$

SCOPE

Reaction chain $^{237}Np(n,2n)^{236s}Np(\beta^-)$ $^{236}Pu(\alpha)^{232}U$ is one of the major sources of the accumulation of ^{232}U in spent fuel.

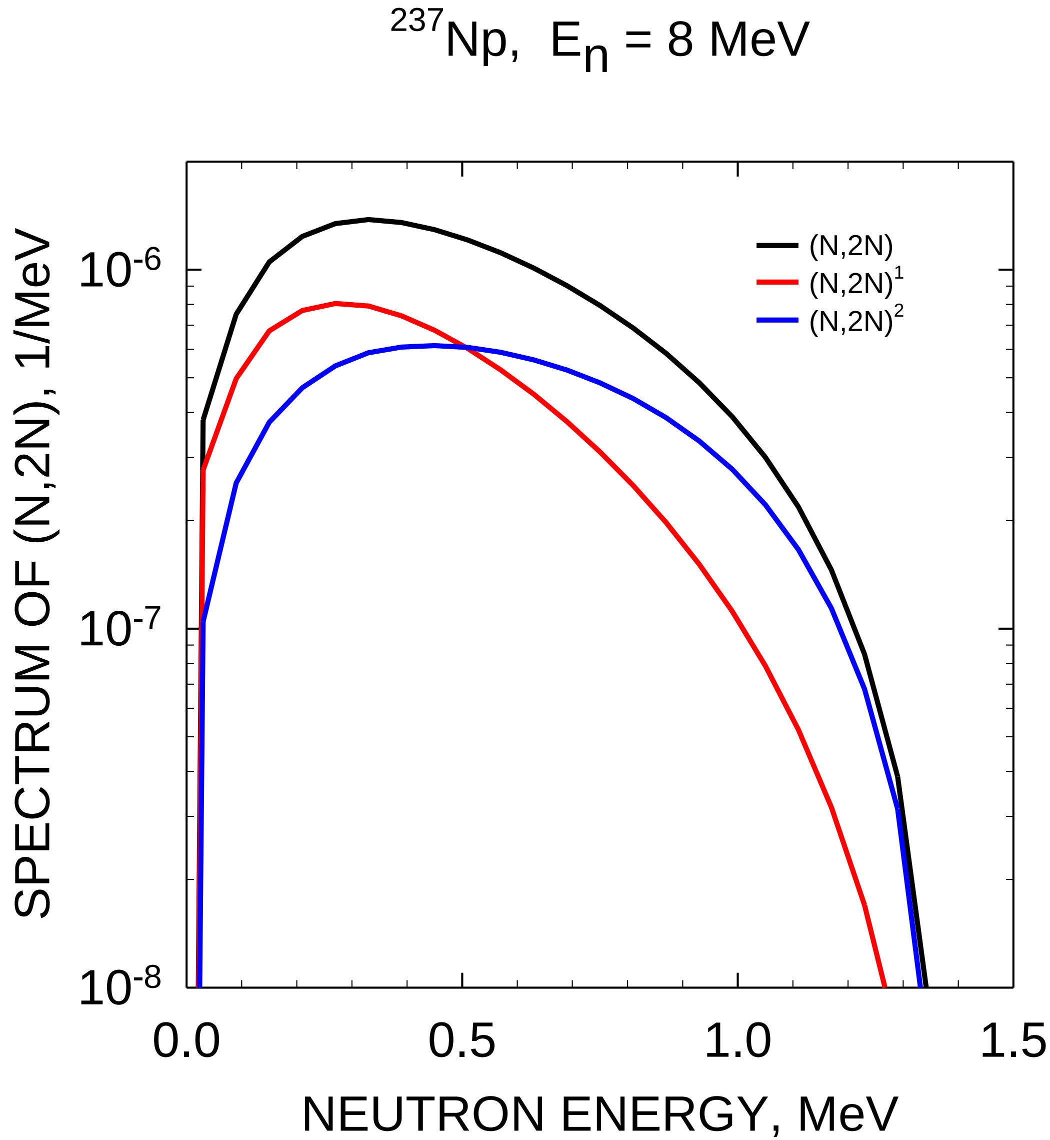
- The half-life of ^{236s}Np ^{236s}Np is 22.4 h
- The half-life of long-lived state
- $^{237}Np(n,2n)$ ^{236l}Np is 155000 y
- ^{236l}Np thermal fission cross section 2000 barn influence the core neutronics.
-

$$\frac{d\sigma^1_{n2nx}}{d\varepsilon} = \frac{d\sigma^1_{nnx}(\varepsilon)}{d\varepsilon}\frac{\Gamma^A_n(E_n-\varepsilon)}{\Gamma^A(E_n-\varepsilon)}$$

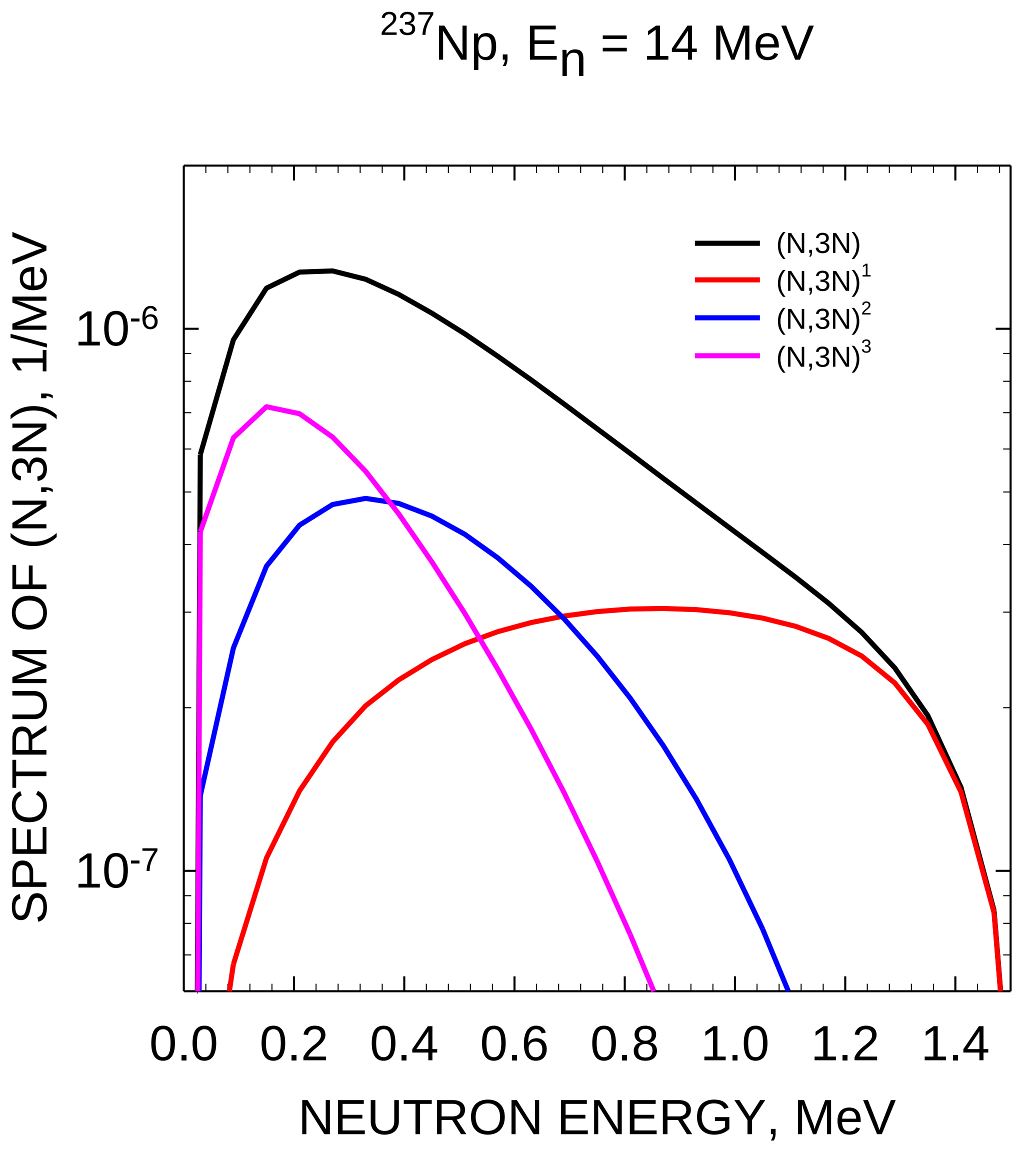
$$\frac{d\sigma^1_{n2n}}{d\varepsilon} = \int_0^{E_n-B^A_n}\frac{d\sigma^1_{n2nx}(\varepsilon)}{d\varepsilon}\frac{\Gamma^{A-1}_n(E_n-B^A_n-\varepsilon-\varepsilon_1)}{\Gamma^{A-1}(E_n-B^A_n-\varepsilon-\varepsilon_1)}d\varepsilon_1$$

$$\frac{d\sigma^2_{n2nx}}{d\varepsilon} = \int_0^{E\ -B^A_n-\varepsilon}\frac{d\sigma^1_{n2nx}(\varepsilon)}{d\varepsilon}\frac{\Gamma^A_n(E_n-B^A_n-\varepsilon-\varepsilon_1)}{\Gamma^A(E_n-B^A_n-\varepsilon-\varepsilon_1)}d\varepsilon_1$$

$$\frac{d\sigma^2_{n2n}}{d\varepsilon} = \int_0^{E\ -B_n}\frac{d\sigma^2_{n2nx}(\varepsilon)}{d\varepsilon}\frac{\Gamma^{A-1}_n(E_n-B^A_n-\varepsilon_1-\varepsilon_2)}{\Gamma^{A-1}(E_n-B^A_n-\varepsilon_1-\varepsilon_2)}d\varepsilon_1$$



^{237}Np, E_n = 8 MeV
SPECTRUM OF (N,2N), 1/MeV
NEUTRON ENERGY, MeV
(N,2N)
(N,2N)^1
(N,2N)^2
10^{-6}
10^{-7}
10^{-8}
0.0
0.5
1.0
1.5



