Extensive study of the quality of fission yields from experiment, evaluation and GEF for anti-neutrino studies and applications

Appendix: Independent yields *

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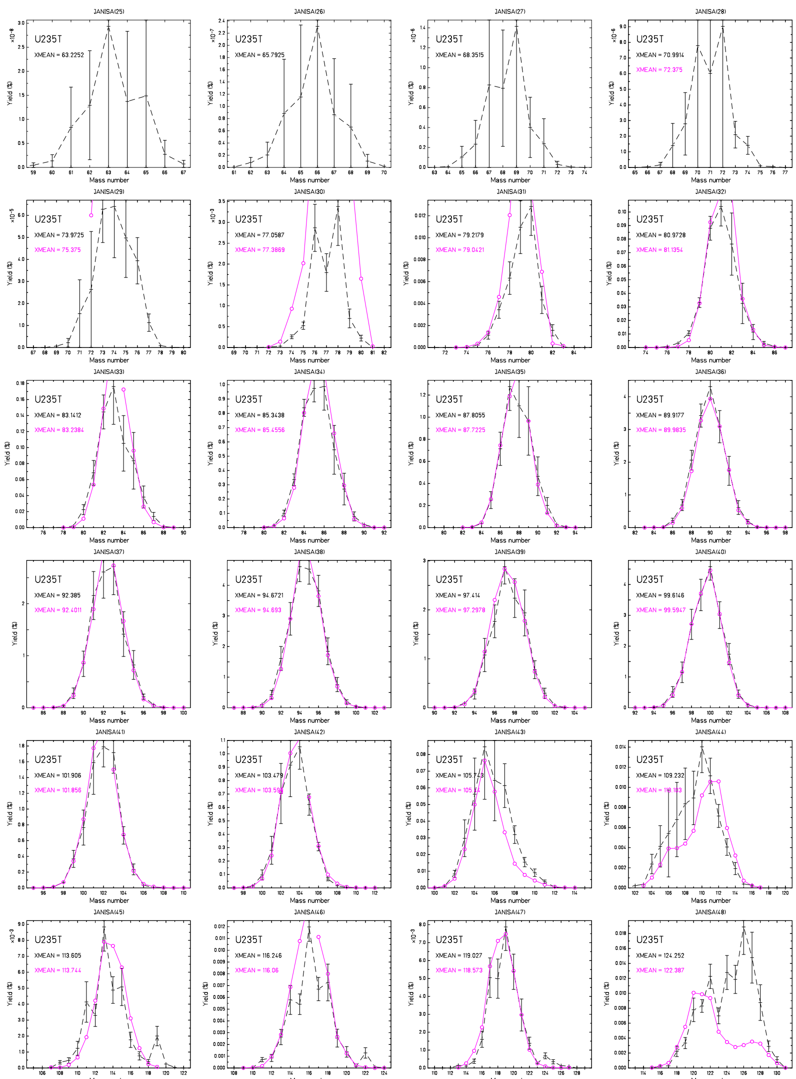

Figure 1: Isotopic distributions of the system ^{235}U(n$_{th}$,f), comparison of JEFF 3.3 (black symbols and error bars) and GEF (magenta symbols), linear scale.

