Dosimetry Reactions which need updating or were recommended for evaluation and inclusion in IRDFF at RCM-1 and RCM-2.

Following the recommendations adopted by RCM-1 (July 2013, *INDC(NDS)-0639*, p. 19-20) and RCM-2 (March 2015, *INDC(NDS)-0682*), advices from the Fusion community, and an assessment of possibility to implement new (re)evaluations made by K. Zolotarev and NDS/IAEA staff we come to following summary.

Summary

(i) we decided to do for the next version of IRDFF:

- re-evaluate **^{23}Na(n,γ) and ^{23}Na(n,2n)^{22}Na**
  (the closest alternatives/perspectives are **^{37}Cl(n,γ)^{38}Cl** or **^{127}I(n,γ)^{128}I**);
- newly evaluate **^{27}Al(n,2n)^{26}Al.**

(ii) the high energy applications evaluate and eventually include in IRDFF like the high threshold reactions:

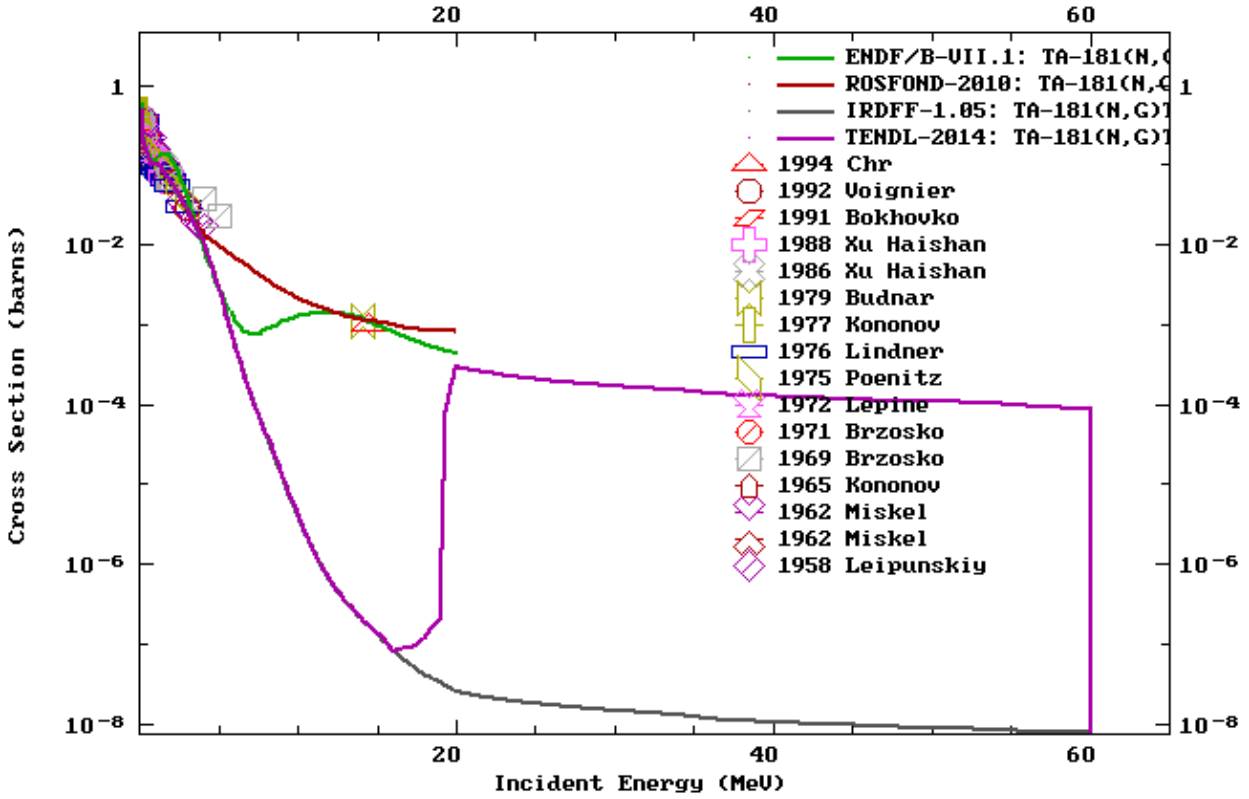
(n,xn) on **^{197}Au(n,3-5n), ^{169}Tm(n,2-3n), ^{209}Bi(n,3-10n)** ***(see Evaluation made by V. Pronayev)*,** **^{59}Co(n,3-5n), ^{89}Y(n,2-4n), ^{93}Nb(n,2-4n), ^{103}Rh(n,4-8n), ^{139}La(n,4-10n), ^{175}Lu(n,2-4n), ^{63}Cu(n,?);**

