# SANDA WP2/Task 2.2 report

Alberto Mengoni on behalf of the Task 2.2 partners: ENEA, CIEMAT, JRC-Geel, Uni Lodz, IRSN







## SANDA WP2/Task 2.2 definition

Task 2.2: Neutron capture cross sections

Task coordinator: ENEA, partners: CIEMAT, JRC, ULODZ, IRSN

#### Subtask 2.2.1. Capture measurements of fissile isotopes.

CIEMAT, ULODZ and JRC will perform various cross section measurements at GELINA and n\_TOF on the high priority reactions <sup>239</sup>Pu(n,g) and <sup>239</sup>Pu(n,f). The methodology developed within CHANDA for the absolute measurement of the <sup>235</sup>U alfa ratio will be applied to the <sup>239</sup>Pu case. A new ionization chamber built by ULODZ will be tested in a <sup>239</sup>Pu(n,f) measurement at JRC, which also deliver the <sup>239</sup>Pu samples. The combined measurement of the <sup>239</sup>Pu(n,g) and <sup>239</sup>Pu(n,f) cross sections will be carried out at CERN with the use of the Total Absorption Calorimeter.

#### Subtask 2.2.2. Capture measurement of stable isotopes.

ENEA will measure the 92,94,95 Mo(n,g) cross sections at GELINA and at the n\_TOF facility with the high performance total energy detectors developed during the CHANDA project. The impact of the new evaluated nuclear data and their uncertainties will be verified in criticality safety and reactor applications at IRSN as end-user. The data will be part of an evaluation done in WP4 by IRSN.

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# SANDA WP2/Task 2.2 definition

**Deliverable: 2.3** Report on the 239Pu(n,g), 92,94,95Mo(n,g) cross measurements at n\_TOF and GELINA when: month 40 updated to: month 56

#### **Milestones**

M.2.11 "Measurement of the 239Pu(n,g) at n\_TOF"; M36 M.2.12 "Measurement of the Mo isotopes at GELINA and n\_TOF"; M34







# Update on the status of the <sup>239</sup>Pu data analysis

A. Sanchez-Caballero<sup>1</sup>, V. Alcayne<sup>1</sup>, J. Andrzejewski<sup>2</sup>, D. Cano-Ott<sup>1</sup>, J. García-Pérez<sup>1</sup>, E. Gónzalez-Romero<sup>1</sup>, J. Heyse<sup>3</sup>, T. Martínez<sup>1</sup>, E. Mendoza<sup>1</sup>, J. Perkowski<sup>2</sup>, J. Plaza del Olmo<sup>1</sup>, A. Plompen<sup>3</sup>, P. Schillebeeckx<sup>3</sup>, G. Sibbens<sup>3</sup>

<sup>1</sup>CIEMAT, Spain <sup>2</sup>University of Lodz, Poland <sup>3</sup>JRC-Geel, Belgium



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#### <sup>239</sup>Pu production in LWR

Standard fresh nuclear fuel for thermal reactors has a 5% <sup>235</sup>U and a 95% <sup>238</sup>U. <sup>239</sup>Pu is produced during the reactor operation mainly by neutron captures in <sup>238</sup>U + decays of <sup>239</sup>U and <sup>239</sup>Np. The <sup>239</sup>Pu is fissile and thus its neutron induced fission contributes to the power.