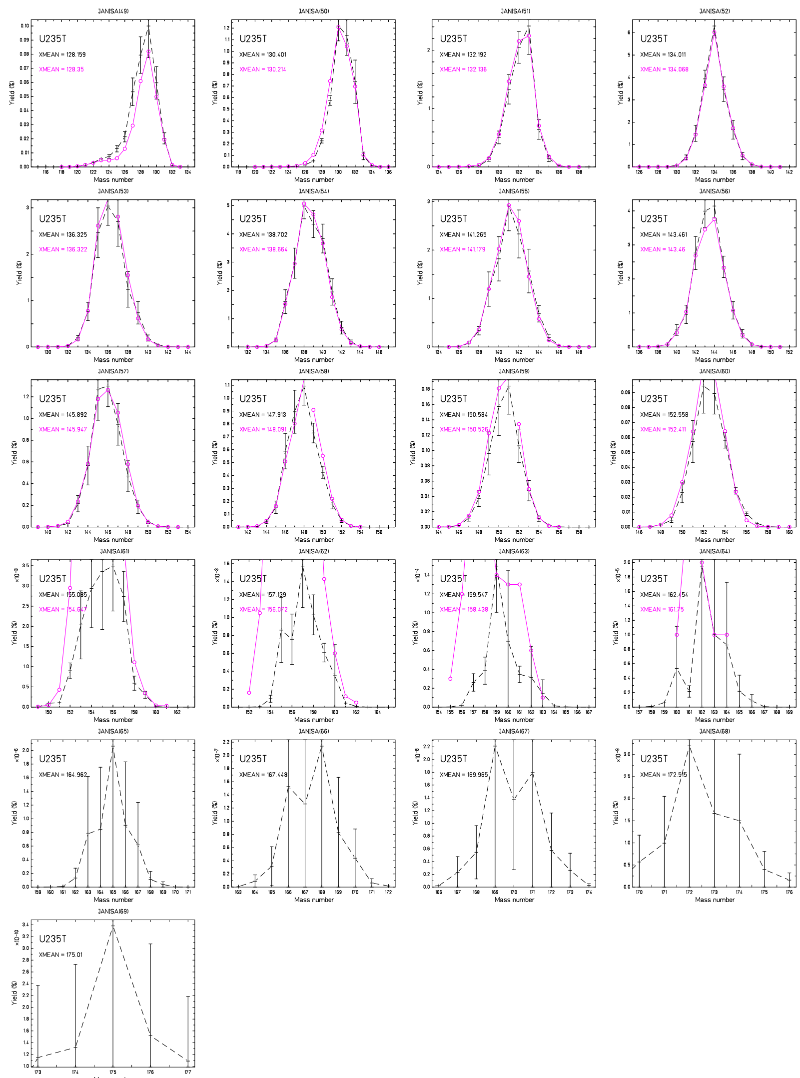

Figure 2: Isotopic distributions of the system ^{235}U(n$_{th}$,f), comparison of JEFF 3.3 and GEF, linear scale.

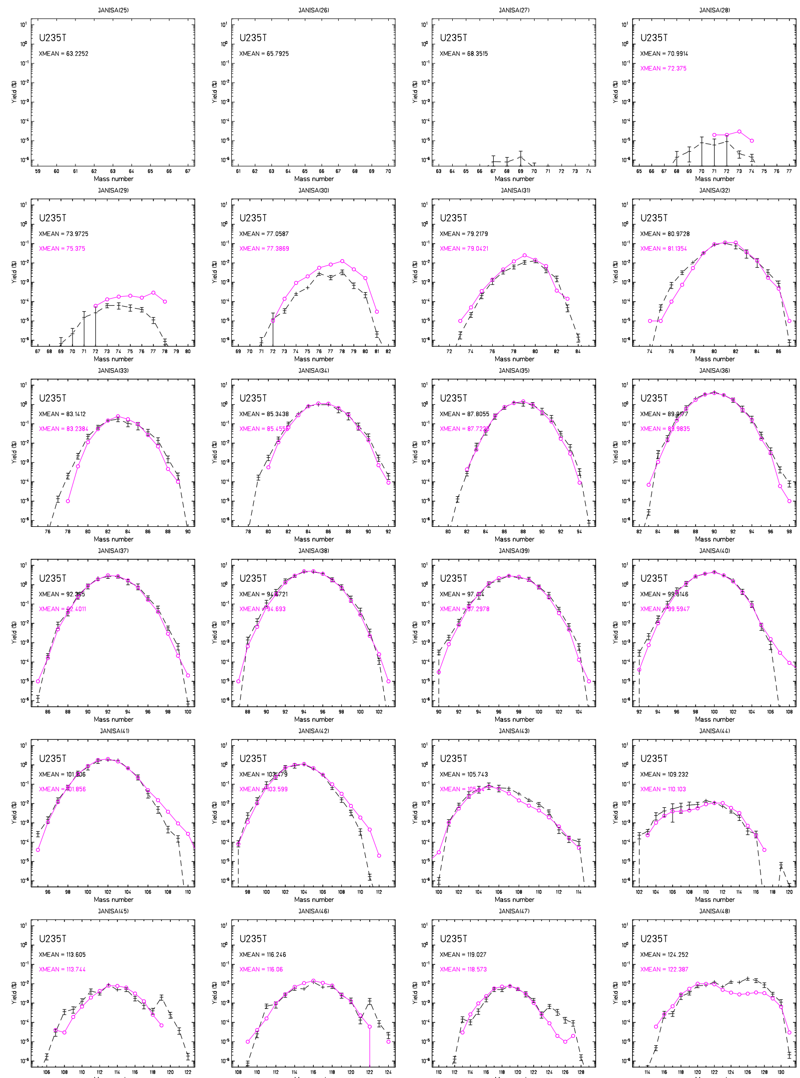

Figure 3: Isotopic distributions of the system ^{235}U(n_{th},f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