237Np, En = 14 MeV
(N,3N)
(N,3N)1
(N,3N)2
(N,3N)3
10-6
10-7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
SPECTRUM OF (N,3N), 1/MeV
NEUTRON ENERGY, MeV

The γ-decay of the excited nucleus is described by the kinetic equation n

$$\frac{\partial \omega_k(U,J^\pi,t)}{\partial t} = \sum_{J'\pi'} \int_0^{U_g} \omega_{k-1}(U',J^\pi{}',t)\frac{\Gamma_\gamma(U',J^\pi{}',U,J^\pi)}{\Gamma\,(U',J^\pi{}')}dt - \omega_k(U,J^\pi,t)\frac{\Gamma_\gamma(U,J^\pi)}{\Gamma\,(U,J^\pi)}$$

$\omega_k(U,J^\pi)$ is the population of state Jπ at U after emission of k γ – quanta

Integrating over t , in the long run, one gets W(U,Jπ) after emission of k γ-quanta

$$\omega_k(U,J^\pi,\infty) - \omega_k(U,J^\pi,0) = \sum_{J'\pi'} \int_U^{U_g} \frac{\Gamma_\gamma(U',J^\pi{}',U,J^\pi)}{\Gamma\,(U',J^\pi{}')} \int_0^\infty \omega_{k-1}(U',J^\pi{}',t)\,dt\,dU' -$$

$$\frac{\Gamma_\gamma(U,J^\pi)}{\Gamma\,(U,J^\pi)} \int_0^\infty \omega_k(U,J^\pi,t)\,dt$$

$$\frac{\partial \omega_k(U,J^{\pi},t)}{\partial t} = \sum_{J'\pi'} \int_0^{U_g} \omega_{k-1}(U',J^{\pi}{}',t) \frac{\Gamma_{\gamma}(U',J^{\pi}{}',U,J^{\pi})}{\Gamma(U',J^{\pi}{}')} dt - \omega_k(U,J^{\pi},t) \frac{\Gamma_{\gamma}(U,J^{\pi})}{\Gamma(U,J^{\pi})}$$

$$\omega_k(U,J^{\pi},t=0) = \delta_{ko}\omega_0(U,J^{\pi})$$

$$\omega_k(U,J^{\pi},\infty) - \omega_k(U,J^{\pi},0) = \sum_{J'\pi'} \int_U^{U_g} \frac{\Gamma_{\gamma}(U',J^{\pi}{}',U,J^{\pi})}{\Gamma(U',J^{\pi}{}')} \int_0^{\infty} \omega_{k-1}(U',J^{\pi}{}',t)\,dt\,dU' -$$

$$\frac{\Gamma_{\gamma}(U,J^{\pi})}{\Gamma(U,J^{\pi})} \int_0^{\infty} \omega_k(U,J^{\pi},t)\,dt$$

$$W_k(U,J^{\pi}) = \frac{\Gamma_{\gamma}(U,J^{\pi})}{\Gamma(U,J^{\pi})} \int_0^{\infty} \omega_k(U,J^{\pi},t)\,dt$$

$W_k(U, J^{\pi})$ population of state after emission of k gamma-quanta

$$W_k(U, J^{\pi}) = \sum_{J'\pi'} \int_{U}^{U_g} \frac{\Gamma_{\gamma}(U', J^{\pi}{}', U, J^{\pi})}{\Gamma(U', J^{\pi}{}')} W_{k-1}(U', J^{\pi}{}') dU' + \omega_k(U, J^{\pi}, 0)$$

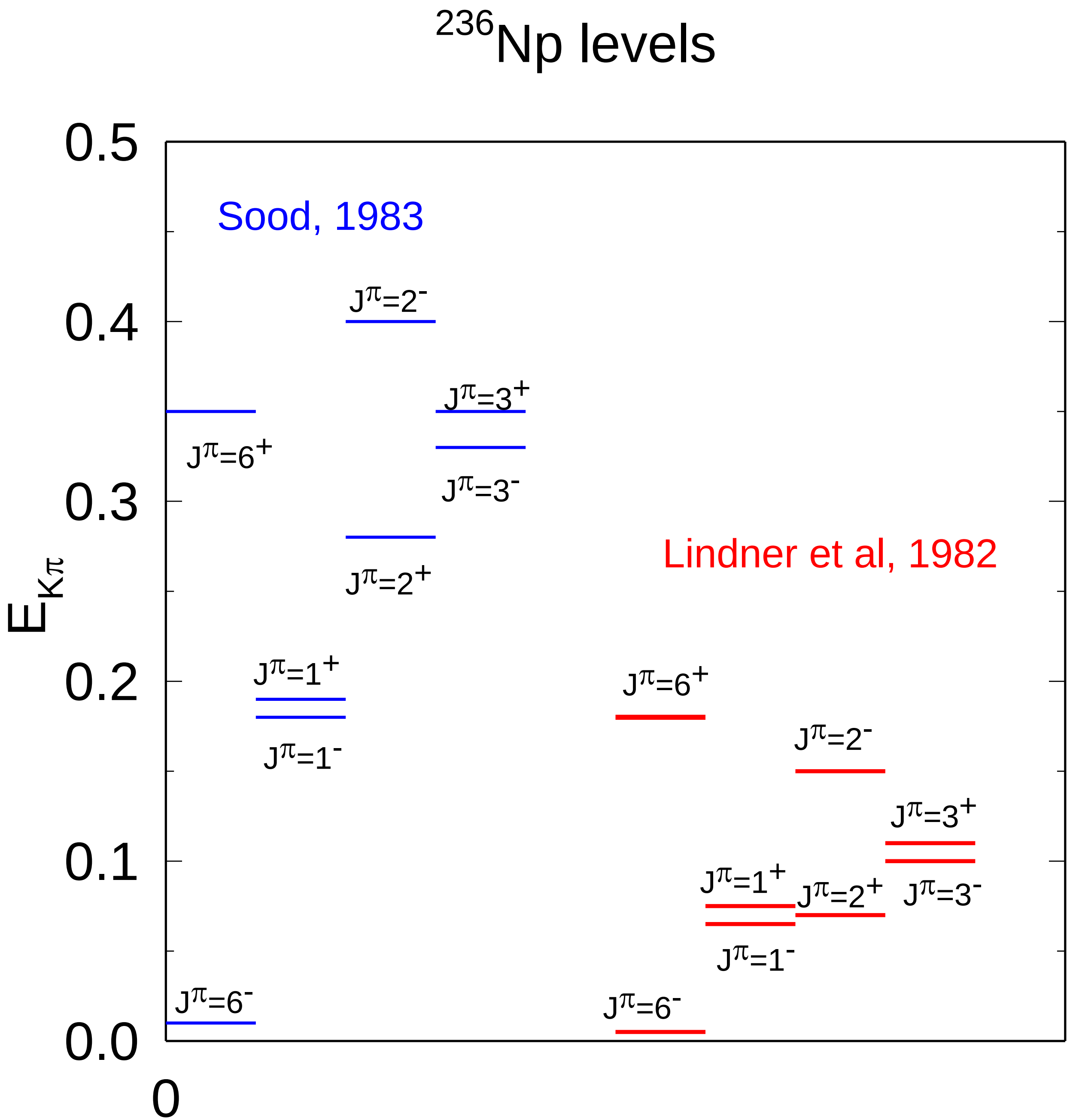
$$W(U, J^{\pi}) = \sum_{k} W_k(U, J^{\pi})$$

$$W(U, J^{\pi}) = \sum_{J'\pi'} \int_{U}^{U_g} \frac{\Gamma_{\gamma}(U', J^{\pi}{}', U, J^{\pi})}{\Gamma(U', J^{\pi}{}')} W(U', J^{\pi}{}') dU' + W_0(U, J^{\pi})$$

$$r(E_n) = \frac{\sum\limits_{J > (J_l + J_s)/2} W(U, J^\pi)}{\sum\limits_{J \le (J_l + J_s)/2} W(U, J^\pi)}$$

$$r(E_n) = \sigma^l_{\mathrm{n2n}}(E_n) / \sigma^s_{\mathrm{n2n}}(E_n)$$

$$\sigma^s_{\mathrm{n2n}}(E_n) = \sigma_{\mathrm{n2n}}(E_n) / (1 + r(E_n))$$



236Np levels
Sood, 1983
Lindner et al, 1982
E_Kπ
0.5
0.4
0.3
0.2
0.1
0.0
0
Jπ=2-
Jπ=3+
Jπ=6+
Jπ=3-
Jπ=2+
Jπ=1+
Jπ=1-
Jπ=6-
Jπ=6+
Jπ=2-
Jπ=3+
Jπ=1+
Jπ=2+
Jπ=3-
Jπ=1-
Jπ=6-