|   | Cm 238<br>2,4 h   | Cm 239<br>3 h  | Cm 240<br>27 d<br>sf<br>• 6.291; 6.248<br>sf  | Cm 241<br>32,8 d<br>5,539<br>7 472: 431: 132  | Cm 242<br>162,94 d<br>sf a6,113:6,008<br>st:p<br>7,44);e <sup>+</sup><br>7,44);e <sup>+</sup><br>m = 5   | Cm 243<br>29,1 a<br>sf = 5785 5742<br>c sf p<br>1275 2281<br>210, cr<br>130; cr 620                   | Cm 244<br>18,10 a<br>sf<br>v 6305; 6762<br>st g<br>v (43); e<br>v 15; e, 1,1                             | Cm 245<br>8500 a<br>sf<br>c 6.361; 5.304<br>st.g<br>7175; 133<br>r 350; m 2100   | Cm 246<br>4730 a<br>a 5,386; 5,343<br>sf; g<br>Y (45); e <sup>-</sup><br>o 1,2; or 0,16 |
|---|---|--|---|---|--|---|--|--|---|
| Am 236 ?<br>3,7 m   | Am 237<br>73,0 m<br>51<br>909<br>9  | Am 238<br>1,63 h<br>\$5,54<br>933,919,561<br>605<br>9  | Am 239<br>11,9 h<br>st <sup>x</sup><br>* 5774<br>y <sup>270,225</sup><br>9  | Am 240<br>50,8 h<br>*<br>*<br>*<br>*<br>*<br>*<br>*   | Am 241<br>432,2 a<br>st<br>sty 60, 5,443<br>sty 60, 25<br>sty 60, 25<br>sty 60, 25                       | Am 242<br>141 a 16 h<br>5f 5 1491, 4 P 0.65'<br>55,201 0.72, 1<br>17195 1749, 1749, 1<br>17195 4,2100 | Am 243<br>7370 a<br>st 5,275; 5230<br>st; 775; 44.<br>e 75; 45<br>m 0,074                                | Am 244<br>26 m   10,1 h<br>51 p 1.5 p 0.4<br>9 (1084   | Am 245<br>2,05 h<br>st (241;296)<br>(241;296)<br>(7:9                                   |
| Pu 235<br>25,3 m  | Pu 236<br>2,858 a<br>st<br>s;788;5,721<br>s;Mg 28<br>y (48;109); er<br>oj 160   | Pu 237<br>45,2 d<br>sf<br>• 5.334<br>y 60; e <sup>-</sup><br>• 1,2300  | Pu 238<br>87,74 a<br>sf<br>sf,5499; 5,456<br>st; Sk Mg<br>y (43, 100); eT<br>e 510; or, 17  | Pu 239<br>2,411 · 10 <sup>4</sup> a<br>1,5,157; 5,144<br>15; y 152<br>6; m<br>7270; ny 752        | Pu 240<br>6563 a<br>st<br>«5,168;5,124<br>st; (45)<br>e; e<br>«290; e; ~ 0,048                           | Pu 241<br>14,35 a<br>sf<br># 0,02: g<br># 4,480<br>1143   | Pu 242<br>3,750 · 10 <sup>5</sup> a<br>a 4,901; 4,856<br>d; y 143)<br>e; g<br>e 19; o <sub>1</sub> < 0,2 | Pu 243<br>4,956 h<br>sf<br>#840<br>#440<br>#440<br>#40   | Pu 244<br>\$,00 - 10 <sup>7</sup> a<br>6,4,588,4,546<br>\$1,7<br>0,1,7                  |
| Np 234<br>4,4 d<br>«; β <sup>+</sup><br>γ 1559; 1528;<br>1602<br>σ1 * 900                                   | Np 235<br>396,1 d<br>c; a 5,025;<br>5,007<br>y(26; 84); e <sup>-</sup><br>g; $\sigma$ 160 + ?   | Np 236<br>22,5 h 1.54 10 <sup>5</sup> a<br>4 870.5 4 87 ca<br>1 962<br>683. 5 e 104 6<br>0, m 2700 4 m 2600  | Np 237<br>2,144 - 10 <sup>6</sup> a<br>sf<br>= 4,790; 4,774.