composite reactions resulting to the production of the same radioactive residual:
^{27}Al(n,x)^{24}Na, ^{nat}Fe(n,x)^{54}Mn, ^{nat}Fe(n,x)^{56}Mn, ^{nat}Fe(n,x)^{51}Cr, ^{nat}Ti(n,x)^{47}Sc, ^{nat}Ti(n,x)^{48}Sc, ^{nat}Ni(n,x)^{57}Co, ^{nat}Ni(n,x)^{60}Co, ^{nat}Ni(n,x)^{57}Ni, natCu(n,x)^{64}Cu,
as well as ^{10}B(n,X)^{4}He, ^{11}B(n,X)^{4}He, ^{6}Li(n,X)^{4}He, and ^{7}Li(n,X)^{4}He.

(iii) include the **^{58}Co/^{58m}Co energy dependant branching ratio** in IRDFF (ratio data are available in V. Semkova et al. Nucl Phys A730(2004)255)

Noticed deficiencies in the IRDFF evaluations.

1. ^{181}Ta(n,γ) - thousands times underestimation at 14 MeV was "discovered" in Nov 2015:



Existing Experimental total ^{181}Ta(n,γ)^{182}Ta cross sections at 14.5 MeV
= 1.0 ± 0.2 mb (C. Necheva, I. Phys. G: Nucl. Pan. Phys. 20(1994)L33)
= 1.13 ± 0.17 mb (M. Budnar, INDC(YUG)-6,1979)

Current source of the ^{181}Ta(n,γ) evaluation in IRDFF is IRDF-2002, which in turn has adopted the **JENDL/D-99 evaluation**!

Detailed assessment of the dosimetry reactions status and possibility of further updating or new evaluations.

I. IRDFF reactions which need further update.

- **^{23}Na(n,γ)^{24}Na, ^{23}Na(n,2n)^{22}Na, ^{181}Ta(n,γ)^{182}Ta** and **^{63}Cu(n,γ)^{64}Cu** reactions excitation functions and related uncertainties **need re-evaluation**.

The **^{23}Na(n,γ)^{24}Na** reaction excitation function in the current IRDFF version was taken from the ENDF/B-VII.1 library. The cross section in ENDF/B-VII.1 was calculated in the energy range 1.000E-05 eV – 600 eV using a Breit-Wigner shape and parameters for the first resonance: E_r = 2.81 keV, Γ_n = 376 eV, and Γ_γ = 0.353 eV. In the energy range 600 eV – 500 keV the capture cross section is described by single level Breit-Wigner resonance parameters. From 500 keV to 20 MeV the capture cross section is the same as in ENDF/B-IV file.

As it evident the evaluation for the ^{23}Na(n,γ)^{24}Na reaction included in the IRDFF v-1.03 library does not take into account the results of new measurements of Firestone et al. at 0.0253 eV [1] and experimental information obtained after 1975 years.

The **^{23}Na(n,2n)^{22}Na** reaction excitation function was adopted from the JENDL/D-99 library.

JENDL/D-99 evaluation was carried out in August 1996 and does not take into account the later measurements [2-4].

The **^{181}Ta(n,γ)^{182}Ta** reaction data for IRDFF v-1.03 were taken from JENDL-3.2. The ^{181}Ta(n,γ)^{182}Ta reaction excitation function presented in JENDL-3.2 library was evaluated by N. Yamamuro in March 1987. In the RR region 1.00E-05 eV – 1 keV the ^{181}Ta(n,γ) cross-section was described by MLBW resonance parameters. In the energy interval 1 – 100 keV cross-section are is represented by unresolved parameters.

The evaluation carried out for ^{181}Ta(n,γ)^{182}Ta reaction in JENDL-3.2 library does not take into account the measurements [5-13], which provide additional experimental information in the energy interval 1.97 keV – 3 MeV and at 14 MeV. Uncertainty in the JENDL-3.2 capture cross section for ^{181}Ta(n,γ) in the energies range 1.000E-05 eV – 20 MeV are given by simple LB = 1 matrix. The ^{181}Ta(n,γ)^{182}Ta reaction excitation function presented in JENDL-3.2 library significantly underestimates the cross sections in the energy range above 7 MeV. At 14.5 MeV point the evaluated capture cross section is 6003 times lower than equivalent experimental data of C. Necheva et al. [10].

