**EFNUDAT – Fast Neutrons Workshop**
**EC/JRC/IRMM, Geel, Belgium, 28-30 April 2009**

# On Consistent analysis of $^{50,52,53,54}$Cr fast-neutron activation (problems)

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http://tandem.nipne.ro/~vavrig/, http://fp6.cordis.lu/fp6/partners/RCN 49105

- **Present status of fast-neutron activation analysis for $^{50,52,53,54}$Cr isotopes**
  - EFFDOC-1045 (May 2008): nuclear models calculations @ $E_n$<60 MeV
    - Global Approach: TALYS-1.0; EMPIRE-2.19
    - Local Approach: STAPRE-H
- **Related questions of neutron OMP**
- **Related questions of proton OMP**
- **Related questions of E1 gamma-ray strengths functions**
- **Related questions of nuclear level densities**
- **Consistent disagreement of calculated activation cross sections**
- **(Conclusions)**

PHYSICAL REVIEW C VOLUME 58, NUMBER 2 AUGUST 1998



# Excitation functions of $(n,2n)$, $(n,p)$, $(n,np+pn+d)$, and $(n,\alpha)$ reactions on isotopes of chromium

A. Fessler,[1,2] E. Wattecamps,[2] D. L. Smith,[2,3] and S. M. Qaim[1]
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[2]*Commission of the European Communities, Joint Research Centre, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium*
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(Received 23 April 1998)

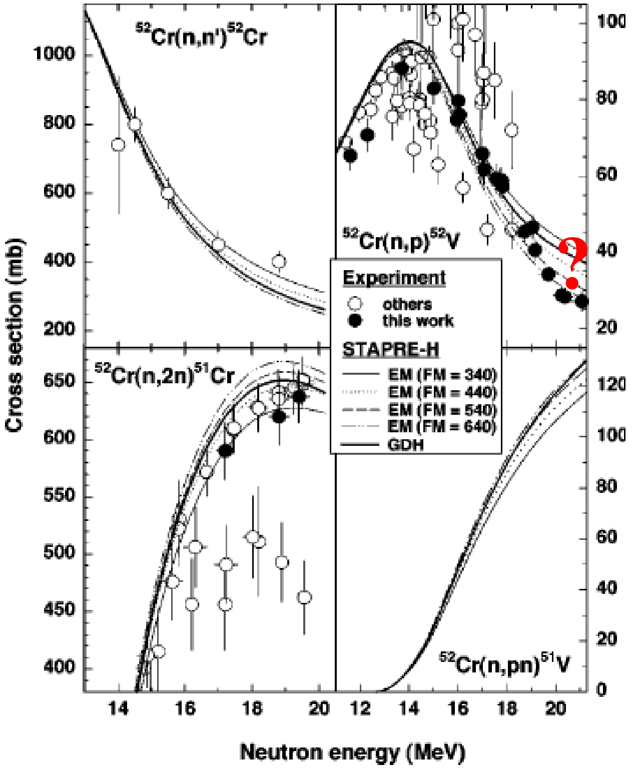


FIG. 8. Influence of the $F_M$ parameter in the exciton mo the excitation functions of different reactions on $^{52}$Cr, and co son with the results of the GDH model.

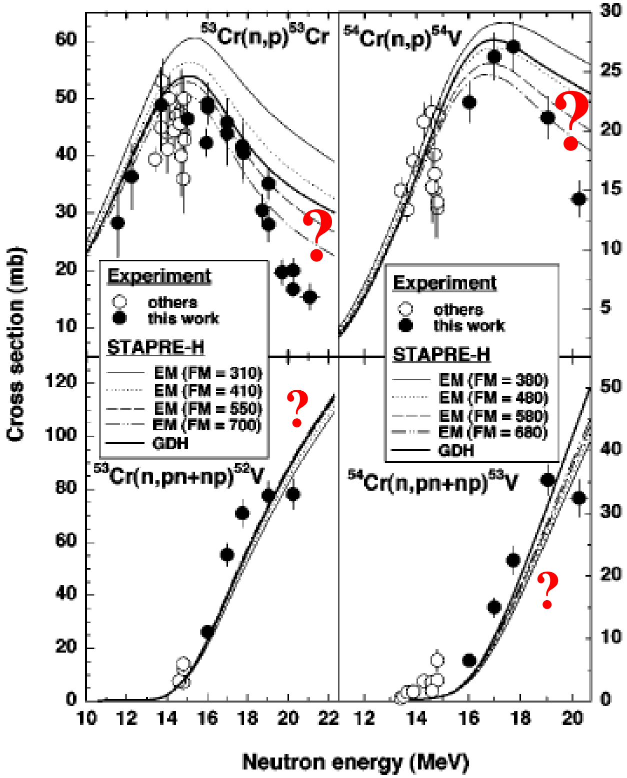


FIG. 9. Influence of the $F_M$ parameter in the exciton mod the excitation functions of different reactions on $^{53}$Cr and $^{54}$Cr comparison with the GDH model.

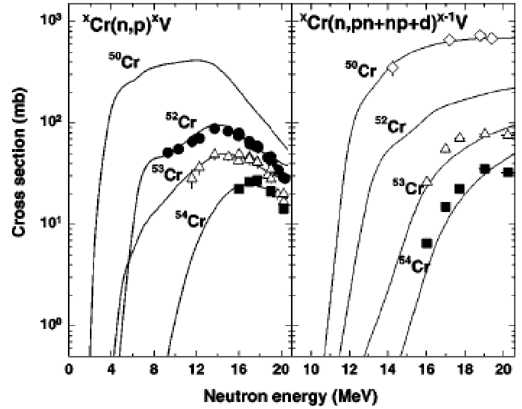


FIG. 10. Systematics of excitation functions of $(n,p)$ and $(n,pn+np+d)$ reactions on Cr isotopes. The symbols represent the experimental data points of this work, the solid lines the STAPRE-H calculations. The data points for the $^{50}$Cr$(n,pn+np+d)^{49}$V process were taken from a recent measurement [67].

[21] M. Avrigeanu and V. Avrigeanu, "Recent Improvements of the STAPRE-H Preequilibrium and Statistical Model Code," Report No. NP-86-1995, IPNE, Bucharest, Romania, 1995.
[27] V. Avrigeaunu, P. E. Hodgson, and M. Avrigeanu, Phys. Rev. C 40, 2136 (1994).
[30] M. Avrigeanu, A. Harangozo, and V. Avrigeanu, "Surface effects in Feshbach-Kerman-Koonin analysis of $(n,n')$ and $(n,p)$ reactions at 7 to 26 MeV," Report No. NP-85-1995, IPNE, Bucharest, Romania, 1995.
[33] M. Avrigeanu and V. Avrigeanu, J. Phys. G **20**, 613 (1994).
[34] M. Avrigeanu, M. Ivascu, and V. Avrigeanu, Z. Phys. A **335**, 299 (1990).

ELSEVIER Nuclear Physics A 748 (2005) 75–111

# Systematic analysis of *n*-activation for $^{50,52}$Cr isotopes

## Calculations and analysis of n + $^{50,52,53,54}$Cr reactions in the $E_n \leqslant 250$ MeV energy range

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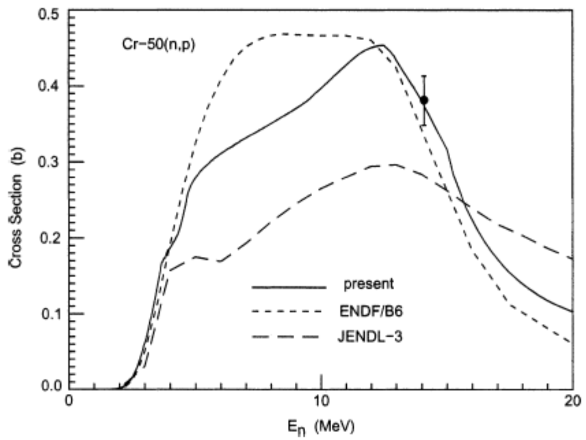
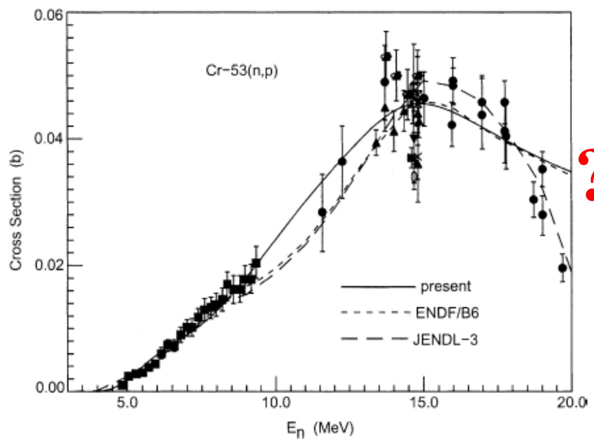



Fig. 22. Calculated (n, p) reaction cross section (solid line) compared with experimental data (sy evaluated data (ENDF/B6 and JENDL-3 libraries) for n + $^{50}$Cr reaction.