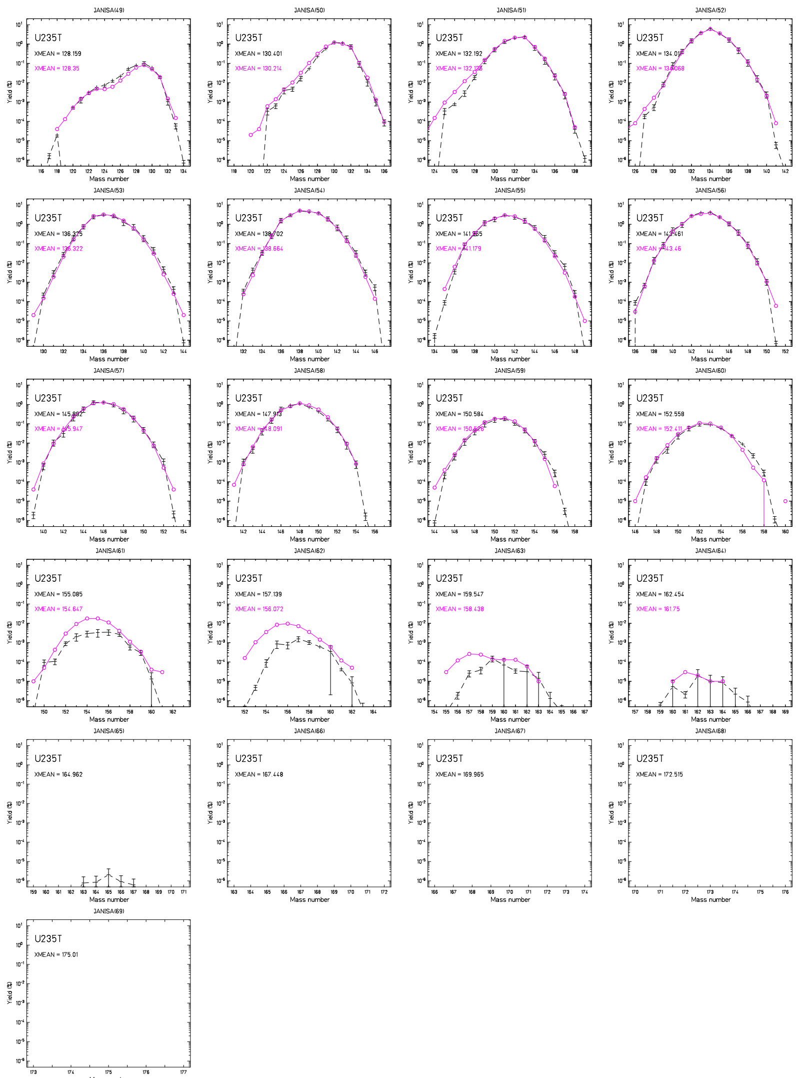

Figure 4: Isotopic distributions of the system ^{235}U(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