<br>7 29; 67; 6 <sup>-</sup><br>= 150; o <sub>1</sub> 0.020                       | Np 238<br>2,117 d<br>β= 1,2<br>γ 984; 1029;<br>1026; 924, e <sup>-</sup><br>κ σ <sub>1</sub> 2100 | Np 239<br>2,355 d<br>β <sup>-</sup> 0,4;1.7<br>γ 106; 278,<br>228e <sup>-</sup> ; 9<br>σ 32 + 19; σt < 1 | Np 240<br>7,22 m 65 m<br>9 7 555; 870.9<br>9 7 555; 8074;<br>67 601;<br>97480                         | Np 241<br>13,9 m<br><sup>β<sup>-</sup>1,3</sup><br>γ 175; (133)<br>9                                     | Np 242<br>2,2 m 5,5 m<br>9°-2,7. p°<br>738, 9×5;<br>748, 9 | Np 243<br>1,85 m<br><sup>β<sup>-</sup><br/>γ 288<br/>9</sup>                            |
| U 233<br>1,592 · 10 <sup>5</sup> a<br>« 4,824; 4,783<br>Ne 25:<br>γ (42; 97); e <sup>-</sup><br>« 47; σ(530 | U 234<br>0,0055<br>2,455 · 10 <sup>5</sup> a<br>0,4775;4729; st<br>Mp 28; Net 1153; 121<br>c <sup>2</sup> ; c <sup>2</sup> 95; s <sub>1</sub> < 0.005 | U 235<br>0,7200<br>25 = 7,038-10 <sup>8</sup> a<br>4,3881<br>9 % 195<br>9 % 195<br>9 % 195   | U 236<br>120 ns (2,342-107a<br>4,445;<br>4,445;<br>4,445;<br>4,145;<br>4,145;<br>4,145;<br>4,145;<br>4,145;<br>115]<br>6 <sup>-</sup> ; = 5,4 | 6,25 d<br>β=0,2<br>γ 60: 208<br>e <sup>-</sup><br>σ= 100: σt < 0,35                               | U 238<br>99,2745<br>270 rs<br>h33<br>h33<br>h33<br>h33<br>h33<br>h33<br>h33<br>h33<br>h33<br>h3          | U 239<br>2.35 m<br>β <sup></sup> 1.2; 1.3<br>γ 75; 44<br>σ 22; σ; 15                                  | U 240<br>14,1 h<br>β <sup>-</sup> 0,4<br>γ 44: (190)<br>e <sup>-</sup><br>m                              |  | U 242<br>16,8 m<br><sup>3<sup>-</sup></sup><br>7 68; 58; 585;<br>573<br>m               |
| Pa 232<br>1,31 d<br>5 <sup>-</sup> 0,3,1,3,;e<br>9,969:894:<br>150,;e <sup>-</sup><br>e 460;e;700           | Pa 233<br>27,0 d<br>β <sup>+</sup> 0,3:0,6<br>γ 312:300:<br>341; 8 <sup>+</sup><br>σ 20 + 19; σ < 0,1   | Pa 234<br>1,17 m 6,70 h<br>( <sup>5</sup> 2.3.,<br>1,(100);<br>1,2.,<br>1,(100);<br>1,2.,<br>1,(100);<br>1,2.,<br>1,17 m<br>1,17 m | Fa 235<br>24,2 m<br><sup>37</sup> 1,4<br>7 <sup>28 - 659</sup>  | Pa 236<br>9,1 m<br>β= 2.0; 3.1<br>γ 642; 687;<br>1763; g<br>βsf ?                                 | Pa 237<br>8,7 m<br>β <sup>-1,4; 2,3</sup> .<br>γ 854; 865;<br>529; 541                                   | Pa 238<br>2,3 m<br>β <sup>-1</sup> ,7;2,9<br>γ 1015;635;<br>448;680<br>9                              |  |  |   |
| Th 231<br>25,5 h<br><sup>β<sup>-</sup>0.3; 0,4</sup><br><sup>γ 26; 84</sup><br>e <sup>-</sup>               | Th 232<br>100<br>1,405 10 <sup>19</sup> a<br>4,013 3,960 sf<br>9 154 f f<br>7,37: ey 0,000005   | Th 233<br>22,3 m<br>sf<br>97,2<br>y 0,19;<br>y 0,19;<br>y 0,19;<br>y 0,19;<br>y 0,19;<br>y 0,19;<br>y 0,19;<br>y 0,19;<br>y 0,19;<br>y 1,50; et 15   | Th 234<br>24,10 d<br>5 0,2<br>7 63:92:93<br>67: m<br>0 1,8: of < 0,01   | Th 235<br>7,1 m<br>β <sup></sup> 1,4<br>γ 417; 727;<br>696  | Th 236<br>37,5 m<br>β <sup>-1,0</sup><br>γ 111; (647;<br>196)  | Th 237<br>5,0 m<br>β <sup>-</sup>   |  |  |   |