II. New dosimetry reactions for evaluation and inclusion in IRDFF

II.1. Fission Reactors

The participants of the 1-st RCM on "Testing and Improving the International Reactor Dosimetry and Fusion File (IRDFF)" elaborated a list of the new perspective reactions which are interesting for the dosimetry applications:

- **^{27}Al(n,γ)^{28}Al** - often present in facilities, short-lived (2.24 min);
- **^{94}Zr(n,γ)^{95}Zr** and **^{96}Zr(n,γ)^{97}Zr** - first resonance at high/low (2.3/0.3 keV) energies;
- **^{70}Zn(n,γ)^{71}Zn** - first resonance at energy above 10 keV but low abundance (0.62%);
- **^{117}Sn(n,n')^{117m}Sn** - low threshold (0.3 MeV), convenient $T_{1/2}$ =14 days and γ-energy 314 keV;
- **^{93}Nb(n,γ)$^{94g+m}$Nb** and **^{94}Nb(n,γ)^{94m}Nb** - for burn up calculations;
- **^{93m}Nb(n,γ)^{94}Nb** - due to 300 keV threshold is interesting for the fast flux measurements

– **^{113}In(n,γ)^{114m}In** – perspective reaction for reactor dosimetry due to the appropriate half-life 49.51 ± 0.01 days and lonely decay line 190 keV with intensity 15.56 ± 0.15%. Its rate, measured using the ^{nat}In activation detector, will give additional information for ^{115}In(n,γ)^{116m}In.

After RCM-1 the excitation function of the ^{113}In(n,γ)^{113m}In reaction was re-evaluated in the energy range 1.000E-05 eV – 20 MeV [18] and included in the IRDFF-1.05.

The results of new evaluation of the ^{94}Nb(n,γ)^{94m}Nb reaction excitation function in the energy range 1.000E-05 eV – 20 MeV were reported at the 1-st RCM. Evaluated data file has been included in IRDFF-1.03.

Comments on the **^{117}Sn(n,n')^{117m}Sn** reaction**.** It is attractive for dosimetry application due to low threshold 317 keV and convenient decay parameters: $T_{1/2}$ = (14.00 ± 0.05) days and two gamma-lines 156.02 keV (Iγ = 2.113%) and 158.56-keV (Iγ = 86.4%), which can be used for the reaction rate measurement. Usage of the activation detectors made of natural tin does not allow to measure correctly the **^{117}Sn(n,n')^{117m}Sn** reaction rate due to processes **^{118}Sn(n,2n)^{117m}Sn, ^{118}Sn(γ,n)^{117m}Sn, ^{119}Sn(n,3n)^{117m}Sn** leading to production of the same isomer ^{117m}Sn. The abundance of ^{117}Sn, ^{117}Sn, ^{117}Sn in natural tin is equal (7.68 ± 0.07) At.%, (24.22 ± 0.09) At.%, and (8.59 ± 0.047) At.%, respectively. This negative impact can be bypassed by using the high enriched ^{117}Sn samples. The experimental information about the ^{117}Sn(n,n')^{117m}Sn reaction cross section is scarce and covered neutron energies range 0.524 – 15.9 MeV. Regrettable the integral experimental data, which can be used for testing of the ^{117}Sn(n,n')^{117m}Sn evaluated reaction excitation function are absent today.

All this currently does not allows an evaluation of the ^{117}Sn(n,n')^{117m}Sn reaction cross section for dosimetry application.

Request from RCM-2 (March 2015):

There is an interest for the ^{117}Sn(n,n')^{117m}Sn reaction because of its unique characteristics combination: $E_{Threshold}$ = 0.314 MeV, $T_{1/2}$ = 14 d, E_{g1} = 158 keV (I_{g1} = 86%). Experimental irradiations of this dosimeter have been done with enriched Tin (93% at. ^{117}Sn) in different spectra. However, nuclear data need additional measurements (see *IRDFF HPRL*) and upgrades (lack of uncertainties, discrepancies between library evaluations) to allow this reaction to be used.

- **^{37}Cl(n,γ)^{38}Cl** and **^{127}I(n,γ)^{128}I** reactions are useful for the reactor dosimetry application and can be **added** to IRDFF.

The usage of the NaCl sample makes possible the measurement of two reactions simultaneously: ^{23}Na(n,γ)^{24}Na and ^{37}Cl(n,γ)^{38}Cl. On other hand, the NaI sample gives an option to measure simultaneously the ^{23}Na(n,γ)^{24}Na and ^{127}I(n,γ)^{128}I reaction rates. It is also worthwhile to note that in several neutron radiative capture cross-sections experiments, the ^{127}I(n,γ)^{128}I reaction was used as standard in energy interval 10 keV – 1 MeV.