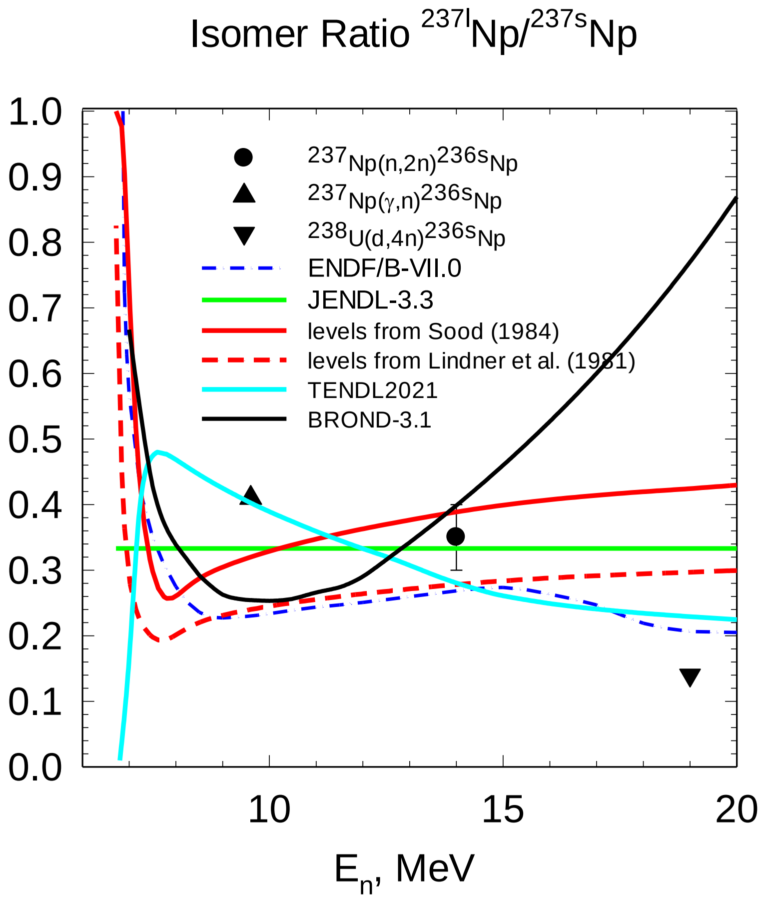
Splitted Gallaher-Moshkowski doublets

$$K^{+} = \left| K_n + K_p \right| \qquad K^{-} = \left| K_n - K_p \right|$$

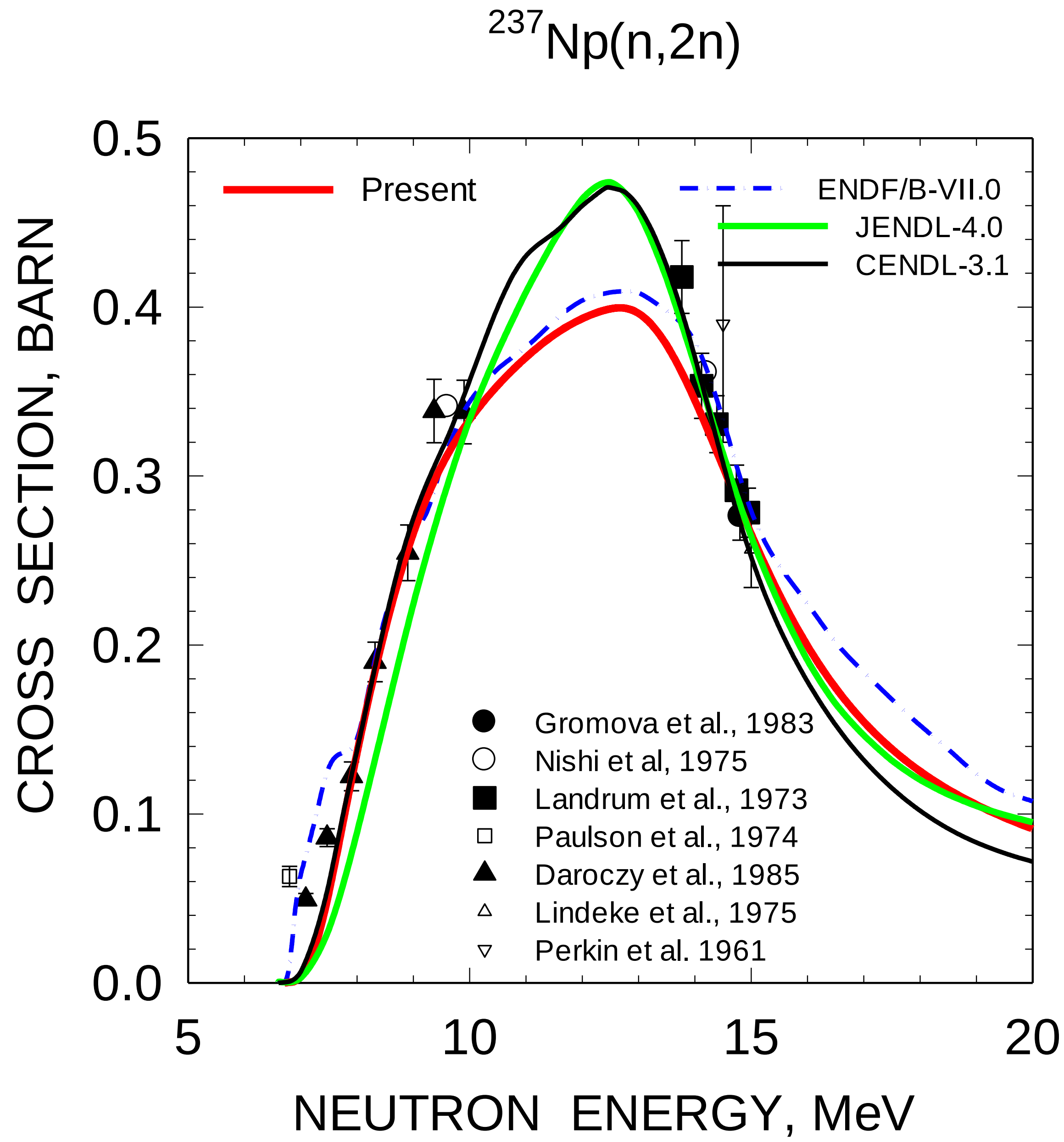
Rotational bands are build on two-quasiparticle states

$$E_{JK\pi} = E_{JK} + 5.5\left[J(J+1) - K(K+1) \right]$$

$$N(U) = e^{2\Delta_0 / T}\left(e^{U/T} - 1\right)$$

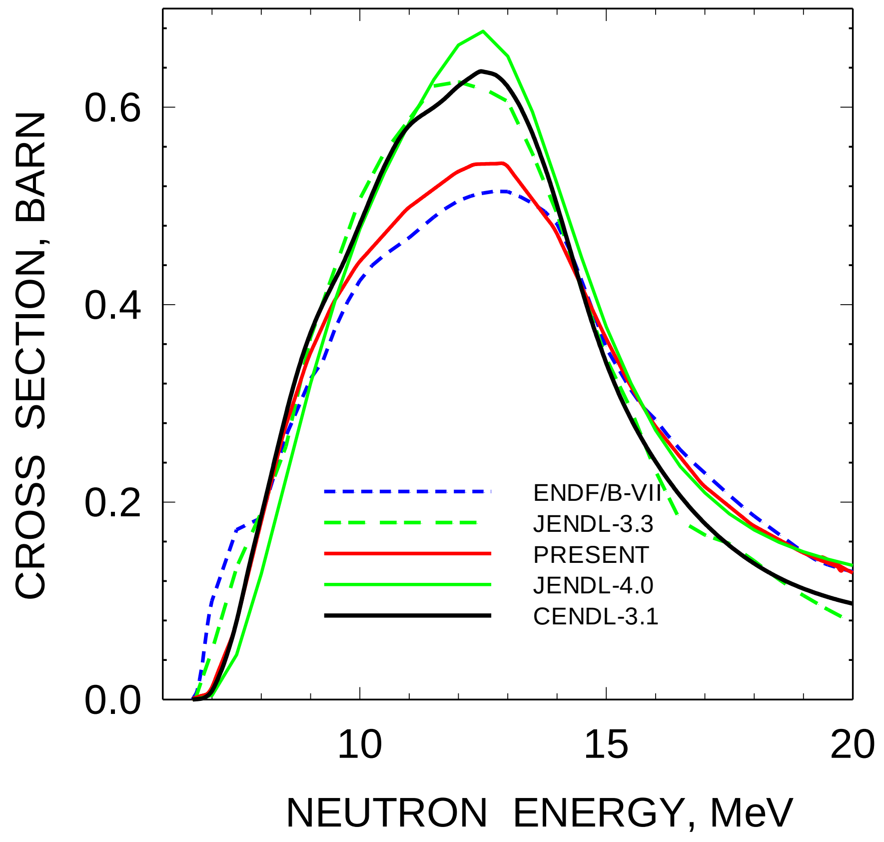


Isomer Ratio $^{237l}Np/^{237s}Np$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10
15
20
E_n, MeV
$^{237}Np(n,2n)^{236s}Np$
$^{237}Np(\gamma,n)^{236s}Np$
$^{238}U(d,4n)^{236s}Np$
ENDF/B-VII.0
JENDL-3.3
levels from Sood (1984)
levels from Lindner et al. (1981)
TENDL2021
BROND-3.1