?

Fig. 24. Calculated (n, p) reaction cross section (solid line) compared with experimental data ( evaluated data (ENDF/B6 and JENDL-3 libraries) for n + $^{53}$Cr reaction.



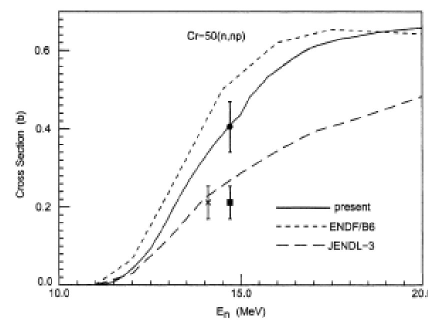



Fig. 28. Calculated (n, np) reaction cross section (solid line) compared with experimental data ( evaluated data (ENDF/B6 and JENDL-3 libraries) for n + $^{50}$Cr reaction.

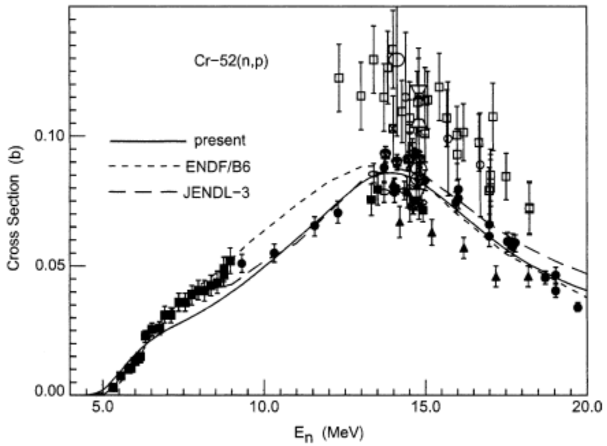



Fig. 23. Calculated (n, p) reaction cross section (solid line) compared with experimental data evaluated data (ENDF/B6 and JENDL-3 libraries) for n + $^{52}$Cr reaction.

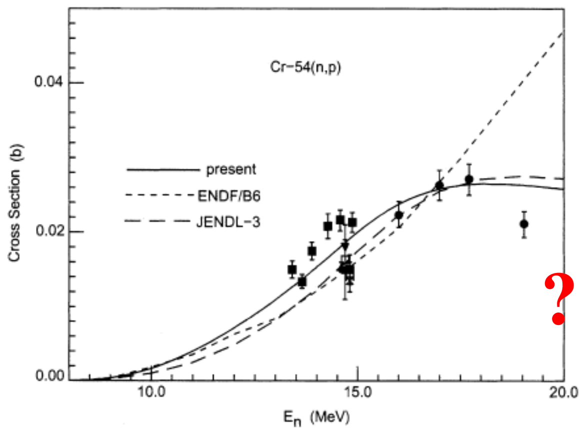



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Fig. 25. Calculated (n, p) reaction cross section (solid line) compared with experimental data ( evaluated data (ENDF/B6 and JENDL-3 libraries) for n + $^{54}$Cr reaction.

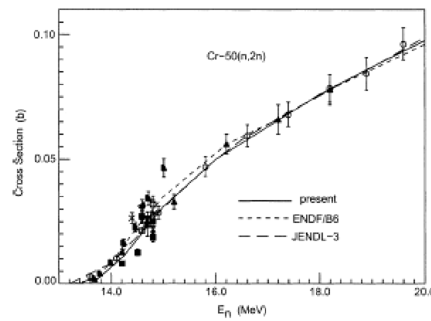



Fig. 29. Calculated (n, 2n) cross sections (solid line) compared with experimental data (symbols) data (ENDF/B6 and JENDL-3 libraries) for n + $^{50}$Cr reaction.

# Original comparison of measurements and results of EMPIRE-II v.2.18 for the target nucleus $^{52}$Cr

[M. Hermann et al., EMPIRE-II v.2.19, p. 171-172; http://www-nds.iaea.org/empire/ ]

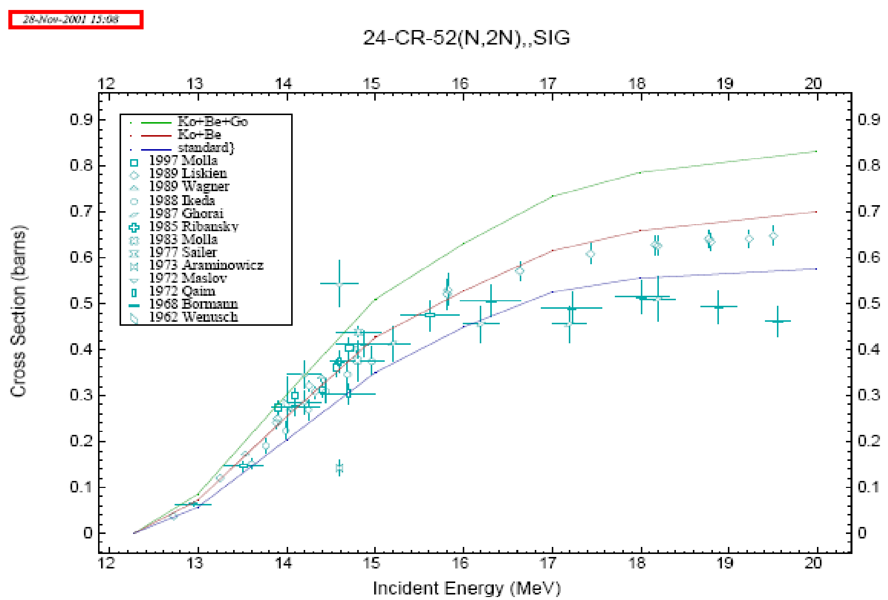



Figure 4.3: Comparison of experimental data with results calculated using three sets of parameters for the $^{52}$Cr(n,2n) reaction (see text).

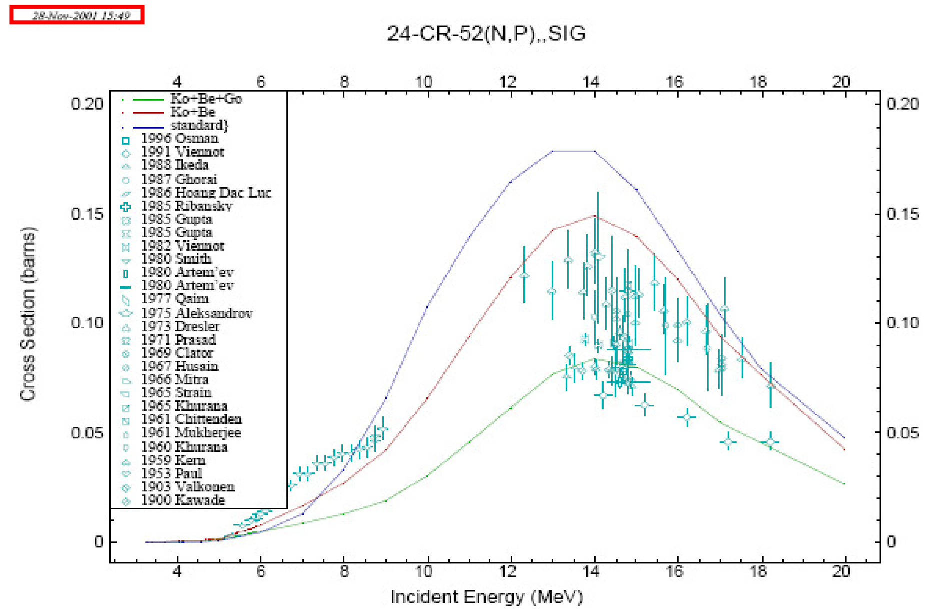



Figure 4.4: Comparison of experimental data with results calculated using three sets of parameters for the $^{52}$Cr(n,p) reaction (see text).