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#### **Experimental technique**

Fission tagging:  $\gamma$ -rays in coincidence (fission background) and anticoincidence (capture signal) with the fission detector.

J. Balibrea et al. (The n\_TOF Collaboration), PRC 102, 044615, (2020)

$$Y_{\gamma} = \frac{c_{aco,\gamma} - \frac{1 - \epsilon_f^*(E_n)}{\epsilon_f^*(E_n)} c_{tag} - c_{oth,\gamma}}{\epsilon_{\gamma} \phi_N}$$

 $c_{tot}$  = counts in the TAC.  $c_{tag}$  = counts in the TAC in coincidence. with the ionisation chambers.  $c_{oth}$  = background in the TAC.  $\epsilon_{f}^{*}$  = fission tagging efficiency.  $\epsilon_{\gamma}$  = capture detection efficiency.







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#### A new fission chamber

A new multi target fission chamber has been built taking into account the following important characteristics:

- 1. Low mass intercepting the neutron beam, to minimize the background in the TAC due to captures and elastically scattered neutrons.
- 2. Good discrimination between alphas (2 MBq/mg) and fission fragments (5 mm gap).
- 3. Small **pile-up** effects.





#### A quick reminder

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In 2022 we measured the <sup>239</sup>Pu(n,γ) and <sup>239</sup>Pu(n,f) (α-ratio) cross-sections in EAR1. The experiment consisted in two different setups: Fission Chamber configuration (thin samples) and Thick Sample configuration.



- Re-processed of the entire exp. dataset with a refined version of the new Pulse Shape Analysis
  routine was performed at the beginning of 2023 (see <sup>239</sup>Pu presentation at the n\_TOF Collaboration
  meeting in May 2023). Improvements in the preliminary results.
- BaF<sub>2</sub> time and energy calibrations were performed and validated with Monte Carlo simulations.
- Pileup/Dead-time analysis performed.







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#### The PFB effect in the final capture yield (1/2)

Comparing the yield\* (before dividing by neutron flux) with and without the post-fission background for the TAC event conditions of the analysis. In general, the effect is small, reaching up to  $\sim$ 3% change in some resonances.







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#### **Evaluation of TOF DT model (2/2)**

We can validate this Dead Time model using the experimental data.



The prediction of the DT model agrees with observed data even for high neutron energies



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#### **Comparison with evaluations (1 BPD)**

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#### Conclusions

- Significant progress in the <sup>239</sup>Pu data analysis have been done in the last months, including a better understanding and characterization of the backgrounds for the capture measurement, determination and validation of dead-time and pile-up models, etc.
- Determination of the neutron flux for the <sup>239</sup>Pu measurement, including the boron concentration correction and the beam intersection factor calculation for a wide neutron energy range.
- These improvements allow us to provide a <sup>239</sup>Pu(n,f) yield that agrees with evaluations within ~2% (integrating in 1 bin per decade) from 0.02 eV to 10 MeV in one single measurement.
- The fission yield is ready to be released (paper in preparation).
- The analysis of  $^{239}$ Pu(n, $\gamma$ ) data is in progress.









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### SANDA WP2/Task 2.2 report







Supplying Accurate Nuclear Data for energy and non-energy Applications



### <sup>94,95,96</sup>Mo measurements

Molybdenum is relevant for nuclear astrophysics and nuclear technology and presently known with large uncertainties.