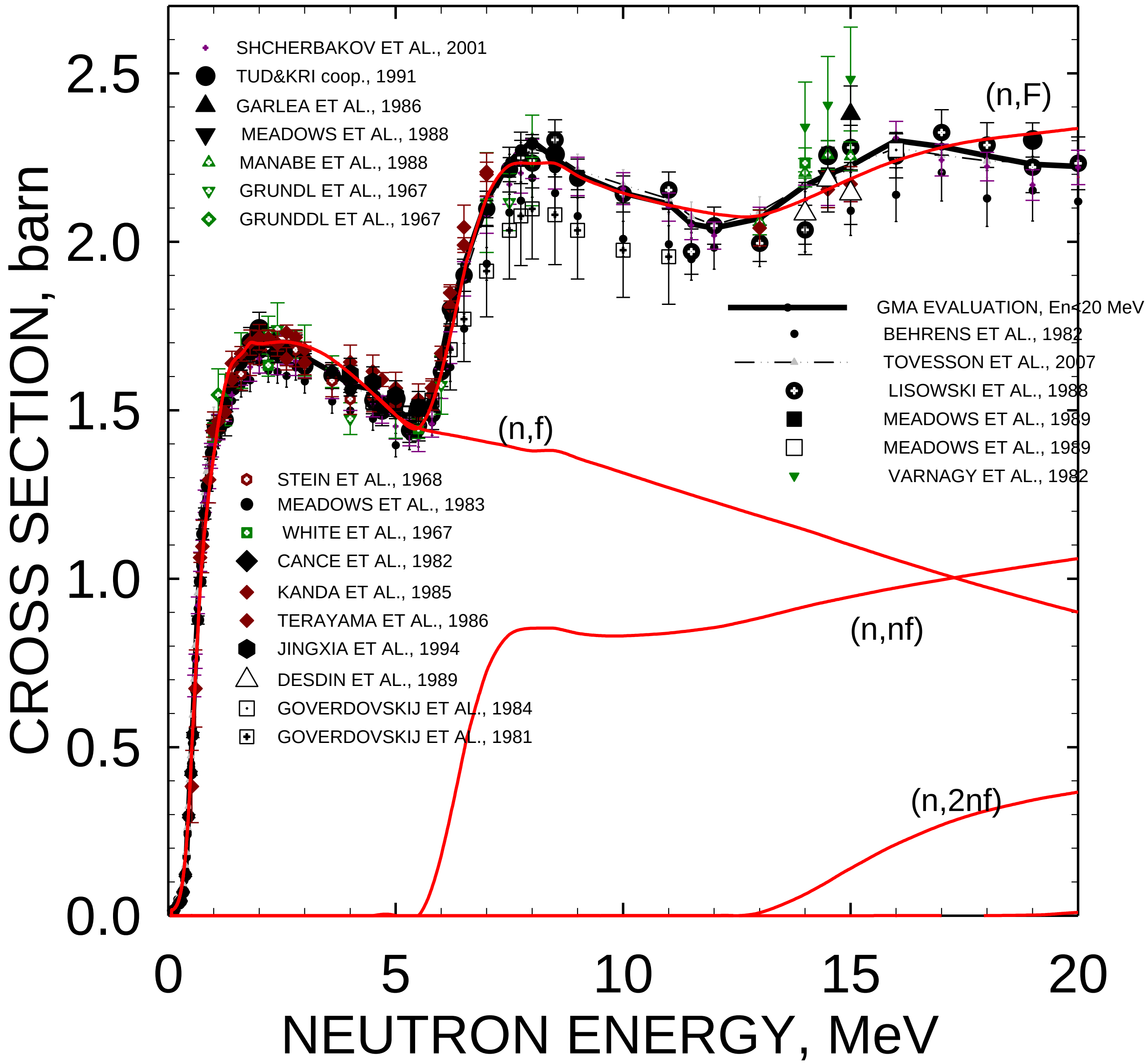


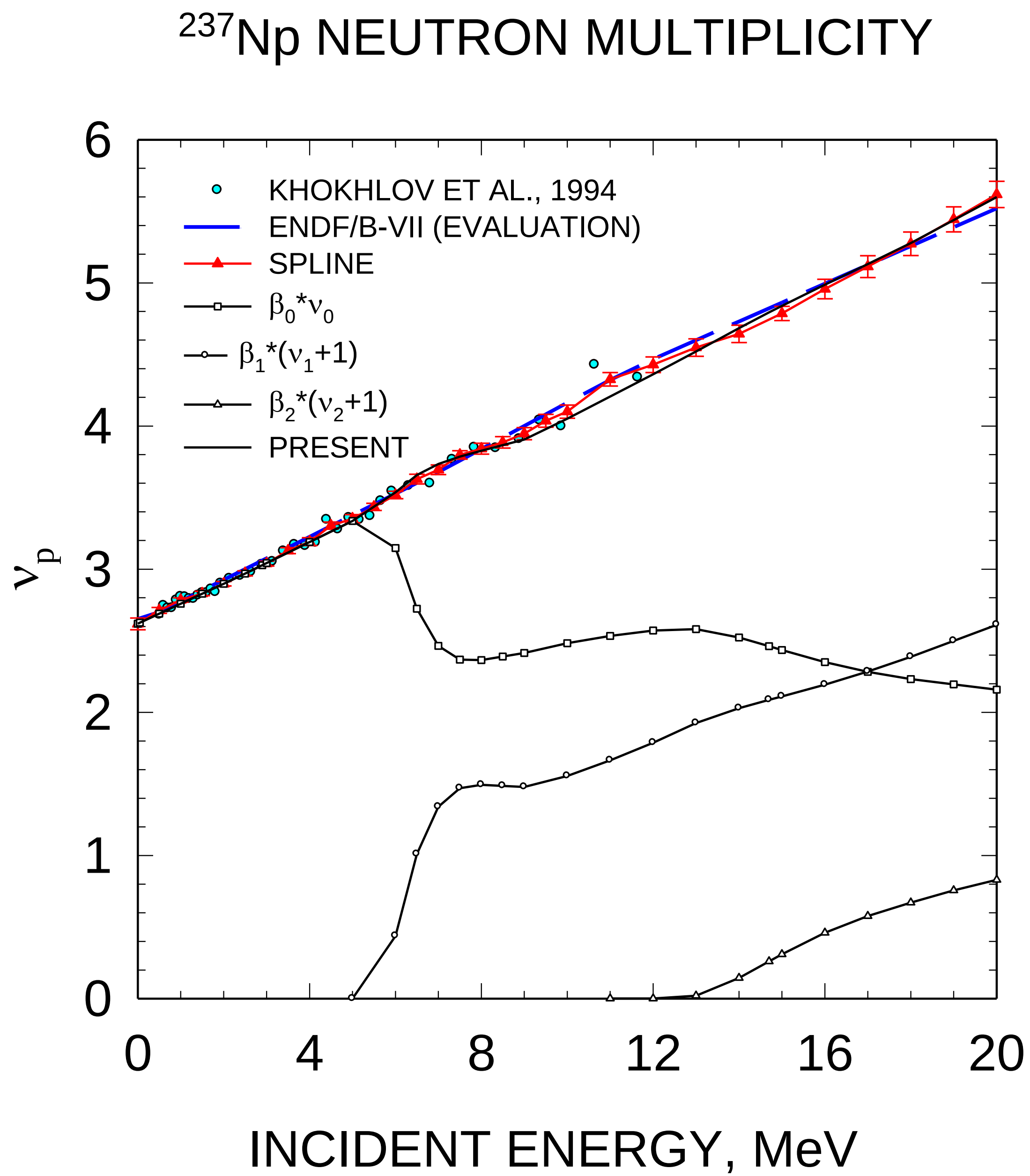
^{237}Np(n,2n)
0.5
0.4
0.3
0.2
0.1
0.0
CROSS SECTION, BARN
5
10
15
20
NEUTRON ENERGY, MeV
Present
ENDF/B-VII.0
JENDL-4.0
CENDL-3.1
Gromova et al., 1983
Nishi et al, 1975
Landrum et al., 1973
Paulson et al., 1974
Daroczy et al., 1985
Lindeke et al., 1975
Perkin et al. 1961