where:

| | |
|---|---|
| standard | Wilmore-Hodgson S-OMP for neutrons and Becchetti-Greenlees for protons, EMPIRE-specific level densities with internal systematics, and discrete levels up to $N_{max} = 10$ (note that in EMPIRE-2.19 Koning-DeLaroche potential is a standard), |
| Ko-Be | Koning-DeLaroche S-OMP for neutrons and protons, discrete levels up to the $N_{max}$ recommended by RIPL-2 (limited to 40 by the ENDF-6 format), and EMPIRE-specific level densities, |
| Ko-Be-Go | as above but using HF-BCS microscopic level densities[53] instead of the EMPIRE-specific ones. |

# Nuclear data (ND) *consistent* model calculations

[ E.D. Arthur – P.G. Young, LANL, '80 ]

[ IAEA/NDS RCs (12), Bucharest, 1982-2005 ]

**YES**

i. unitary use of ***common model parameters*** for different mechanisms

ii. use of ***consistent sets*** of input parameters - determined by ***analyses of various independent*** experimental data

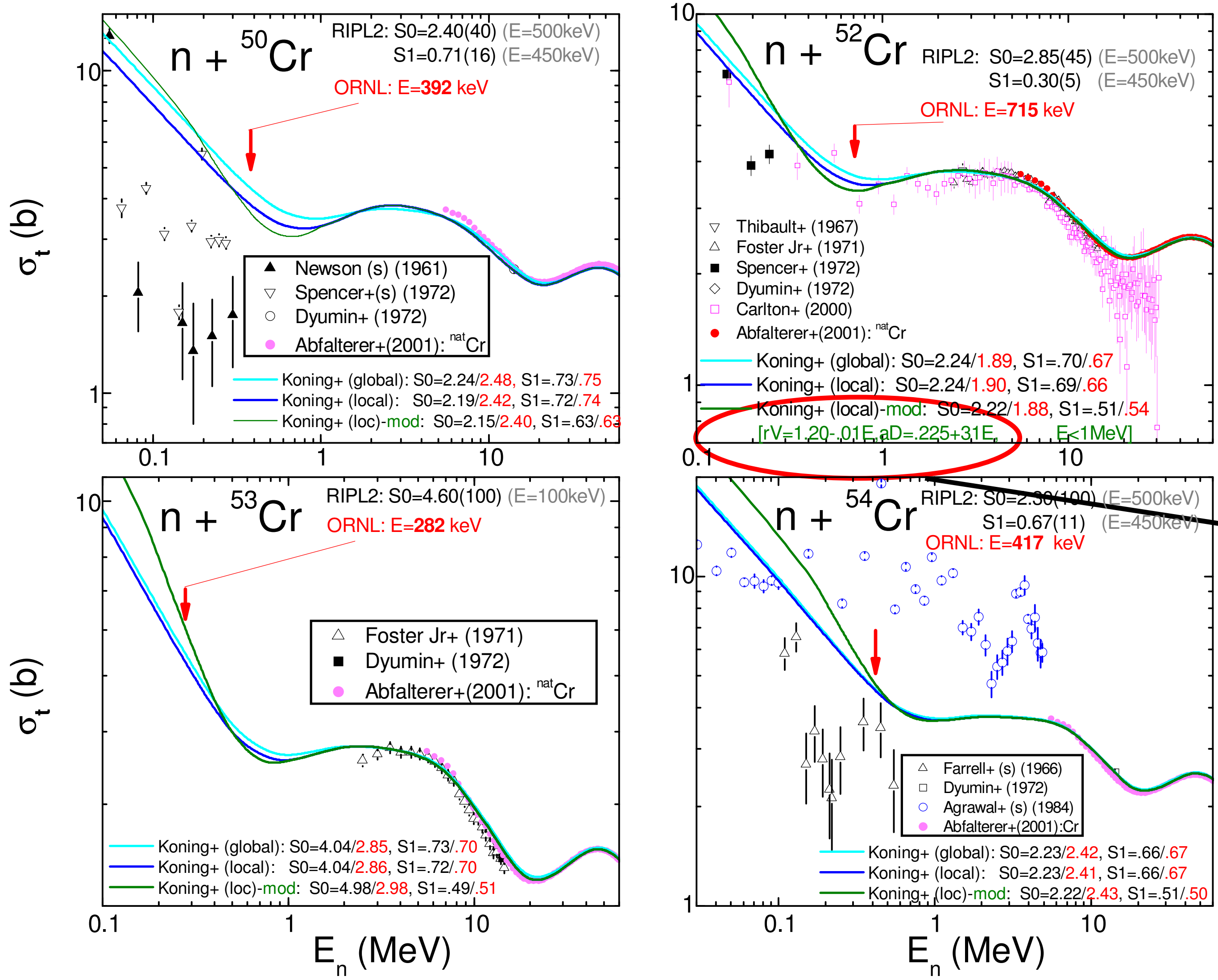
iii. unitary account of ***whole body*** of related experimental data for ***isotope chains*** and ***neighboring elements***

[ activation & particle-emission spectra ]

[ enlarged incident-energy range ]

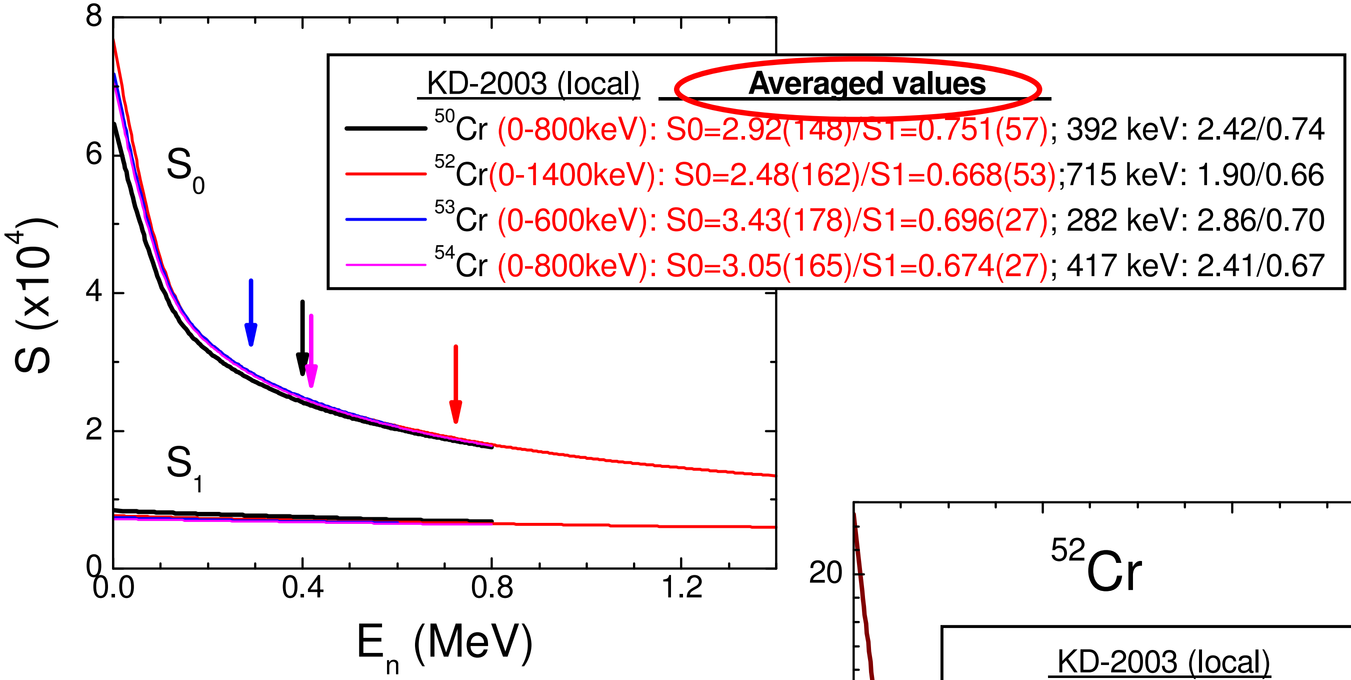
**NO** re-normalization or free parameters (widely-used within ND libraries)