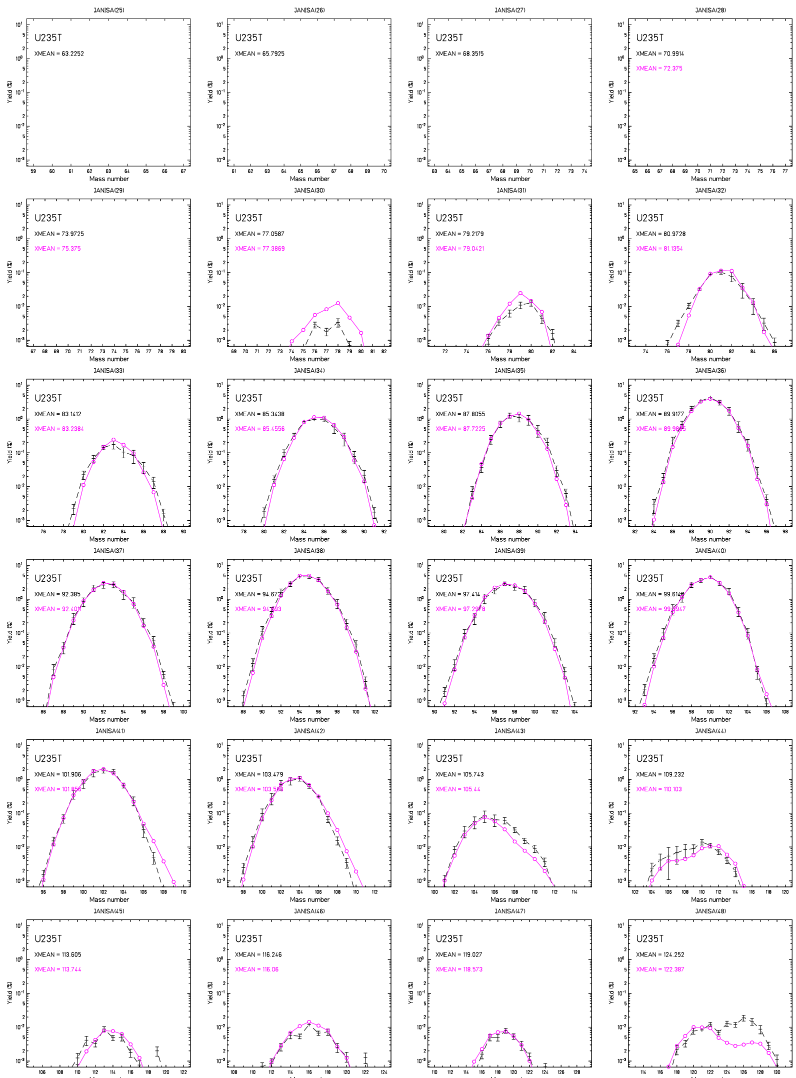

Figure 5: Isotopic distributions of the system ^{235}U(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

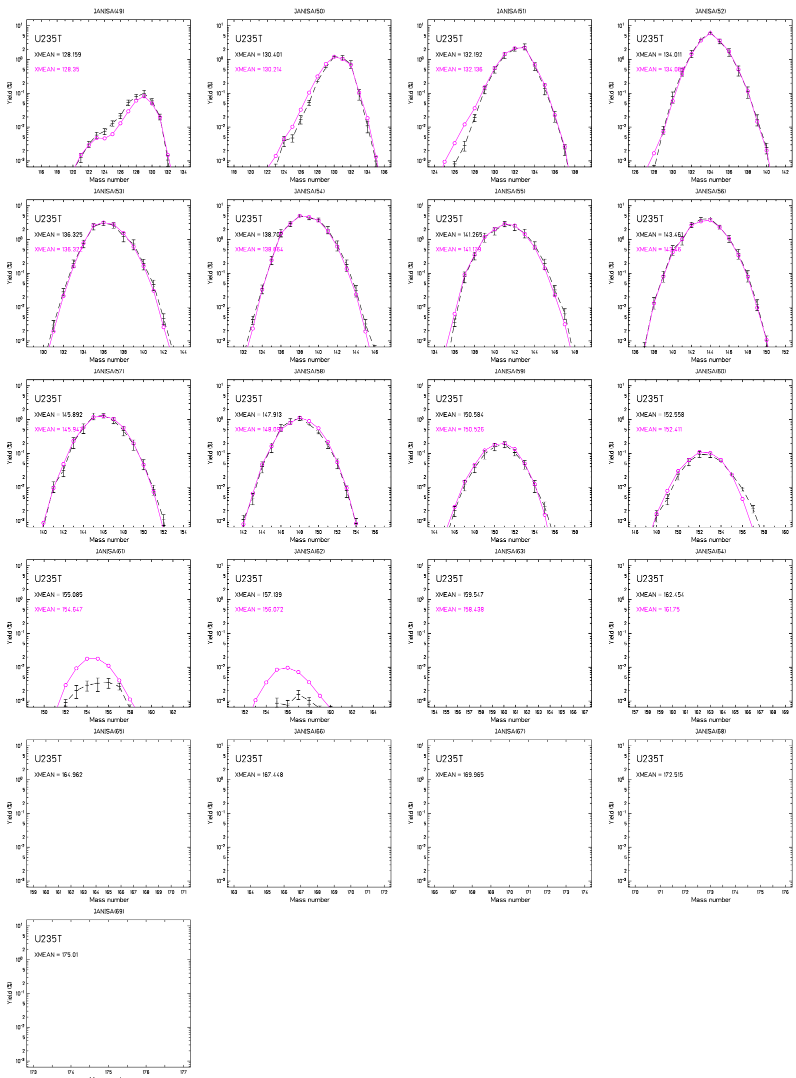

Figure 6: Isotopic distributions of the system ^{235}U(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