^{237}Np (N,2N) CROSS SECTION



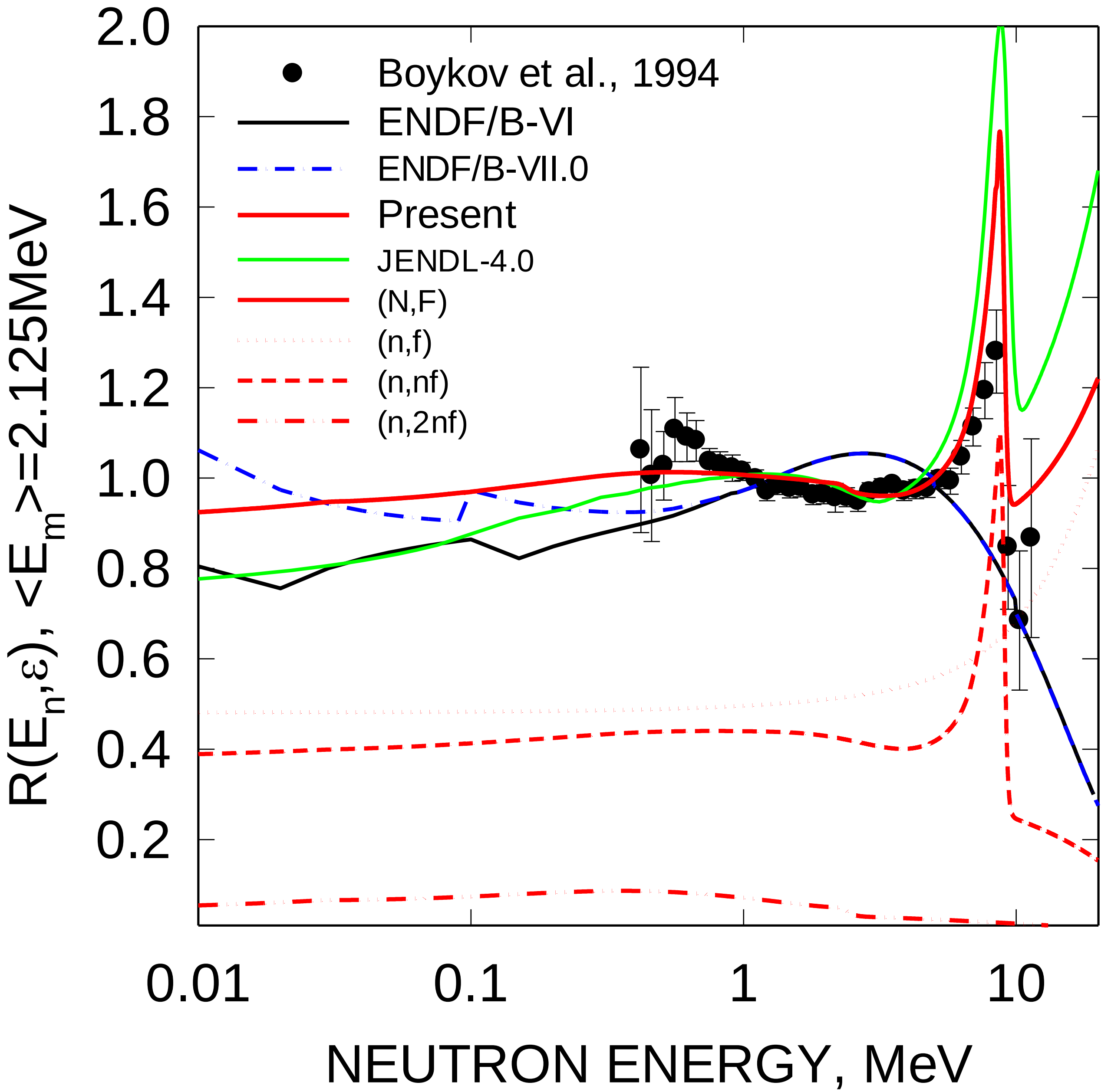
^{237}Np FISSION CROSS SECTION



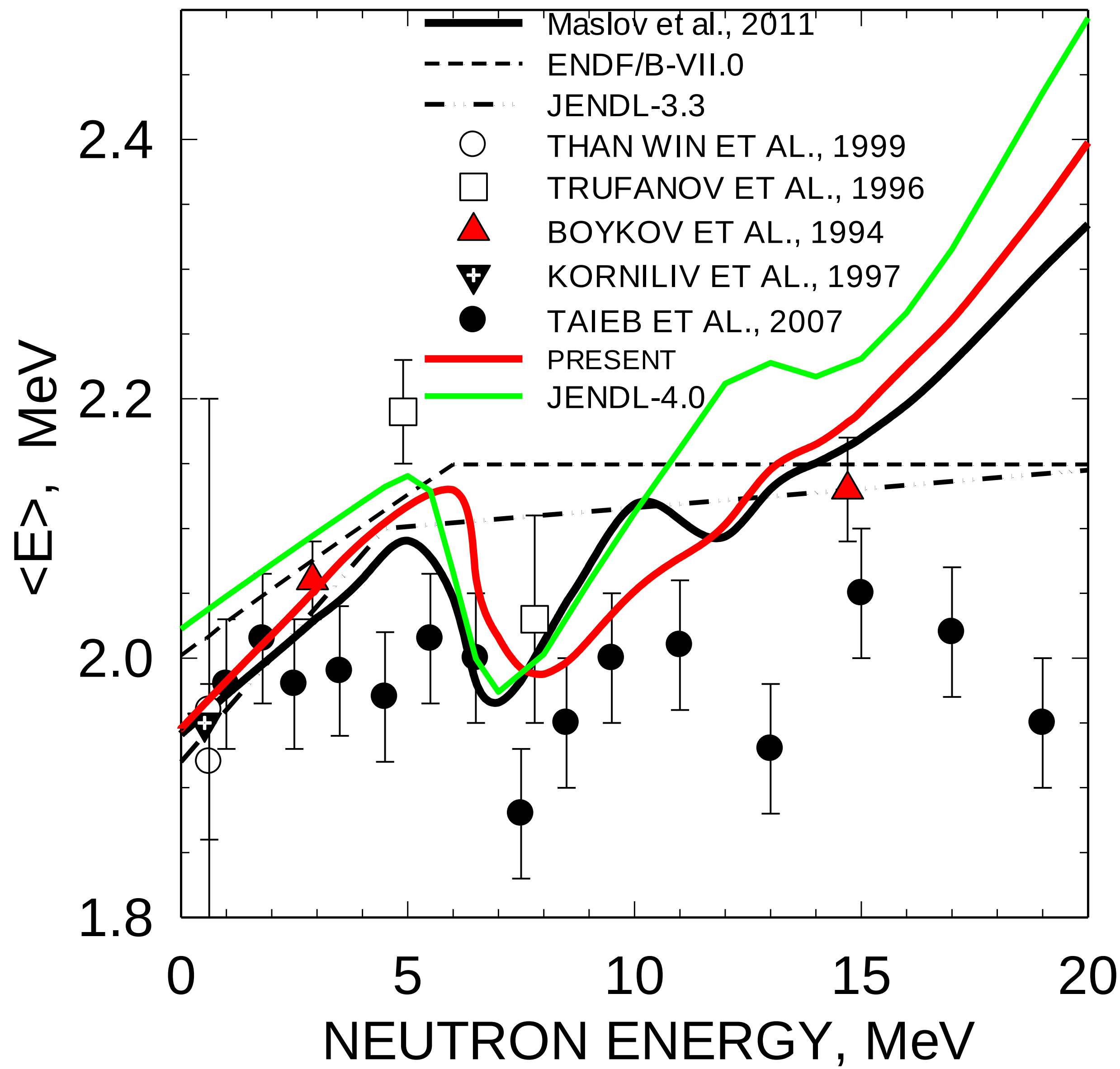


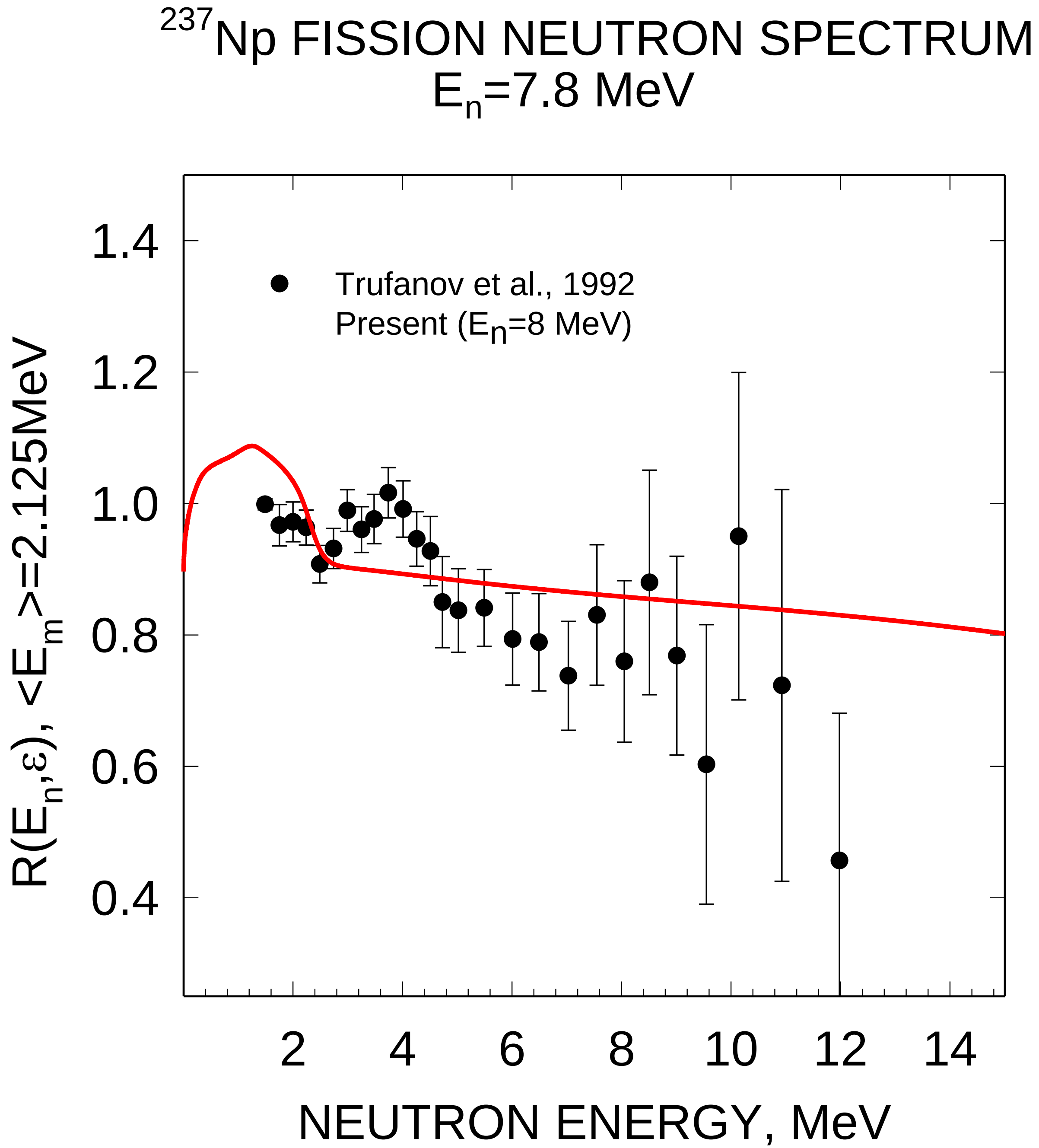
237Np NEUTRON MULTIPLICITY
KHOKHLOV ET AL., 1994
ENDF/B-VII (EVALUATION)
SPLINE
β0*ν0
β1*(ν1+1)
β2*(ν2+1)
PRESENT
νp
INCIDENT ENERGY, MeV
0
1
2
3
4
5
6
0
4
8
12
16
20

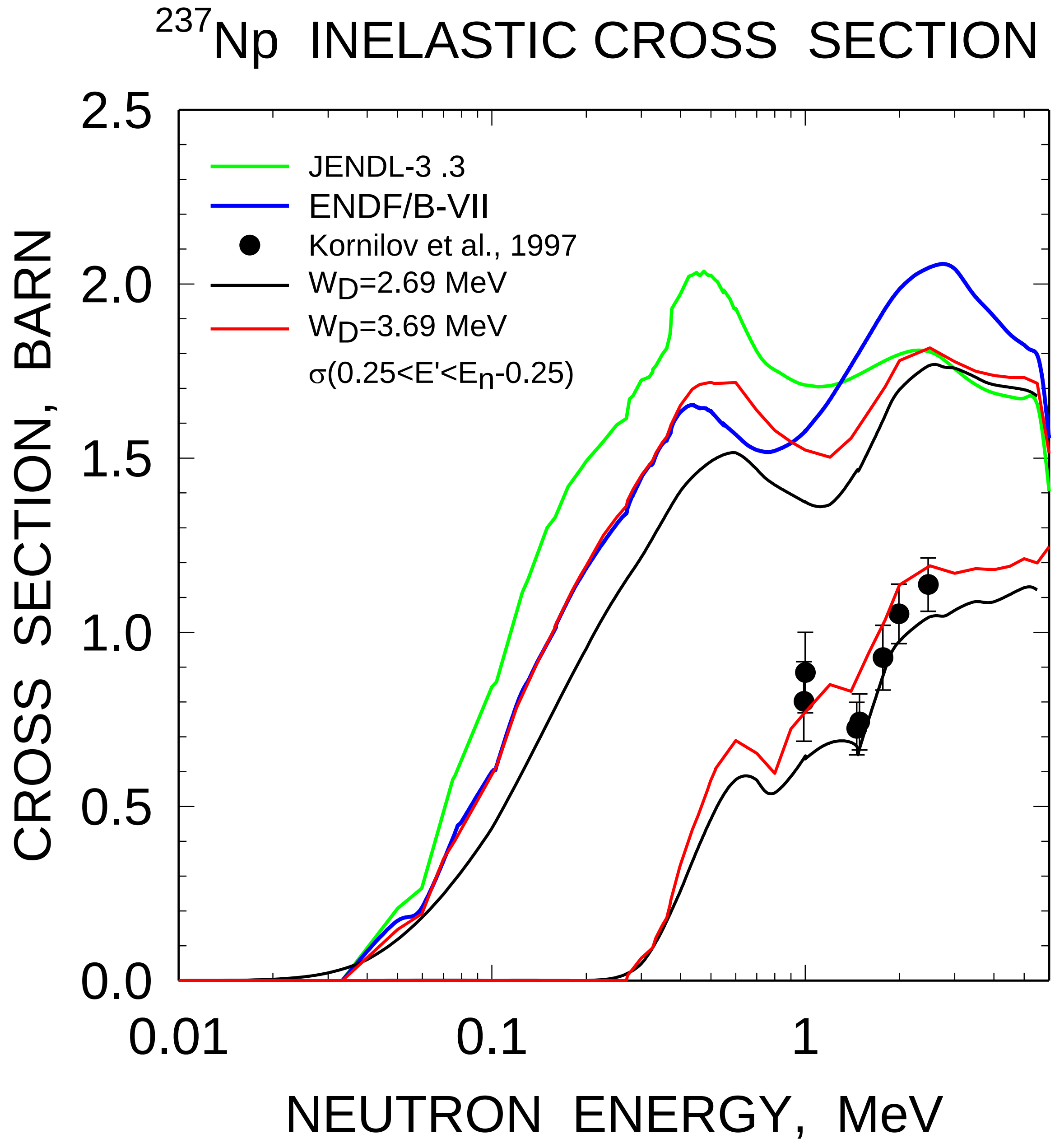
^{237}Np FISSION NEUTRON SPECTRUM, E_n=14.7MeV