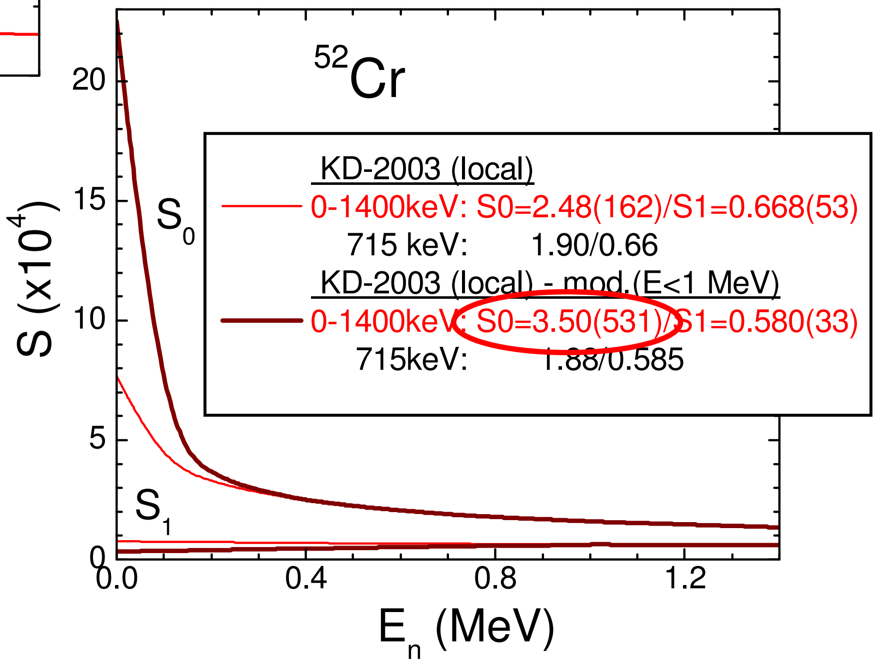
# Comparison of calculated and experimental neutron total cross sections for $^{50,52,53,54}Cr$




$\sigma_t$ decrease of ~7% at $E_n \leq 1$ MeV

# Comparison of calculated and experimental neutron total cross sections for $^{50,52,53,54}Cr$



# Comparison of calculated and experimental neutron total cross sections for $^{50,52,53,54}Cr$

PHYSICAL REVIEW C VOLUME 30, NUMBER 6 DECEMBER 1984

## Parity dependence of the level densities of $^{53}Cr$ and $^{55}Cr$ at high excitation

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*State University of New York, Albany, New York 12222*

J. A. Harvey
*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

(Received 16 July 1984)

The neutron total cross sections of $^{52}Cr$ and $^{54}Cr$ have been measured in the energy range from a few tens of keV to about 900 keV using a neutron time-of-flight technique and a pulsed electron linear accelerator. The nominal resolution of the measurements was about 0.06 ns/m. The total cross-section data have been analyzed using an *R*-matrix multilevel multichannel code to determine values of the resonance parameters ($E_0$, $g\Gamma_n$, and $J^\pi$) and to investigate the parity dependence of the level densities of $^{53}Cr$ and $^{55}Cr$ at high excitation. From these analyses we obtain the following values for the average properties of the resonance parameters for *s*-wave resonances up to about 900 keV and for *p*-wave resonances up to 600 keV: $D_0=(45\pm6)$ keV, $S_0(\times10^4)=(3.0\pm1.0)$, $D_1=(8.5\pm0.6)$ keV, $S_1(\times10^4)=(0.70\pm0.12)$ for $^{52}Cr$; and $D_0=(60\pm9)$ keV, $S_0(\times10^4)=(2.6\pm0.9)$, $D_1=(9.2\pm0.5)$ keV, $S_1(\times10^4)=(0.67\pm0.11)$ for $^{54}Cr$. The distributions of reduced neutron widths for *s*- and *p*-wave resonances for each
Porter-Thomas distribution. The values of the $\Delta_3$ statist
resonances for both $^{52}Cr$ and $^{54}Cr$ are found to be in rea
diction of Dyson and Mehta. The values for the ratio *L*
pected from a $(2J+1)$ level dependence, indicative of a
$^{53}Cr$ and $^{55}Cr$ at high excitation.

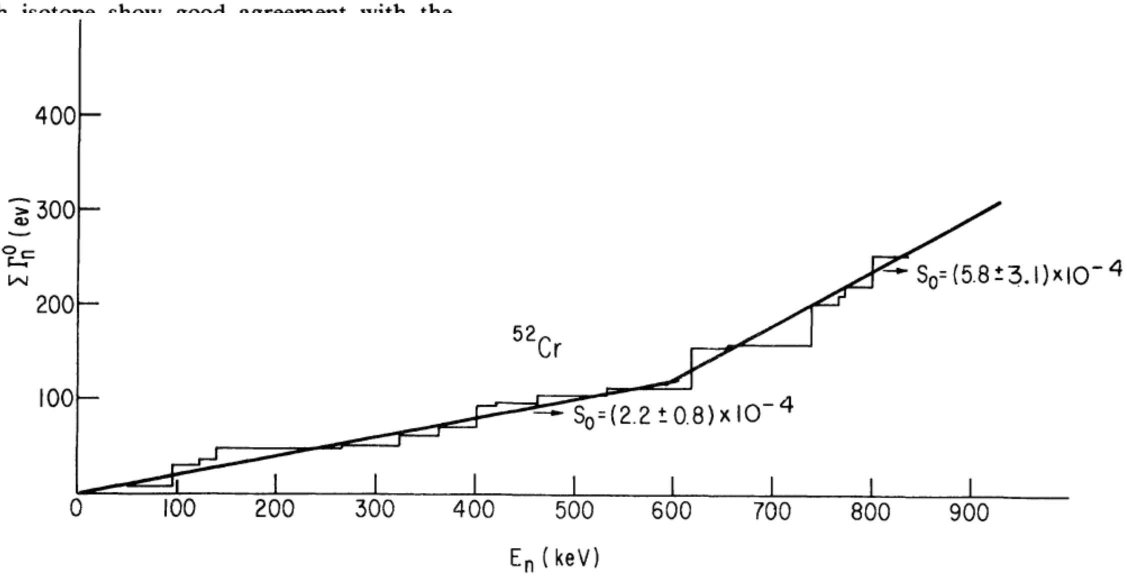
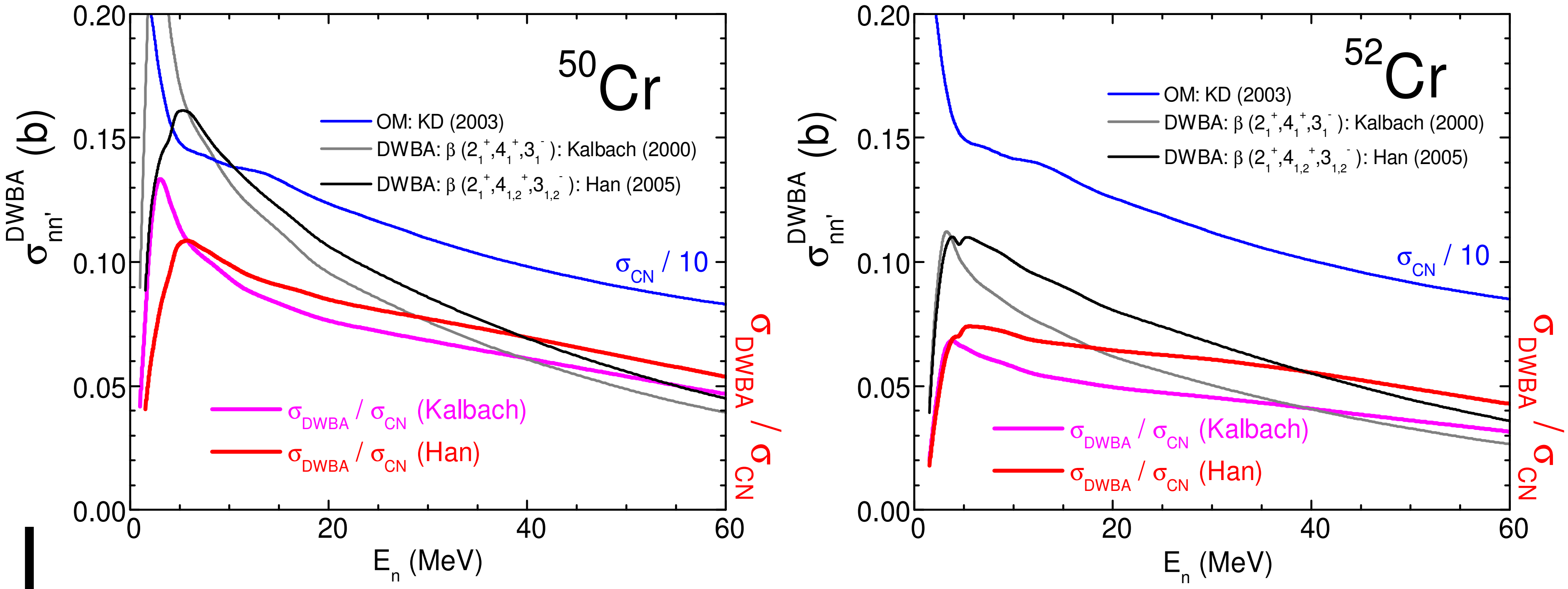