| Tc 92<br>4.4 m<br><sup>β<sup>+</sup> 4.2</sup><br>γ 1510; 773;<br>329; 148   | Tc 93<br>43.5 m 2.7 h<br>1y 392 (************************************  | Tc 94           53 m         4.9 h           \$\vec{\beta}\$ + 0.8           \$\vec{\beta}\$ + 2.5           \$\vec{\beta}\$ + 371           \$\vec{\beta}\$ + 371 | Tc 95           60 d         20 h           ε; β*         γ204;           γ204;         ε           582;         γ766;           γ1074         1074 | Tc         96           52 m         4.3 d <sup>1</sup> γ (34)         e           e <sup>-</sup> ro β <sup>+</sup> γ 778;         850;           1200         813                                    | Tc 97<br>92.2 d 4.0 ·<br>10 <sup>5</sup> a  | Tc 98<br>4.2 $\cdot$ 10 <sup>6</sup> a<br>$\beta^{-}$ 0.4<br>$\gamma$ 745; 652<br>$\sigma$ 0.9 + ? | Tc         99           6.0 h         2.1·           10 <sup>5</sup> a         μγ141           θ <sup>-</sup> β <sup>-</sup> 0.3           γ(90)         γ(90)           γ(322)         γ(90) | Tc 100<br>15.8 s<br>β <sup></sup> 3.4<br><sup>ε</sup><br>γ 540; 591  | Tc 101<br>14.2 m   | Tc         102           4.3 m         5.3 s           β <sup>-1.6;</sup> 3.2.           γ 475;         β <sup>-4.2</sup> 628         γ 475                      |
|--|--|--|---|---|---|--|---|--|--|--|
| Mo 91<br>65 s 15.5 m<br><sup>1γ 653</sup><br><sup>β<sup>+</sup> 2.5;<br/>4.0<sup>(1)</sup><br/>γ 1508;<br/>γ 1687)<br/>1208; m g</sup> | Mo 92<br>14.77<br>σ2E-7 + 0.06   | MO 93<br>6.9 h 3.5 ·<br><sup>1</sup> γ 1477; 10 <sup>3</sup> a<br>685;<br>263; ε<br>γ (950) ε<br>9 m   | Mo 94<br>9.23<br>σ 0.02   | Mo 95<br>15.90<br>σ 13.4<br>σ <sub>n, α</sub> 0.000030  | Mo 96<br>16.68<br>or 0.5  | Mo 97<br>9.56<br><sup>σ 2.5</sup><br>σ <sub>n, α</sub> 4E-7  | Мо 98<br>24.19<br>10 0.14   | Mo 99<br>66.0 h<br>β <sup>-</sup> 1.2<br>γ740; 182;<br>778<br>m; g   | Mo 100<br>9.67<br>1.15 · 10 <sup>19</sup> a  | Mo 101<br>14.6 m<br><sup>β<sup>-</sup> 0.8; 2.6<br/>γ 192; 591;<br/>1013; 506</sup>  |
| Nb         90           18.8 s         14.6 h           β <sup>+</sup> 1.5<br>γ 1129;<br>2319;<br>e <sup>-</sup> 1129;<br>2319;<br>141 | Nb 91<br>60.9 d 680 a<br><sup>by</sup> (105)<br>e <sup>-</sup><br>ε; β <sup>+</sup><br>γ 1205 β <sup>+</sup> | Nb 92<br>10.15 d 3.6 ·<br>10 <sup>7</sup> a<br><sup>6</sup><br><sup>6</sup><br><sup>6</sup><br><sup>7</sup> 561;<br>934  | Nb 93<br>16.13 a 100<br><sup>Iy</sup> (31)<br>e <sup>-</sup> 0.86 +<br>0.29   | Nb         94           6.26 m         2 · 10 <sup>4</sup> a           β <sup>-</sup> 0.5         γ 871;           e <sup>-</sup> 703           β <sup>-</sup> σ 0.6 +           γ (871)         14.4 | Nb         95           86.6 h         34.97 d <sup>1</sup> / <sub>2</sub> 236         β <sup>-</sup> 0.2;           θ <sup>-</sup> 0.9           γ 204,         γ 766           γ 204,         σ < 7 | Nb 96<br>23.4 h<br><sup>β<sup></sup>0.7</sup><br><sub>γ</sub> 778; 569;<br>1091                    | Nb         97           53 s         74 m           Ιγ 743         β <sup>-1.3</sup><br>γ 658   | Nb 98           51 m         2.9 s           β <sup>-</sup> 2.0;         2.9           γ 787;         β <sup>-</sup> 4.6           723;         γ 787;           1169         1024 | Nb         99           2.6 m         15 s           β=3.2         γ           γ 86; 254;         β=3.1           2854         γ           iy 365 ?         98 | Nb         100           3.1 s         1.5 s           β <sup>-</sup> 6.2           γ 535:         γ 535;           600:         528;           1280         159 |
| Zr 89<br>4.16 m 78.4 h<br>hy 588<br>6<br>\$+0.9;<br>2.4<br>y 1507; g<br>m  | Zr 90<br>51.45<br>σ~0.014  | Zr 91<br>11.22<br>σ 1.2  | Zr 92<br>17.15<br>σ0.2  | Zr 93<br>1.5 · 10 <sup>6</sup> a<br><sup>β<sup>-</sup> 0.06<br/><sup>m</sup><br/>σ &lt;4</sup>  | Zr 94<br>17.38<br>σ0.049  | Zr 95<br>64.0 d<br><sup>β<sup>-</sup> 0.4; 1.1</sup><br>γ757; 724<br>9                             | Zr 96<br>2.80<br>3.9 · 10 <sup>19</sup> a   | Zr 97<br>16.8 h<br><sup>β<sup>-</sup>1.9</sup><br><sup>γ 508; 1148;<br/>355</sup><br>m   | Zr 98<br>30.7 s<br><sup>β<sup>-</sup> 2.3</sup><br><sup>no γ</sup><br>9  | Zr 99<br>2.1 s<br>β <sup>-3.5; 3.6</sup><br>γ 469; 546;<br>594<br>g; m   |