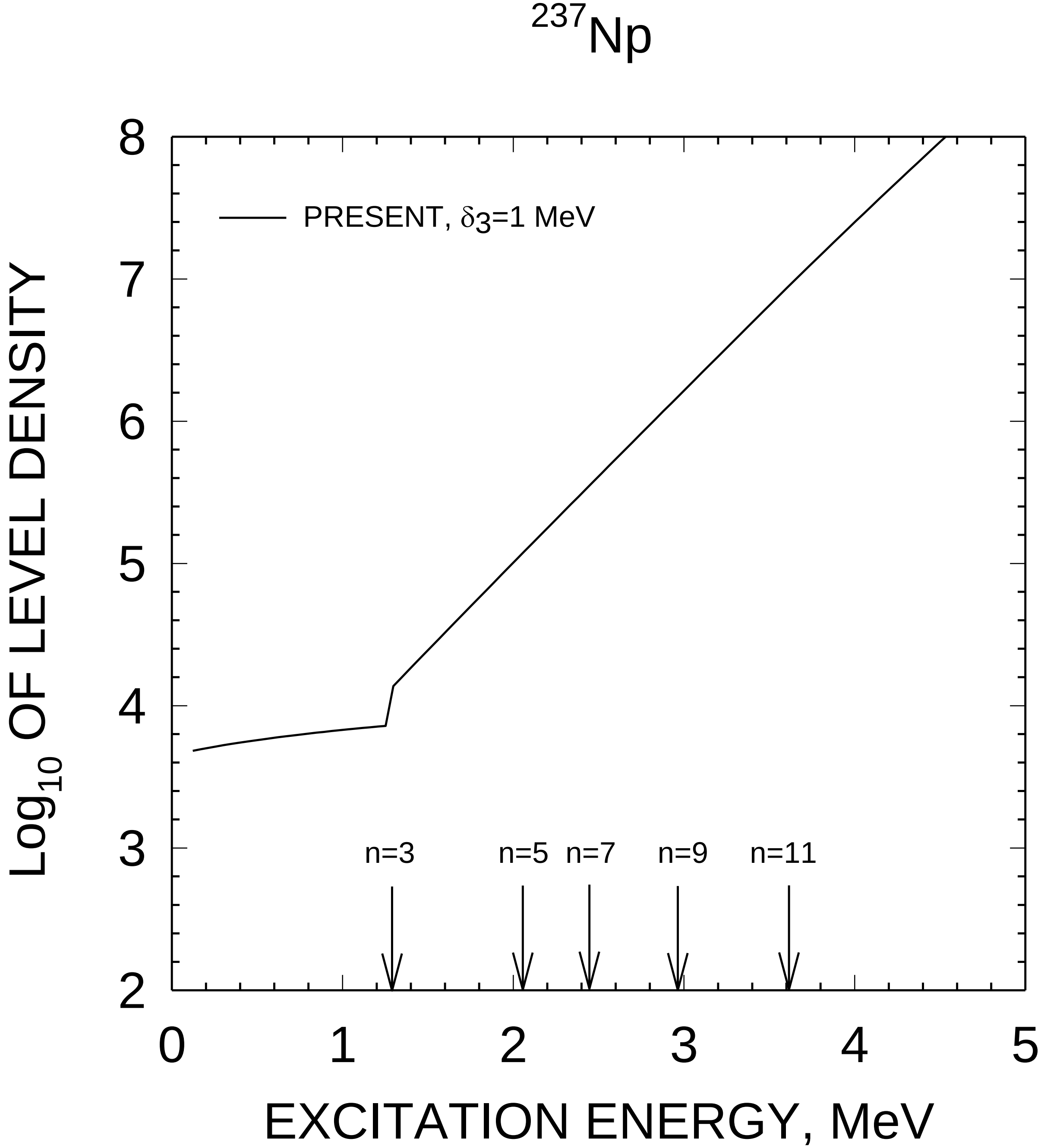
^{237}Np, AVERAGE PROMPT FISSION NEUTRON ENERGY



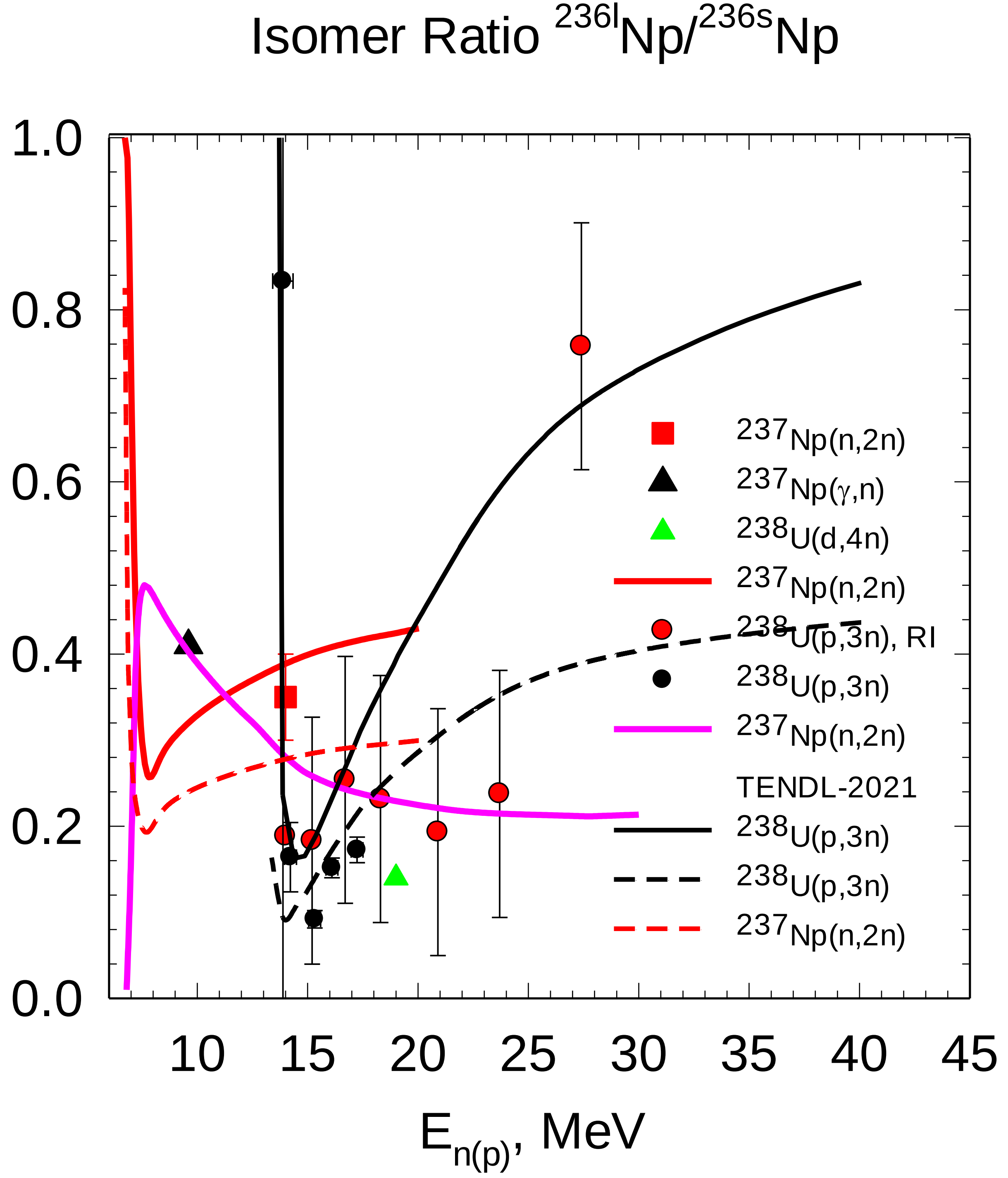

237Np FISSION NEUTRON SPECTRUM
En=7.8 MeV
Trufanov et al., 1992
Present (En=8 MeV)
R(En,ε), <Em>=2.125MeV
NEUTRON ENERGY, MeV
1.4
1.2
1.0
0.8
0.6
0.4
2
4
6
8
10
12
14