The isotopic abundance of ^{37}Cl in natural chlorine is (24.22 ± 0.0010) atom percent [14]. ^{38}Cl produced in the (n,γ) reaction undergoes 100% β^- decay mode with a half-life of (37.230 ± 0.014) minutes. The ^{37}Cl(n,γ)^{38}Cl reaction rate can be measured by detecting 1642.43 keV (I_γ = 0.333 ± 0.007) and 2167.54 keV (I_γ = 0.444 ± 0.000) gamma radiations. The ^{37}Cl(n,γ)^{38}Cl reaction rate can be measured also by detecting β^- particles with end-point energies 1106.3 keV (I_β = 0.331 ± 0.008),

2748.9 keV (I_β = 0.113 ± 0.005) and 4916.5-keV (I_β = 0.556 ± 0.009). Recommended decay data for ^{38}Cl (half-life, gamma and β^- emission probabilities per decay of ^{38}Cl) were taken from Ref. [15].

The isotopic abundance of ^{127}I in natural iodine is 100 atom percent [14]. ^{128}I produced in the (n,γ) reaction undergoes two decay modes with a half-life of (24.99 ± 0.02) minutes. The (93.1 ± 0.8)% of disintegrations occurs by β^- decay mode and (6.9 ± 0.8)% of disintegrations via the ε–capture mode. The ^{127}I(n,γ)^{128}I reaction rate can be measured by detecting 442.90 keV (I_γ = 0.169 ± 0.017) and 526.56 keV (I_γ = 0.0159 ± 0.0017) gamma radiations. Recommended decay data for ^{128}I (half-life and gamma emission probability per decay of ^{128}I) were taken from Ref. [16].

II.2. Fusion Reactors

– **^{28}Si(n,p)^{28}Al** – an appropriate activation reaction for the 14 MeV neutron flux monitoring during planned fusion experiments at JET and ITER

Evaluation of this and contributing ^{29}Si(n,x)^{28}Al reactions was done (see K.I Zolotarev INDC(NDS)-0668) and included in IRDFF-1.05.

– **^{64}Zn(n,2n)^{63}Zn, ^{90}Zr(n,p)^{90}Y, ^{186}W(n,2n)^{185}W, ^{197}Au(n,p)^{197}Pt** – are sensitive to 14 MeV neutrons and look suitable for the fusion applications.

Reaction **^{64}Zn(n,2n)^{63}Zn** can be used as an activation detector. The ^{63}Zn produced in the (n,2n) reaction undergoes 100% ε–capture mode with a half-life of (38.47 ± 0.05) minutes. The ^{64}Zn(n,2n)^{63}Zn reaction rate can be measured by detecting 511 keV (I_γ = 1.855 ± 0.017), 669.62 keV (I_γ = 0.082 ± 0.000), and 962.06 keV (I_γ = 0.065 ± 0.004) gamma radiations. Decay data for ^{63}Zn (half-life and gamma emission probability per decay of ^{63}Zn) were taken from Ref. [19].

Regarding amount of experimental data available in EXFOR the ^{64}Zn(n,2n)^{63}Zn reaction excitation function can be evaluated for dosimetry application in the energy range from threshold to 40 MeV.

Reactions **^{90}Zr(n,p)^{90m}Y** and **^{90}Zr(n,p)$^{90m+g}$Y** can also be used for dosimetry application. The isomeric state of ^{90m}Y undergoes 100% IT mode with a half-life of (3.19 ± 0.06) hours [20]. Isomeric transition is accompanying by emission of 202.53-keV and 497.51-keV gamma-rays with intensities $I_{\gamma1}$ = (97.3 ± 0.4)% and $I_{\gamma2}$ = (90.74 ± 0.05)% [20]. The ^{90g}Y undergoes 100% β^- decay mode with a half-life of (64.053 ± 0.020) hours [20]. The ^{90}Zr(n,p)$^{90m+g}$Y reaction rate can be measured only by detecting β^- particles with end-point energy 2280.1-keV (I_β = 99.9885 ± 0.0014)% [20].

On the basis of experimental data given in EXFOR the ^{90}Zr(n,p)^{90m}Y and ^{90}Zr(n,p)$^{90m+g}$Y reaction excitation functions can be evaluated for dosimetry application in the energy range from threshold to 20-21 MeV.

Reaction **^{186}W(n,2n)$^{185m+g}$W** can be used as an activation detector. The isomeric state of ^{185m}W decays via 100% IT transition with a half-life of (1.63 ± 0.03) min [20]. The ^{185g}W undergoes 100% β^- decay with a half-life of (75.1 ± 0.3) days [21]. The ^{186}W(n,2n)$^{185m+g}$W reaction rate can be measured only by detecting β^- particles with end-point energy 432.5 keV (I_β = 99.928 ± 0.008)% [21].