FIG. 5. Sum of reduced neutron widths for $^{52}Cr$ *s*-wave resonances versus neutron energy.

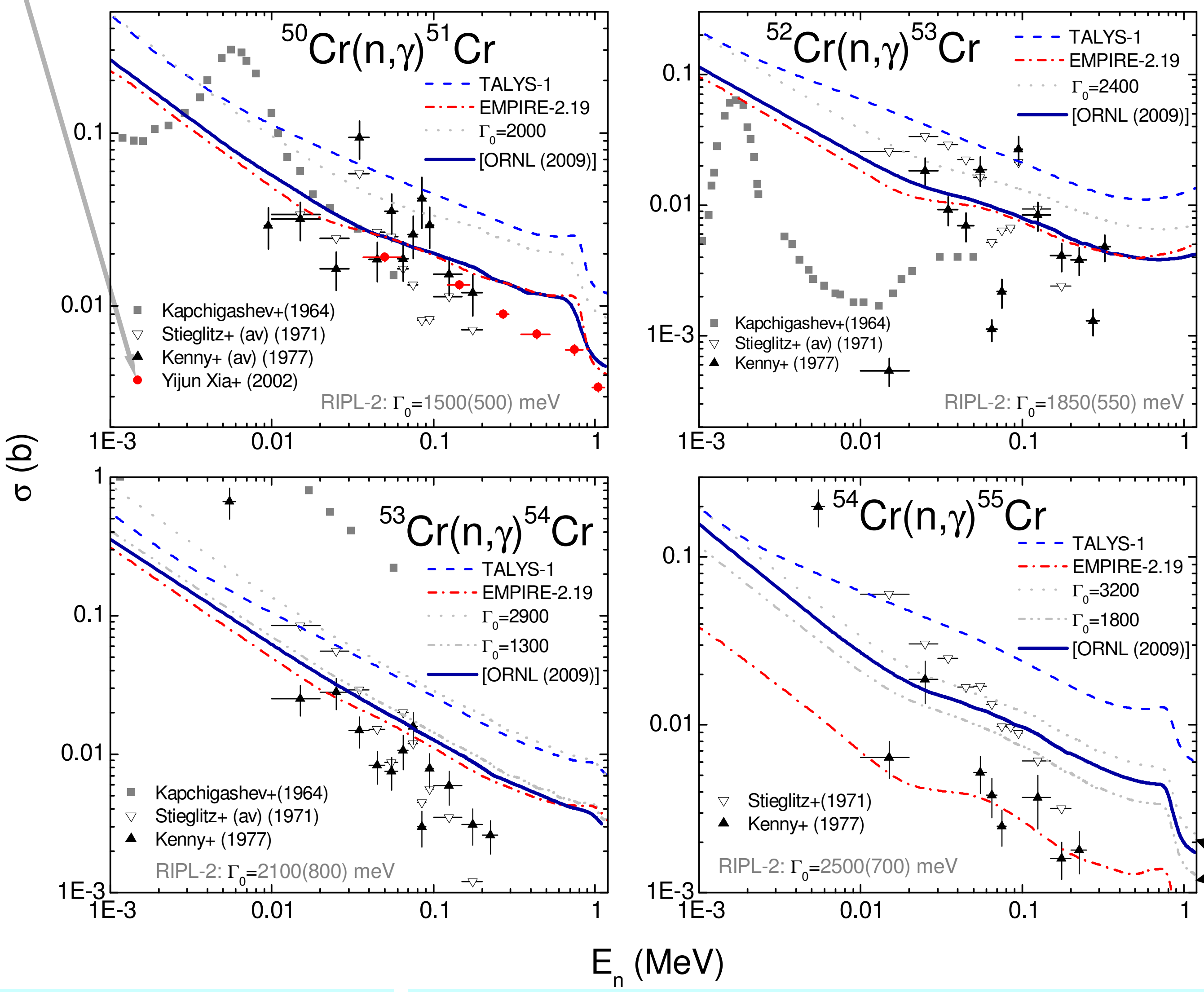
# Direct inelastic scattering cross sections by using the same OMP within the DWBA method, for $^{50,52}Cr$




**Direct Interaction: - as large as ~11% for $^{50}Cr$ and ~7% for $^{52}Cr$, from $\sigma_{CN}$**
**- decreasing with the energy by ~50% up to 60 MeV**

# Gamma-ray Strength Functions $f_{E1}(E_\gamma)$ based on comparison of measured/calculated (n,γ) cross sections: $^{50,52,53,54}$Cr

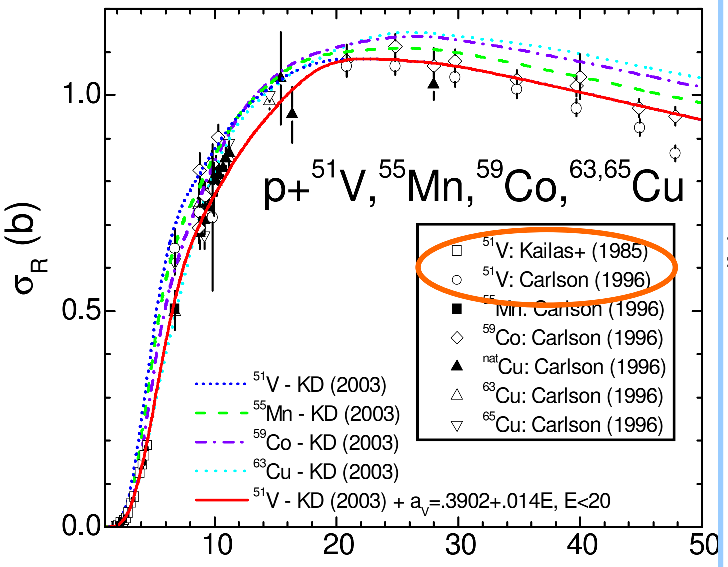
more recent data (2002)

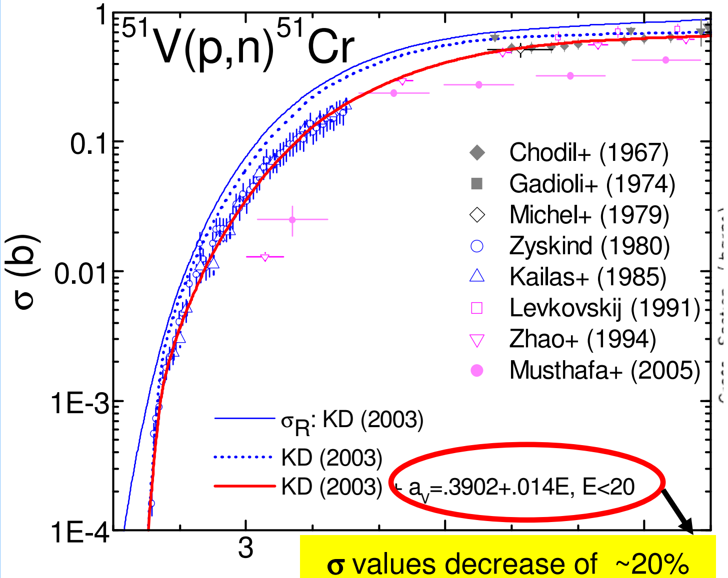



+ EDBW Model (D.G. Gardner, 1982)