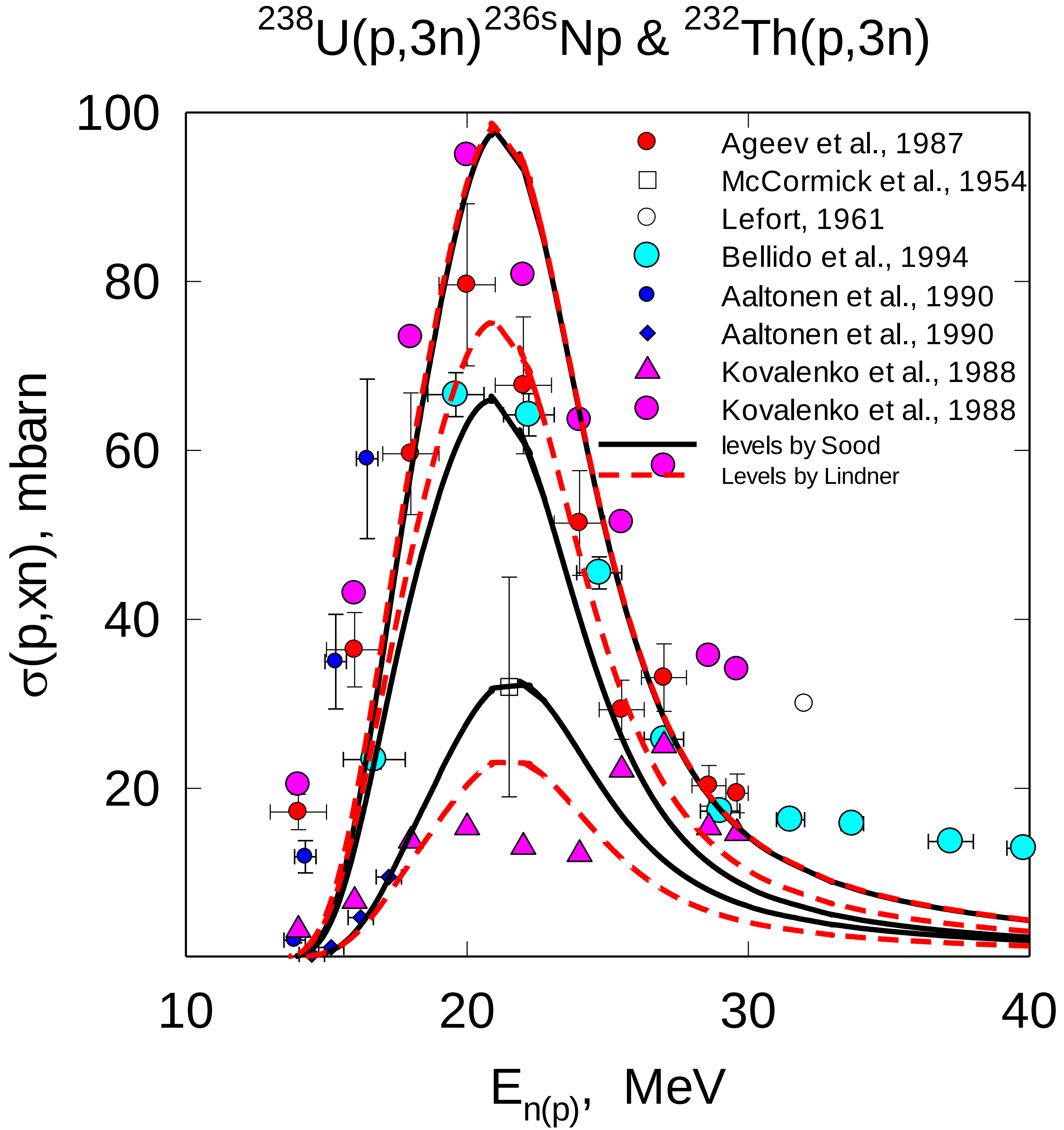
^{237}Np INELASTIC CROSS SECTION
2.5
2.0
1.5
1.0
0.5
0.0
CROSS SECTION, BARN
0.01
0.1
1
NEUTRON ENERGY, MeV
JENDL-3 .3
ENDF/B-VII
Kornilov et al., 1997
W_D=2.69 MeV
W_D=3.69 MeV
$\sigma(0.25<E'<E_n-0.25)$



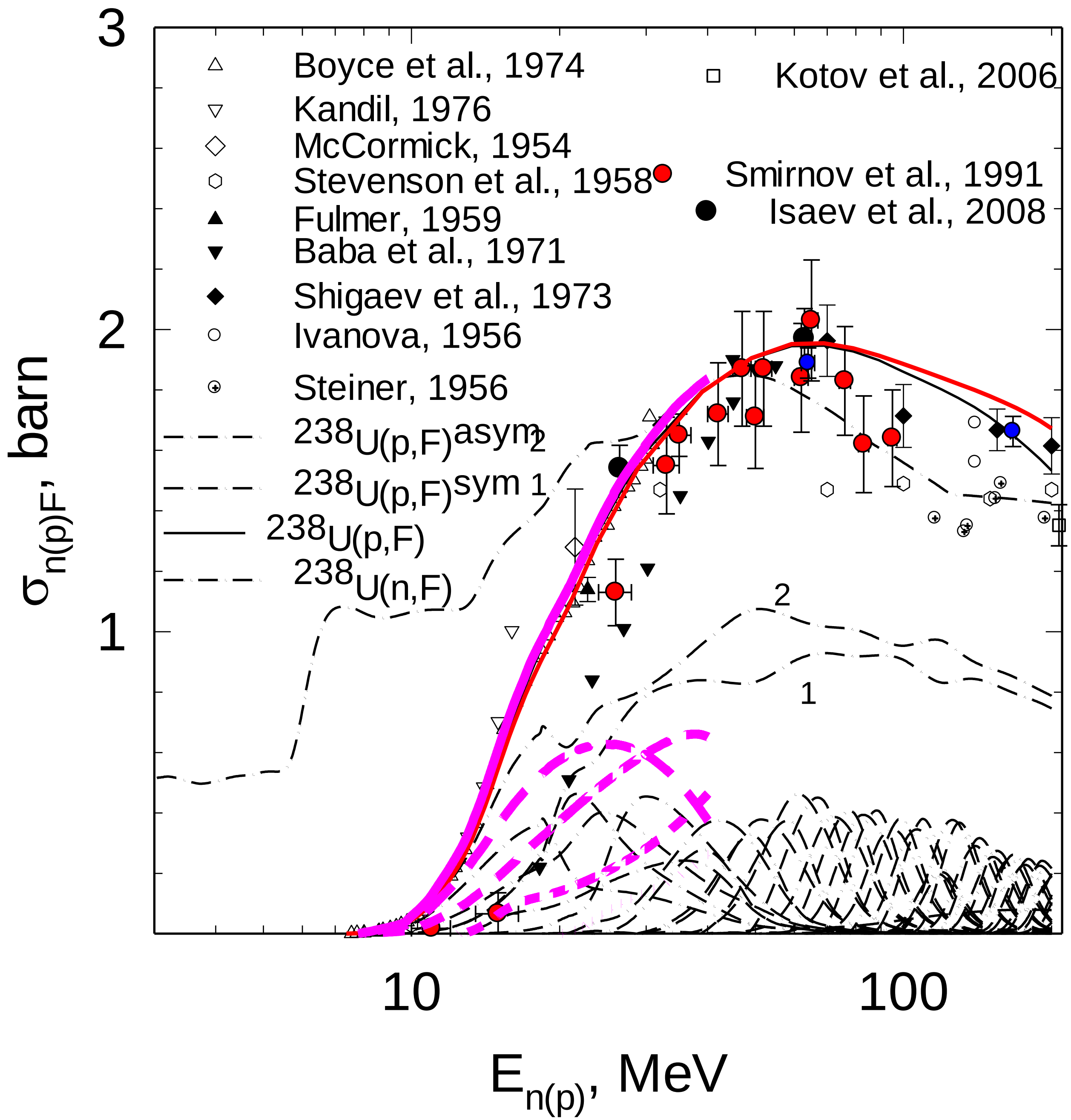
^{237}Np
PRESENT, δ3=1 MeV
Log10 OF LEVEL DENSITY
EXCITATION ENERGY, MeV
8
7
6
5
4
3
2
0
1
2
3
4
5
n=3
n=5
n=7
n=9
n=11



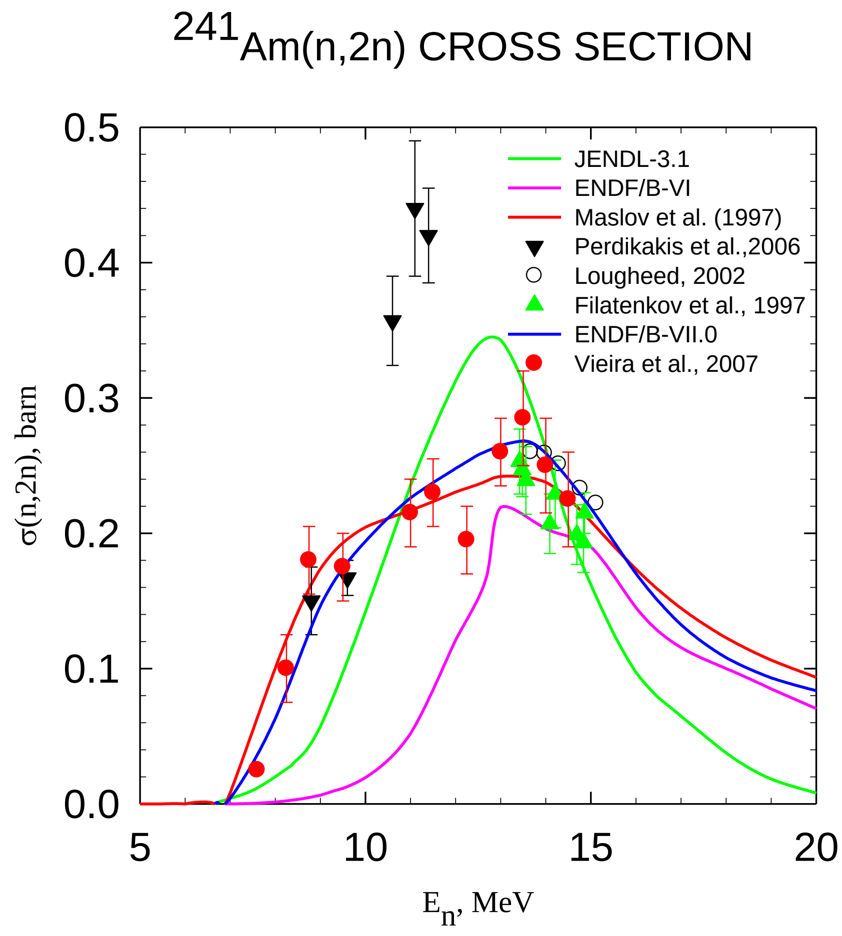
Isomer Ratio 236lNp/236sNp
1.0
0.8
0.6
0.4
0.2
0.0
10
15
20
25
30
35
40
45
En(p), MeV
237Np(n,2n)
237Np(γ,n)
238U(d,4n)
237Np(n,2n)
238U(p,3n), RI
238U(p,3n)
237Np(n,2n)
TENDL-2021
238U(p,3n)
238U(p,3n)
237Np(n,2n)