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# **Enriched pellets preparation**

To avoid the background coming from aluminum capsule three pressed pellets were prepared using enriched powder:

- Pellets prepared at JRC-Geel;
- Self sustaining pellets of ~ 2g;
- Additional <sup>nat</sup>Mo samples prepared using powder with different grain sizes;











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### Mo pellet samples

| Atomic %         | <sup>92</sup> Mo | <sup>94</sup> Mo | <sup>95</sup> Mo | <sup>96</sup> Mo | <sup>97</sup> Mo | <sup>98</sup> Mo | <sup>100</sup> Mo |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|-------------------|
| <sup>94</sup> Mo | 0,63%            | 98,97%           | 0,36%            | 0,01%            | 0,01%            | 0,01%            | 0,01%             |
| <sup>95</sup> Mo | 0,31%            | 0,69%            | 95,40%           | 2,24%            | 0,51%            | 0,65%            | 0,20%             |
| <sup>96</sup> Mo | 0,28%            | 0,24%            | 1,01%            | 95,90%           | 1,00%            | 1,32%            | 0,25%             |

| lsotope                  | Mass (mg) | Areal density (atoms/b) |
|--------------------------|-----------|-------------------------|
| <sup>94</sup> Mo         | 1,952.6   | 3,9592E-03              |
| <sup>95</sup> Mo         | 1,974.5   | 3,9558E-03              |
| <sup>96</sup> Mo         | 1,917.5   | 3,8064E-03              |
| <sup>nat</sup> Mo-5 μm   | 2,014.0   | 4,0059E-03              |
| <sup>nat</sup> Mo-350 μm | 1,989.0   | 3,9584E-03              |





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### Measurements

| EAR2_2021                         | EAR1_2022                       | EAR2_2022                       |
|-----------------------------------|---------------------------------|---------------------------------|
| 1.7 10 <sup>18</sup> protons      | 6.0 10 <sup>18</sup> protons    | 1.7 10 <sup>18</sup> protons    |
| 3 B6D6, 1 L6D6, 1 STED            | 4 C6D6                          | 8 STED, 2 L6D6, 1 DSTI          |
| Powder sample in aluminum canning | Pressed pellets in plastic bags | Pressed pellets in plastic bags |

+ additional transmission measurement with enriched pellets at 10m station of GELINA

+ transmission measurements with natural samples at 50m station of GELINA









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- Resonance parameters have been adjusted in all the resolved resonance region (<21 keV);</li>
- Extended resolved resonance region up to 75 keV
- Example of fit showed here compared to the calculation performed with JENDL5 parameters
- Good agreement between transmission and capture data with enriched samples

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- Extended resolved resonance region up to 75 keV using data from capture measurements,
- New resonances not present in literature.