Experimental data for the $^{186}W(n,2n)^{185m+g}W$ reaction cross section cover the energies range only from 7.41 to 14.8 MeV, that make difficult its evaluation.

- **$^{27}Al(n,2n)^{26}Al$**. is perspective reaction for dosimetry in fusion applications as a long term fluence monitor.
  Moreover it proved to be measured by the AMS technique [23] (other recommended reactions are $^{56}Fe(n,2n)^{55}Fe$, $^{238}U(n,3n)^{236}U$) and thus can serve for validation of the **$^{252}Cf(s.f.)$** and **$^{235}U(n,f)$ prompt fission spectra above reaction threshold 13.55 MeV**
  (see also: http://www-nds.iaea.org/IRDFFtest/Cf252U235_HighThreshold.pdf).

The residual nucleus ^{26}Al undergoes 100% decay via the ε–capture mode with a half-life of 717000 years [17]. The $^{27}Al(n,2n)^{26}Al$ reaction rate can be measured by detecting 511 keV (I_γ = 163.5 ± 0.4)% and 1808.65 keV (I_γ = 99.76 ± 0.04)% gamma radiations. The $^{27}Al(n,2n)^{26}Al$ reaction rate can be measured also by detecting β^- particles with end-point energy 1173.42 keV (I_β = 81.73 ± 0.21)%.

- **$^{197}Au(n,p)^{197m}Pt$ and $^{197}Au(n,p)^{197m+g}Pt$** reactions are suitable for activation measurements in the Fusion facilities.

The isomeric state of ^{197m}Pt decays with a half-life of (95.41 ± 0.18) minutes by two modes [22]. The (95.41 ± 0.18)% of disintegrations occurs by the IT transition. The $^{197}Au(n,p)^{197m}Pt$ reaction rate can be measured by detecting of 346.5 keV gamma radiation (I_γ = 11.1 ± 0.3)% [22] and X-rays. The ground state of ^{197g}Pt undergoes 100% β^- decay mode with a half-life of (19.8915 ± 0.0019) hours [21]. The $^{197}Au(n,p)^{197m+g}Pt$ reaction rate can be measured by detecting 77.35 keV (I_γ = 17.0 ± 2.3%) and 191.437 keV (I_γ = 37%) gamma radiations. Uncertainty of intensity for the second gamma-line is not determined.

The fusion community have also interest to the following reactions planned to be used as detectors in TBMs of ITER:

$^{140}Ce(n,2n)^{139m}Ce$; $^{140}Ce(n,\alpha)^{137m}Ba$, $^{27}Al(n,\gamma)^{28}Al$, $^{27}Al(n,p)^{27}Mg$**, $^{52}Cr(n,p)^{52}V$, $^{53}Cr(n,p)^{53}V$, $^{54}Cr(n,p)^{54}V$, $^{54}Cr(n,\alpha)^{51}Ti$,** $^{93}Nb(n,g)^{94m}Nb$**, $^{93}Nb(n,\alpha)^{90m}Y$, $^{93}Nb(n,n\alpha)^{89m}Y$** and $^{93}Nb(n,2n)^{92m}Nb$.

Evaluated data for the $^{27}Al(n,p)^{27}Mg$, $^{93}Nb(n,\gamma)^{94m}Nb$ and $^{93}Nb(n,2n)^{92m}Nb$ reactions are already available in the IRDFF v-1.03 library.

The **$^{93}Nb(n,\alpha)^{90m}Y$** reaction can be also appropriate for the neutron dosimetry in fission reactors.

The **$^{27}Al(n,\gamma)^{28}Al$, $^{52}Cr(n,p)^{52}V$, $^{53}Cr(n,p)^{53}V$, $^{54}Cr(n,p)^{54}V$** and **$^{54}Cr(n,\alpha)^{51}Ti$** reactions, which leads to production short-lived residual nucleus, could be re-evaluated for ITER application. Regrettably the integral experimental data which could be used for the testing of the evaluated $^{140}Ce(n,2n)^{139m}Ce$ and $^{140}Ce(n,\alpha)^{137m}Ba$ reaction excitation functions are not available nowadays.

The lack of such experimental information currently not allows an evaluation of the $^{140}Ce(n,2n)^{139m}Ce$ and $^{140}Ce(n,\alpha)^{137m}Ba$ reaction cross sections for ITER dosimetry application.

The same can be said about $^{93}Nb(n,n\alpha)^{89m}Y$ reaction.

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