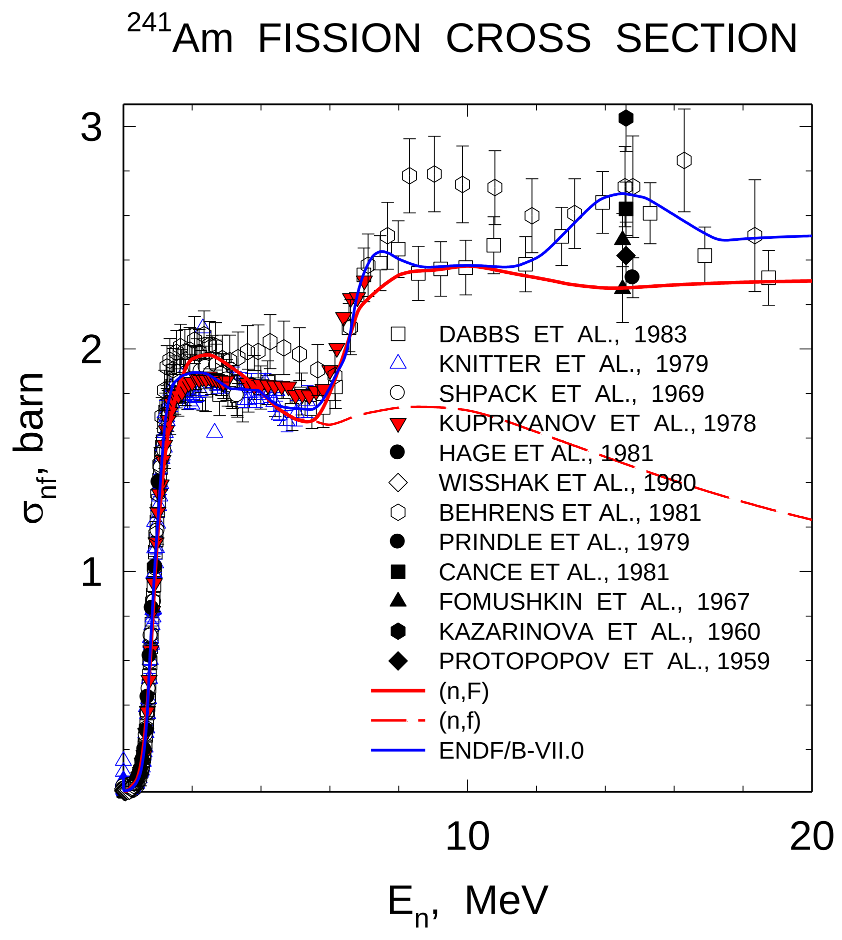
^{238}U(p,3n)^{236s}Np & ^{232}Th(p,3n)
100
80
60
40
20
10
20
30
40
σ(p,xn), mbarn
$E_{n(p)}$, MeV
Ageev et al., 1987
McCormick et al., 1954
Lefort, 1961
Bellido et al., 1994
Aaltonen et al., 1990
Aaltonen et al., 1990
Kovalenko et al., 1988
Kovalenko et al., 1988
levels by Sood
Levels by Lindner



3
2
1
10
100
$\sigma_{n(p)F}$, barn
$E_{n(p)}$, MeV
Boyce et al., 1974
Kandil, 1976
McCormick, 1954
Stevenson et al., 1958
Fulmer, 1959
Baba et al., 1971
Shigaev et al., 1973
Ivanova, 1956
Steiner, 1956
238U(p,F)asym 2
238U(p,F)sym 1
238U(p,F)
238U(n,F)
Kotov et al., 2006
Smirnov et al., 1991
Isaev et al., 2008
2
1



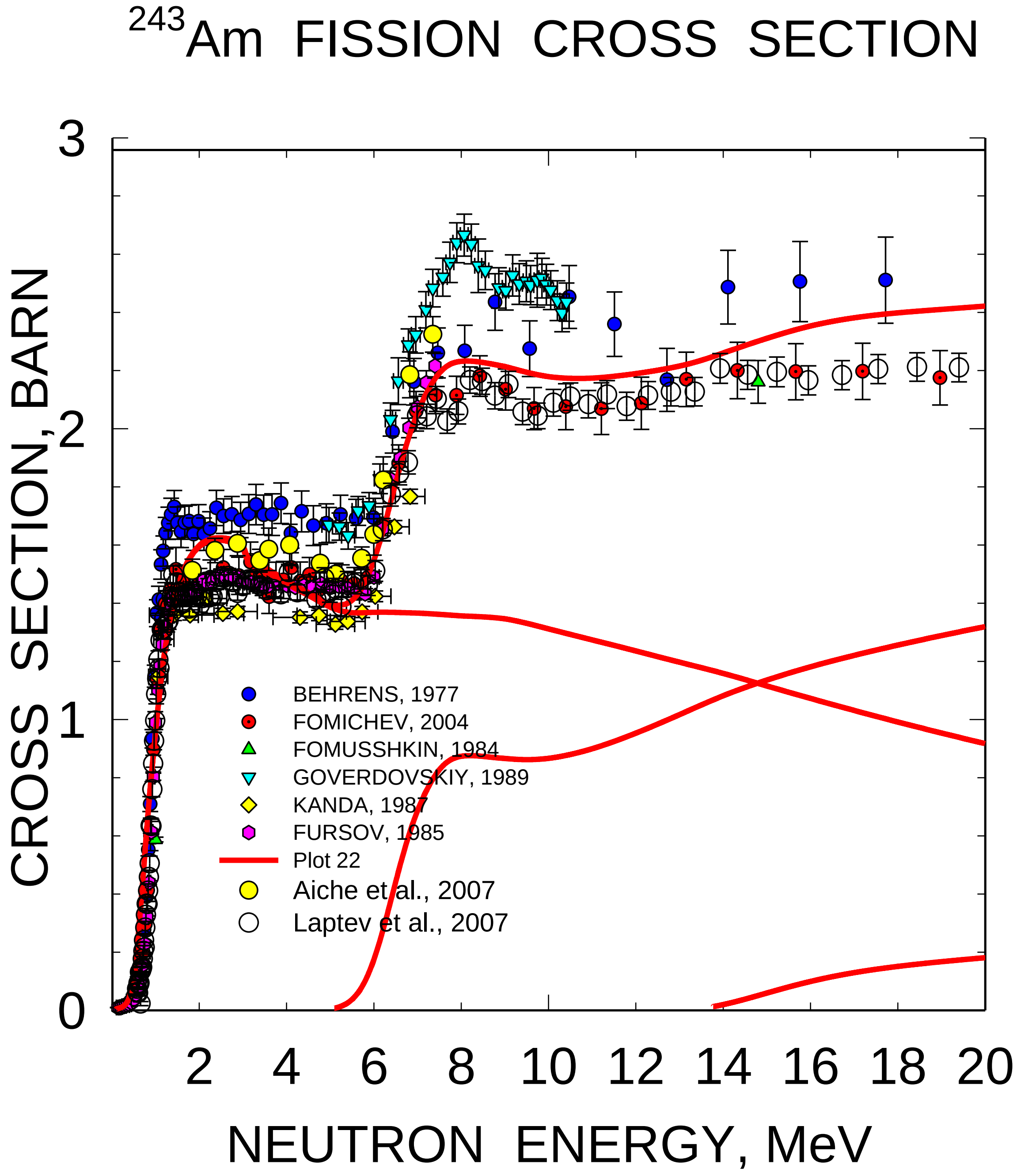
^{241}Am(n,2n) CROSS SECTION
σ(n,2n), barn
E_n, MeV
JENDL-3.1
ENDF/B-VI
Maslov et al. (1997)
Perdikakis et al.,2006
Lougheed, 2002
Filatenkov et al., 1997
ENDF/B-VII.0
Vieira et al., 2007



^{241}Am FISSION CROSS SECTION
σ_{nf}, barn
E_n, MeV
DABBS ET AL., 1983
KNITTER ET AL., 1979
SHPACK ET AL., 1969
KUPRIYANOV ET AL., 1978
HAGE ET AL., 1981
WISSHAK ET AL., 1980
BEHRENS ET AL., 1981
PRINDLE ET AL., 1979
CANCE ET AL., 1981
FOMUSHKIN ET AL., 1967
KAZARINOVA ET AL., 1960
PROTOPOPOV ET AL., 1959
(n,F)
(n,f)
ENDF/B-VII.0

ISOMER RATIOS FOR $^{241}Am(n, \gamma)$ AND $^{243}Am(n, 2n)$ REACTIONS

- Obtained in the same manner


243Am FISSION CROSS SECTION
CROSS SECTION, BARN
NEUTRON ENERGY, MeV
0
1
2
3
2
4
6
8
10
12
14
16
18
20
BEHRENS, 1977
FOMICHEV, 2004
FOMUSSHKIN, 1984
GOVERDOVSKIY, 1989
KANDA, 1987
FURSOV, 1985
Plot 22
Aiche et al., 2007
Laptev et al., 2007