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| J    | L | Energy (eV) | Unc_E    | W_Capture (meV) | Unc_Cap  | Width_ n (meV) | Unc_n    |
|------|---|-------------|----------|-----------------|----------|----------------|----------|
| -0.5 | 1 | 108.7365    | 2.29E-03 | 158.837         | 4.69049  | 0.180556       | 1.22E-03 |
| -1.5 | 1 | 1051.963    | 1.48E-02 | 237.578         | 25.6533  | 2.35311        | 3.02E-02 |
| 0.5  | 0 | 1542.773    | 1.16E-02 | 124.952         | 0.568967 | 1673.86        | 8.59281  |
|      |   |             |          |                 |          |                |          |
| -1.5 | 1 | 1657.322    | 2.08E-02 | 169.781         | 30.3225  | 4.65519        | 6.62E-02 |
| -1.5 | 1 | 2175.49     | 1.01E-02 | 159.592         | 1.06928  | 340.652        | 4.81211  |
|      |   |             |          | •               |          |                |          |
| -1.5 | 1 | 9576.481    | 0.109357 | 122.857         | 2.46143  | 673.324        | 68.231   |
| 0.5  | 0 | 9689.416    | 0.184379 | 98.0503         | 2.40078  | 2383.27        | 162.983  |



1

9797.066

0.132802

-1.5



95.4524



7.68889



230.418

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44.3515



# Capture kernels for <sup>94</sup>Mo



- The preliminary kernels obtained with ٠ SAMMY were compared to the ones in literature (Weigmann and Musgrove capture measurements);
- Main measurements used in libraries; ٠
- Systematic deviation of around 20% ٠ observed









# Presentation and article

- Journal articles
  - *R. Mucciola et al., Evaluation of resonance parameters for neutron interactions with* molybdenum, NIMB **531** (2022) 100
  - R. Mucciola et al., Neutron capture and total cross-section measurements on <sup>94,95,96</sup>Mo at n TOF and GELINA, EPJ Web of Conferences 284, 01031 (2023)
- Contributions to seminar and conferences
  - Nuclei in the cosmos XVII, 17-22 September 2023, Daejeon (Korea). Poster presentation
  - GIANTS XI, 20-21 October 2022, Caserta (Italy). Invited talk
  - ND 2022, 24-29 July 2022, Sacramento (USA). Oral presentation
  - 13th Torino Workshop on AGB stars, 19-24 June 2022, Perugia (Italy). Oral presentation









### Overall status of the 94,95,96 Mo measurements

|       | Transmission<br>measurement         | Capture<br>measurement           | Transmission<br>data analysis       | Capture<br>data analysis   |
|-------|-------------------------------------|----------------------------------|-------------------------------------|--|
| Mo-94 | Performed<br>at 10 m station GELINA | Performed at EAR1 and EAR2 n_TOF | Preliminary resonance<br>parameters | EAR1 preliminary<br>resonance parameters,<br>EAR2 analysis ongoing |
| Mo-95 | Performed<br>at 10 m station GELINA | Performed at EAR1 and EAR2 n_TOF | Transmission spectra obtained       | EAR1 yield obtained,<br>EAR2 analysis ongoing                      |
| Mo-96 | Performed<br>at 10 m station GELINA | Performed at EAR1 and EAR2 n_TOF | Transmission spectra obtained       | EAR1 yield obtained,<br>EAR2 analysis ongoing                      |

# SANDA WP2/Task 2.2 report summary 1/2

 $^{239}$ Pu(n, $\gamma$ ) neutron capture cross section and  $\alpha$  ratio



proposal for measurement at n\_TOF submitted and approved by the CERN Research Board (December 2020)

sample preparation procedure agreed between CERN and JRC-Geel



The ionization chamber that is used for these measurements will be tested at JRC-Geel during 2021

Measurements to be performed at n\_TOF during 2022







# SANDA WP2/Task 2.2 report summary 1/2

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Measurements performed at n\_TOF during 2022





# SANDA WP2/Task 2.2 report summary 2/2

 $^{94,95,96}$ Mo(n, $\gamma$ ) neutron capture and total cross section measurements



proposal for measurement at n\_TOF submitted and approved by the CERN Research Board (December 2020)

sample orders issued to Neonest AB, Sweden. Expected delivery Q1-2021



Total cross section measurements to be performed at JRC-Geel (GELINA) during 2021