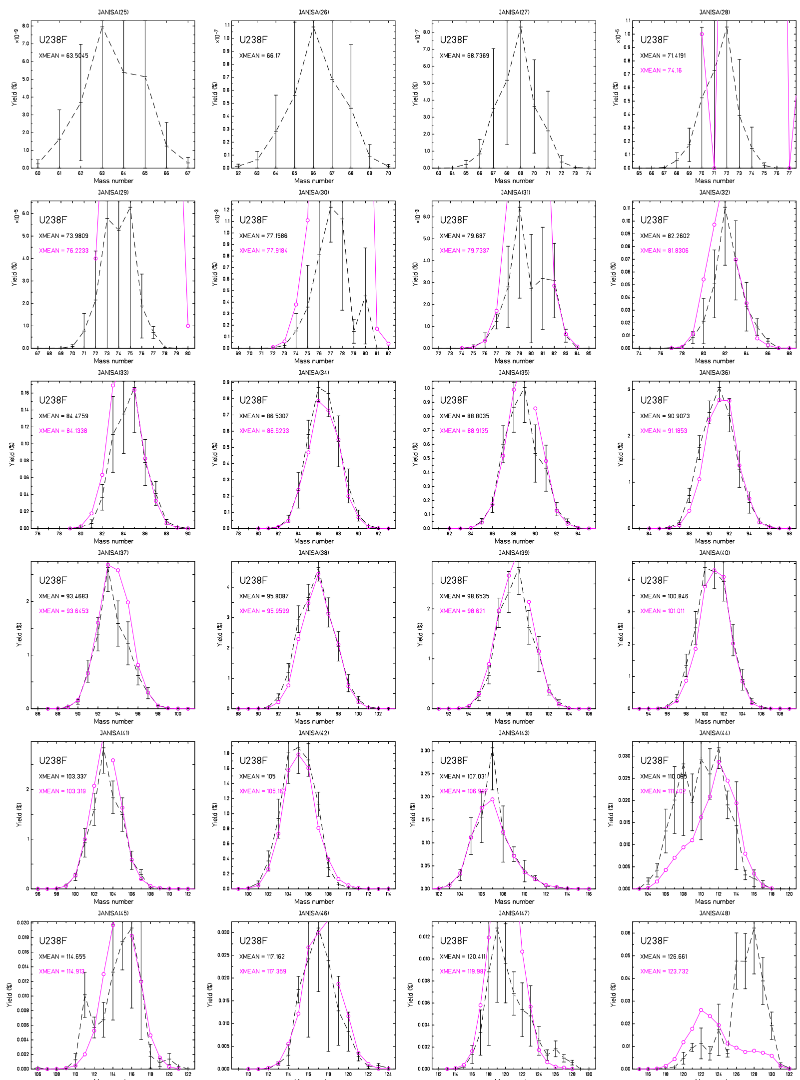

Figure 7: Isotopic distributions of the system ^{238}U(n$_{fast}$,f), comparison of JEFF 3.3 and GEF, linear scale.