RIPL-2 upper/lower limits

# Consistent proton-OMP (PE) validation: $\sigma_R$, (p,γ) & (p,n) reactions analysis




**σ** values decrease of ~20% at statistical-emission $E_p$

# Present status of $^{51}V$*(p,n)* reaction analysis / PE validation

ELSEVIER Applied Radiation and Isotopes 62 (2005) 419–428
www.elsevier.com/locate/apradiso

## Measurement and analysis of cross sections for (p,n) reactions in $^{51}V$ and $^{113}In$

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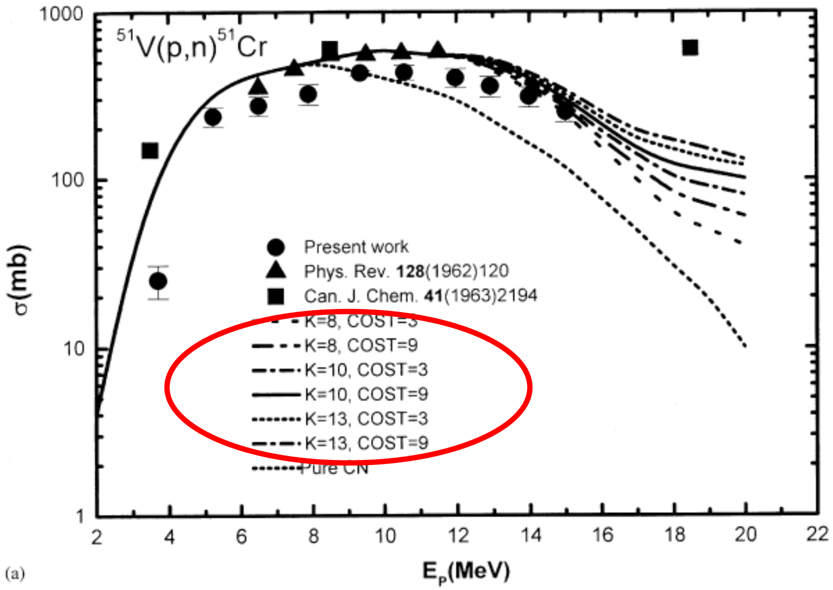
Received 13 January 2002; received in revised form 29 September 2003; accepted 20 October 2003

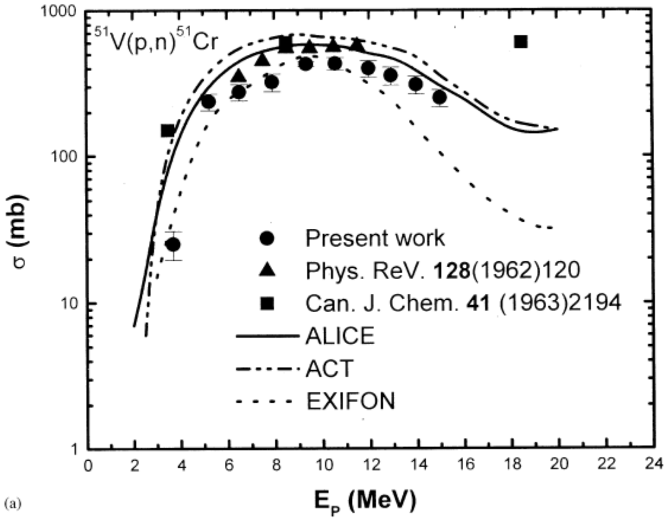
**Abstract**

Excitation functions (EFs) for the reactions $^{51}V(p,n)^{51}Cr$ up to 15 MeV and $^{113}In(p,n)^{113}Sn$ up to 20 MeV from threshold have been measured employing the stacked foil activation technique. To the best of our knowledge EF for the reaction $^{113}In(p,n)^{113}Sn$ has been reported for the first time. The theoretical analysis of the EFs has been done employing both the semi-classical as well as quantum mechanical codes which include compound nucleus and pre-equilibrium (PE) emission into consideration. In general, theoretical calculations agree well with the experimental data. Effect of various free parameters used in the calculations have also been discussed. A significant contribution of pre-equilibrium component has been observed at these energies.

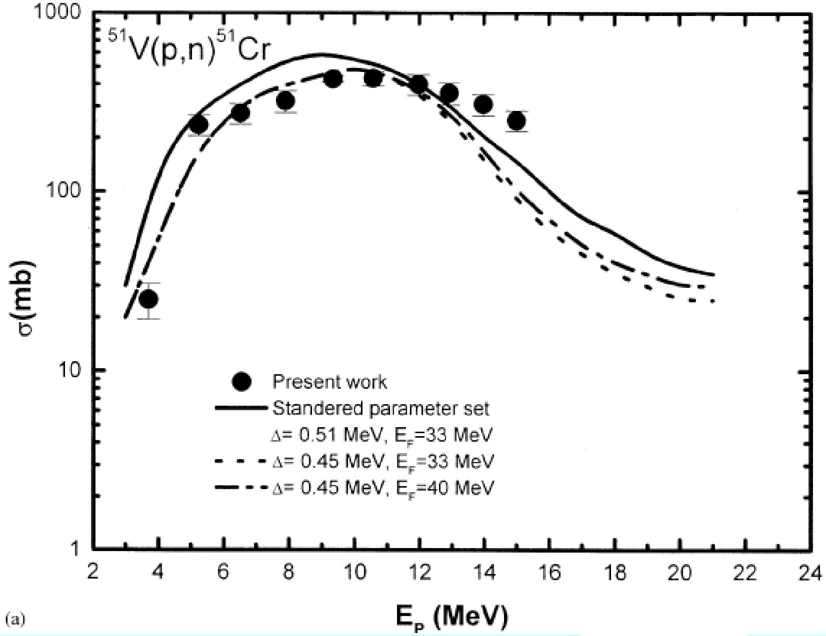





(a)



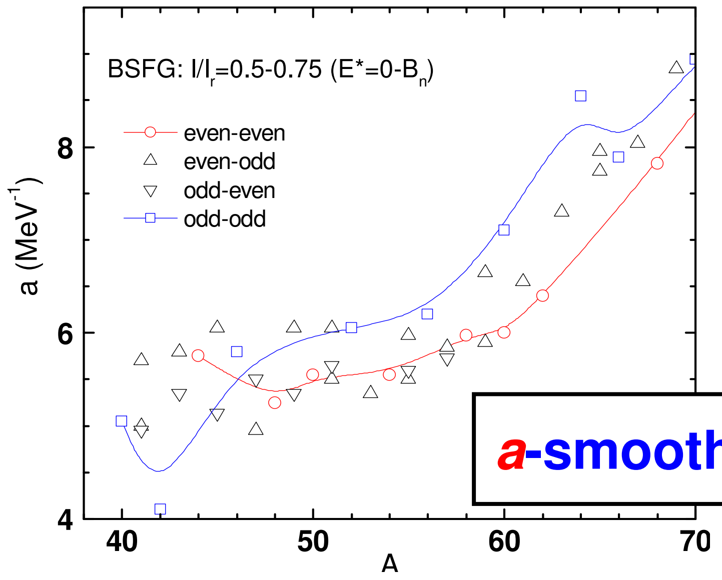

(a)




(a)