Measurements to be performed at n\_TOF during 2022







# SANDA WP2/Task 2.2 report summary 2/2

 $^{94,95,96}$ Mo(n, $\gamma$ ) neutron capture and total cross section measurements



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#### The END



9 February 2021, SANDA meeting



SANDA Supplying Accurate Nuclear Data for energy and non-energy Applications





Liberté Égalité Fraternité



#### SANDA GENERAL MEETING PROGRESS OF IRSN ON WP2&4 WORK PACKAGE 9-11 FEBRUARY 2021

#### IRSN PSN-RES/SNC/LN Pôle Sûreté Nucléaire Service de Neutronique et des risques de Criticité Laboratoire de Neutronique

N. LECLAIRE L. LEAL



MEMBRE DE ETSOI

#### Working package WP2 & 4 – Measurement and assessment of nuclear data

#### ASSESSMENT OF MOLYBDENUM NUCLEAR DATA

<u>Target</u>: produce Mo evaluation with covariance for RP and cross sections

- JEFF-33, ENDF/B-VIII.0: covariance for cross sections BUT <u>no covariance</u> for RP
- JENDL-4.0: no covariance for RP and cross sections

Resonance parameters retrieved from JEFF-3.1.1, JEFF-3.3, JENDL-4.0, ENDF/B-VII.1 and ENDF/B-VIII.0 evaluations

- Identification of available differential measurements in EXFOR
  - Lack of data for <sup>95</sup>Mo

Use of JENDL-4.0 resonance parameters to initiate the evaluation process

Correspondence between spin groups and channel spins addressed

Transmission and capture measurements of <sup>nat</sup>Mo at J-PARC (Japan) on various samples

- ANNRI experimental device
- 0.1, 0.5, 2 mm thick for capture and 0.5, 5 mm thick for transmission

| lsotope           | Composition<br>(%) | Thermal Cross<br>Section (barns) | Resonance<br>Integral<br>(barns) |
|-------------------|--------------------|----------------------------------|----------------------------------|
| <sup>92</sup> Mo  | 14.84              | 0.08±0.02                        | 0.83                             |
| <sup>94</sup> Mo  | 9.25               | 0.34±0.02                        | 1.12                             |
| <sup>95</sup> Mo  | 15.92              | 13.4 <u>+</u> 0.3                | 118 <u>+</u> 7                   |
| <sup>96</sup> Mo  | 16.68              | 0.5±0.3                          | 17±3                             |
| <sup>97</sup> Mo  | 9.55               | 2.2±0.2                          | 14.4±3.0                         |
| <sup>98</sup> Mo  | 24.13              | 0.130±0.006                      | 6.7±0.3                          |
| <sup>100</sup> Mo | 9.63               | 0.199±0.002                      | 3.76±0.15                        |

| Library       | Lower<br>limit<br>RR<br>(eV) | Upper<br>limit RR<br>(eV) | Lower<br>limit<br>URR (eV) | Upper<br>limit URR<br>(eV) |
|---------------|------------------------------|---------------------------|----------------------------|----------------------------|
| JEFF-3.3      | 0                            | 2141.2                    | 0                          | 206269                     |
| ENDF/B-VIII.0 | 0                            | 2141.2                    | 0                          | 206269                     |
| JENDL-4.0     | 0                            | 2000.0                    | 0                          | 400000                     |

#### Working package WP2 & 4 – Measurement and assessment of nuclear data

#### [ ASSESSMENT OF MOLYBDENUM NUCLEAR DATA

- Fit of experimental data with SAMMY code (R-matrix)
  - Preliminary evaluation: sequential fit
    - Resolved resonance description
      - –Use of  $\chi 2$  as figure of merit
      - -Generation of covariance matrix
      - -Updated RP and RP covariance data at each step
  - Use of 0.5 mm sample in 0-600 eV
    - Low data resolution above 350 eV



n\_TOF and GELINA measurements of enriched Mo are planned/underway.

Additional data: a) RPI transmission data for isotopes (<sup>95</sup>Mo, <sup>96</sup>Mo, <sup>98</sup>Mo, <sup>100</sup>Mo); b) Transmission and capture data for <sup>95</sup>Mo from LANL