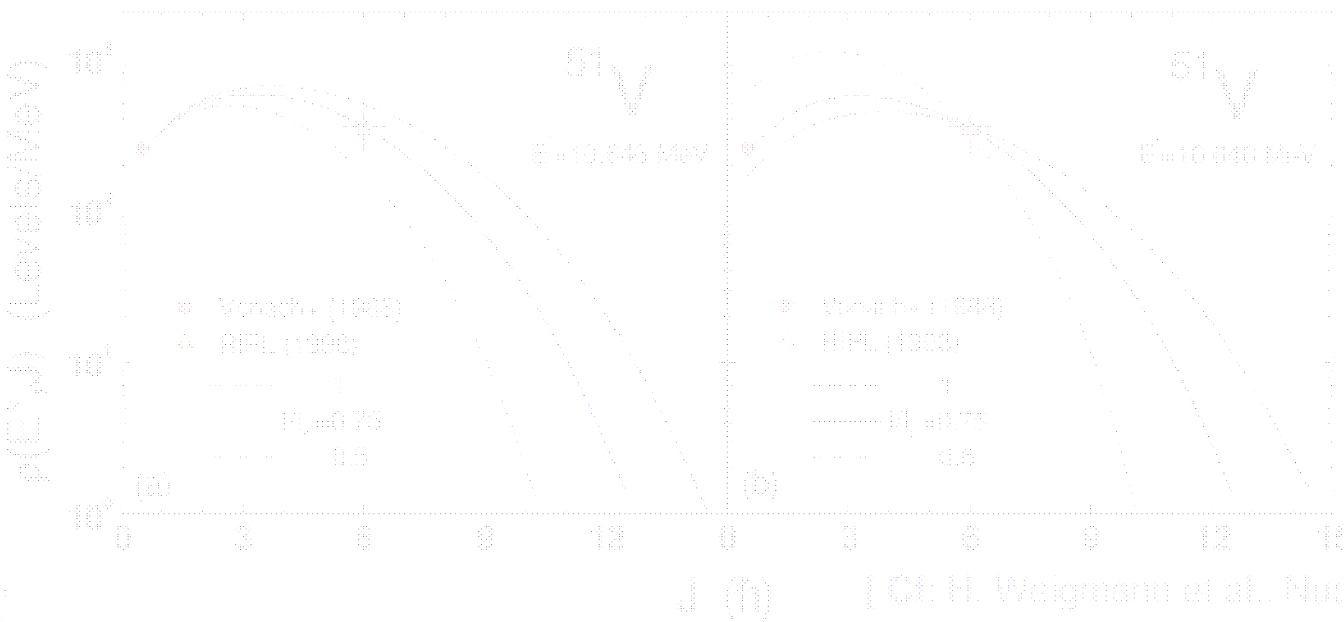
# Level density parameter systematics (E*<15 MeV)

[ *J. Nucl. Sci. Tech. S2, 746 (2002)*
*Nucl. Phys. A730, 255 (2004)*
http://tandem.nipne.ro/~vavrig/ ]




***a*-smooth curve method** → ***Δ*-values for nuclei without resonance data**

l/lr=0.75: describe both neutron (RIPL-2) and proton s-wave resonance spacings:




[ Cf. H. Weigmann et al., Nucl. Phys. A368,117(1981) ]

# Level density parameters @ E*>15 MeV:

***a(E*)*:** A.V. Ignatyuk *et al.*, Yad.Fiz. **2**, 485(1975)
A.R. Junghans *et al.,* Nucl. Phys. **A629**, 635 (1998)
A.J. Koning and M.B. Chadwick, Phys. Rev. C **56**, 970 (1998)

**Transition range from BSFG**: 12 – 25-50 MeV [M. Avrigeanu *et al.,* Z. Phys. **A335**, 299 (1990)]

**Comment**: A. Fessler, PhD Thesis, Jul-3503,1998,p.106:
"*transition … appears to be unjustified… since there are no experimental data available between 20 and 50 MeV*"

# Level density parameters @ E*>15 MeV - former approach

Nuclear Physics **A451** (1986) 171–188
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## DE-EXCITATION OF $^{58,60,62}$Ni COMPOUND NUCLEI FORMED VIA SYMMETRIC AND ASYMMETRIC ENTRANCE CHANNELS

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Received 29 July 1985

**Abstract:** An extensive study of the decay of the compound nuclei $^{58,60,62}$Ni formed in the reactions ($^{12}$C + $^{46}$Ti), ($^{28}$Si + $^{30}$Si), ($^{12}$C + $^{48}$Ti), ($^{30}$Si + $^{30}$Si), ($^{12}$C + $^{50}$Ti), ($^{18}$O + $^{44}$Ca) was undertaken in the energy range ~0.7 to ~1.6 Coulomb barrier in about 20 steps. The fusion cross sections are fragmented in a large number of exit channels, with cross sections from 0.1 to 430 mb. By means of in-beam $\gamma$-ray measurements, the evaporation residues were identified both in $A$ and $Z$. This large data base was compared with fusion-evaporation calculations through individual residue excitation functions and summed evaporation residue cross sections (resulting from nucleons or $\alpha$-emission). The model, with a standard set of parameters, does account for the general features of the experimental data, especially for the stronger exit channels. However, these data are not sensitive enough to the presence of other types of mechanisms and must be complemented by other observables to boost the predictive power of the model.

E | NUCLEAR REACTIONS $^{46,48,50}$Ti($^{12}$C, X), $^{28}$Si, $^{30}$Si($^{30}$Si, X), $^{44}$Ca($^{18}$O, X), $E$ = ~0.7– ~1.6 Coulomb barrier; measured absolute residue cross sections; deduced n, p, $\alpha$ multiplicities. Statistical model calculations.

TABLE 8

Parameters for the evaporation

*Angular momentum distribution in the compound nucleus*
- max. angular momentum $L_c$ derived from $\sigma_{CN}$
- diffuseness $d = 1\hbar$

*Optical potentials for emitted particles*
- neutrons: Wilmore and Hodgson
- protons: Perey
- $\alpha$-particles: Huizenga and Igo

*$\gamma$-decay strengths*
- $\xi$(E1) = 0.0008 W.u. (Weisskopf units)
- $\xi$(M1) = 0.028 W.u. [ref. [10]]
- $\xi$(E2) = 5.5 W.u.

*Level-density parameters*
- region I ($E_x \leq 7$ MeV):
  - discrete levels as far as known experimentally
- region II (7 MeV $\leq E_x \leq$ 15 MeV):
  - Fermi-gas level-density formula with empirical $\alpha$ and $\Delta$ fr
  - effective moment of inertia $\mathcal{T} = 0.85\mathcal{T}_{rigid}$ (or $r_0 = 1.20$ fm
  - known high-spin states included as yrast levels
- region III ($E \geq 15$ MeV):
  - Fermi-gas level density
  - level-density parameters $a_{LDM} = A/8.5$ MeV$^{-1}$
  - moment of inertia for rigid body
  - radius parameter $r_0 = 1.28$ fm
  - deformation from liquid-drop theory
  - deformability $\delta = 10^{-4}$

# Nuclear level-density parity distribution @ E*<15 MeV

Nuclear Physics A568 (1994) 553–571
North-Holland

NUCLEAR
PHYSICS A

## Combinatorial study of nuclear level density for astrophysical applications

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Received 1 July 1992
(Revised 30 August 1993)

[also: Mocelj+, PRC 75,045805(2007)]

**Abstract**

We present some results and remarks based on a combinatorial approach of the evaluation of the nuclear level density. First, we show that it is possible to extract some reliable information from the output of the program whose rough data present a strong statistical fluctuation from bin to bin. This includes smoothing and evaluation of the desired quantities. After some comments about the spin and parity distributions, we consider the question of the non-equipartition of parities, mainly, at low energies. Finally, we present a simple model to include and test this effect in the computation of thermonuclear reaction rates.

Fi

$$\rho(E, J, \pi) = \tfrac{1}{2} f(U, J) \rho(U). \quad \text{(E>15 MeV)} \tag{13}$$

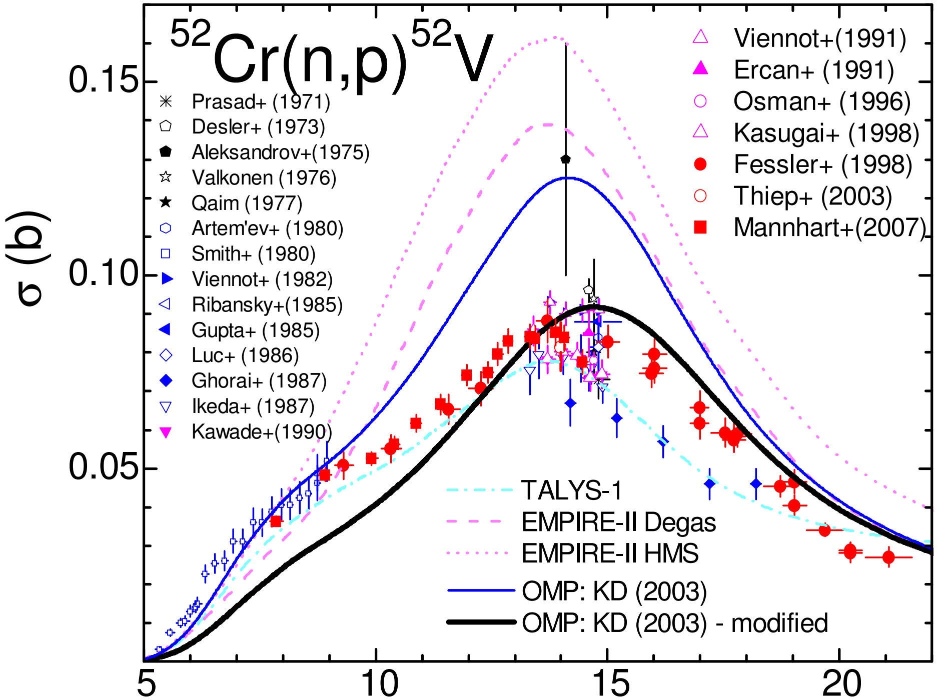
The parity distribution at a given energy can be described in terms of the asymmetry ratio:

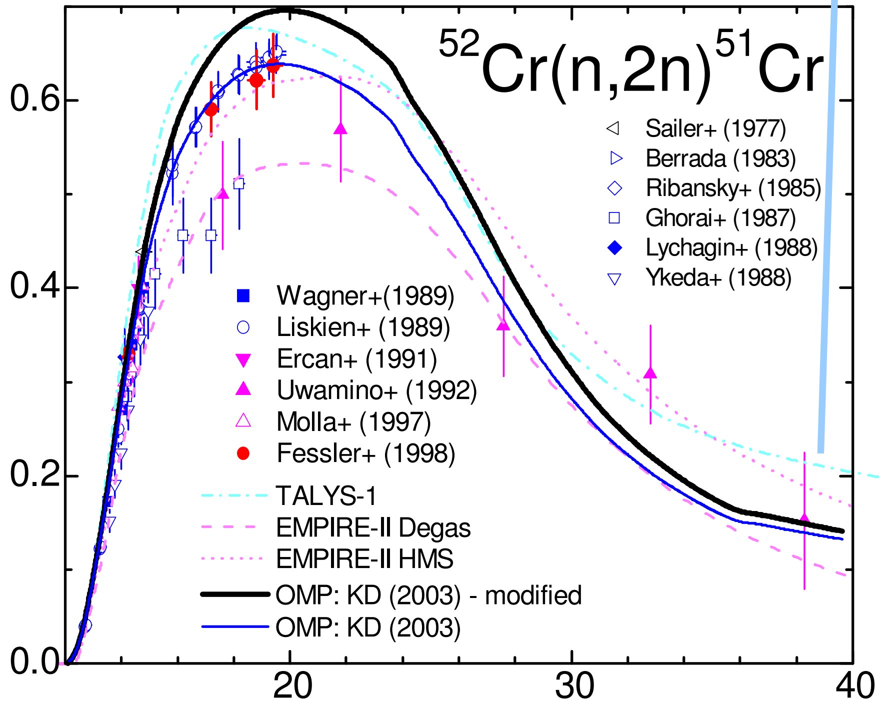
$$A(E) = \frac{N^+(E) - N^-(E)}{N^+(E) + N^-(E)}, \tag{14}$$

where $N^\pi$ are the number of levels with parity $\pi = \pm 1$. Of course $A(E=0) = \pi_g$ where $\pi_g$ is the parity of the ground state, and the equipartition of parities is realized when $A(E) \simeq 0$. **(E=15 MeV)**

# Comparison of measurements and global/local calculations of reaction cross sections for $^{52}$Cr

NFS@SPIRAL2 ?



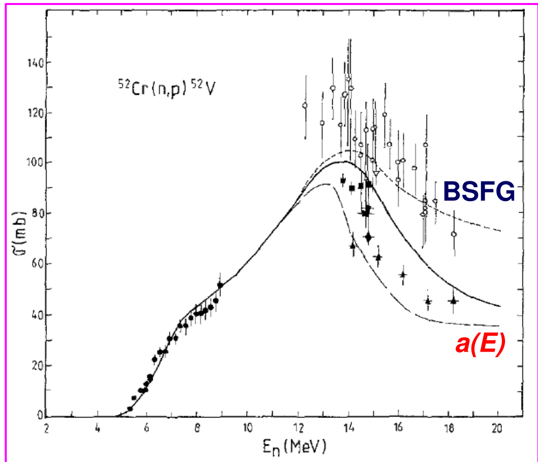




**Fig. 7.** Comparison of experimental and calculated cross sections of the reaction: $^{52}$Cr$(n,p)^{52}$V. The curves shown have the same significance as in Fig. 6. Experimental data: ○ [58], ▽ [59], △ [60], □ [61], × [62], ● [63], ■ [64], ▼ [65], ▲ [56], ◆ [57]

Z. Phys. A – Atomic Nuclei 335, 299–313 (1990)

Zeitschrift für Physik A
Atomic Nuclei



20 years ago

**Nuclear Level Densities Below 40 MeV Excitation Energy in the Mass Region $A \simeq 50$**

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Institute for Physics and Nuclear Engineering, Bucharest, Romania

Received May 22, 1989; revised version July 25, 1989

Consistent pre-equilibrium emission and statistical model calculations of fast neutron induced reaction cross sections are used to validate nuclear level densities for excitation energies up to 40 MeV in the mass region $A \simeq 50$. A "composed" level density approach has been employed by using the back-shifted Fermi gas model for excitation energies lower than 12 MeV and a realistic analytical formula for higher excitations. In the transition region from the BSFG model range to that of full applicability of the realistic formula, an interpolation between the predictions of the two models is adopted. The interpolation rule, suggested by microscopic level density calculations, has been validated through the comparison of the calculated and experimental cross sections.

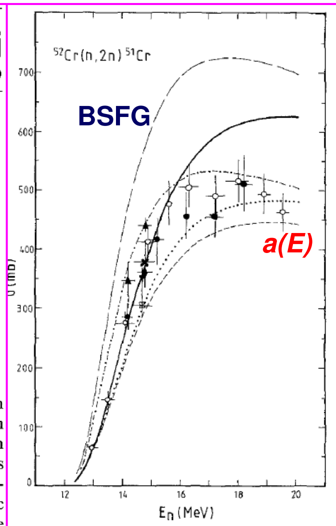


**Fig. 9.** Same as Fig. 6, for the reaction $^{52}$Cr$(n,2n)^{51}$Cr. Experimental data: ○ [68], ⊗ [69], △ [70], ▼ [52], ▲ [53], ● [56], ◆ [57], ✕ [71]

# (Conclusions)

- **Achievements (?)**
  - **Unitary description of all neutron activation experimental data by using a local parameter set in STAPRE-H code: accuracy ~5 %**
  - **Good results of blind calculations and global parameters within TALYS and EMPIRE-II codes : accuracy ~20 %**

- **<u>Final aim</u>: rising global-prediction accuracy**
  **to the level proved by the local approach**
  **<u>based on their differences understanding</u>**

- **Experimental-data critical role:**
  - **@ E ≤ 20 MeV (including particle-emission spectra): parameter validation**
  - **@ E>20 MeV: model validation (PE, basic assumptions)**

- **Experimental data and analysis needs:**
  **- neutron strength functions within smaller energy ranges (?)**
  **- *(p,n)*-reaction data at $E_p$>5 MeV**
  **- consistent *(n,$\gamma$)* reaction data !!**
  **- NLD parity-distribution consideration for BSFG parameters (?)**

THANK YOU, EFNUDAT

THANK YOU, IRMM