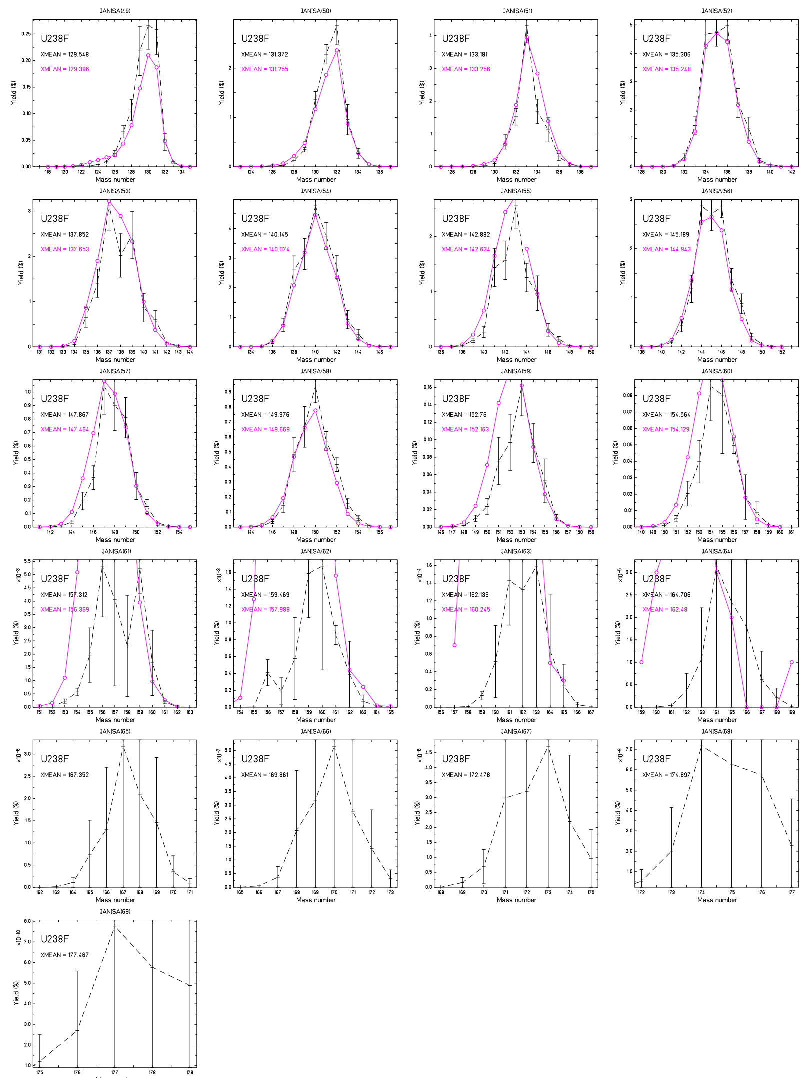

Figure 8: Isotopic distributions of the system ^{238}U(n$_{fast}$,f), comparison of JEFF 3.3 and GEF, linear scale.

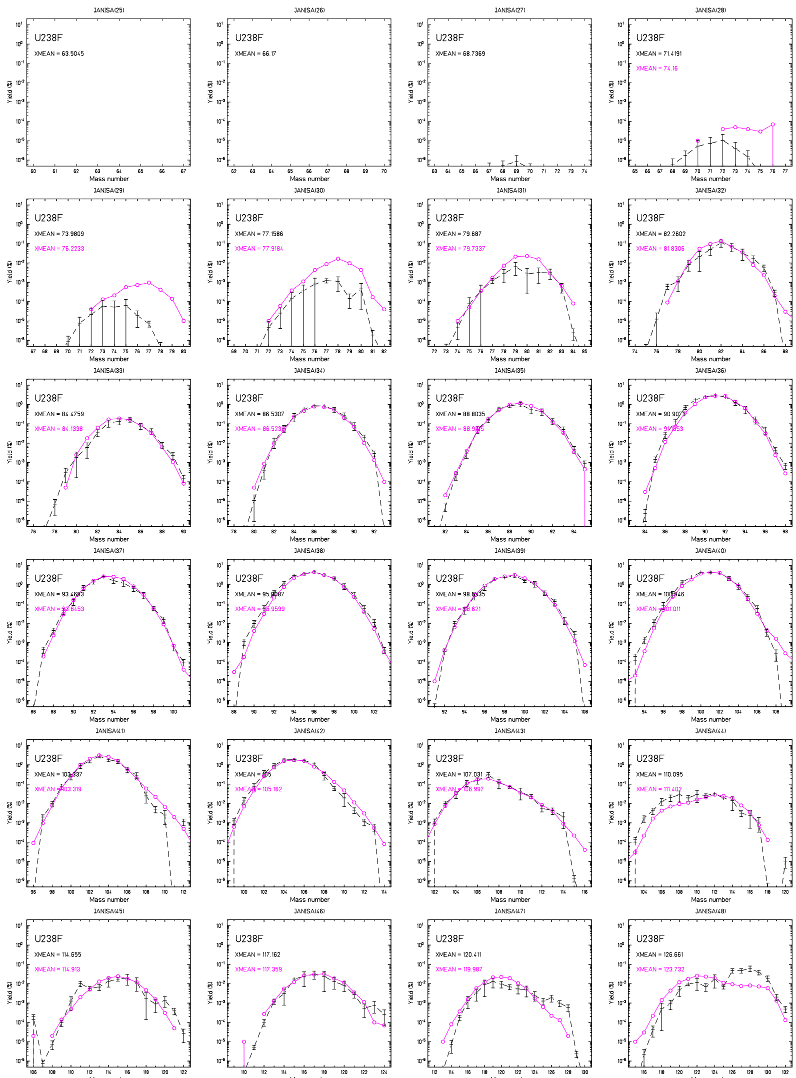

Figure 9: Isotopic distributions of the system ^{238}U(n$_{fast}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

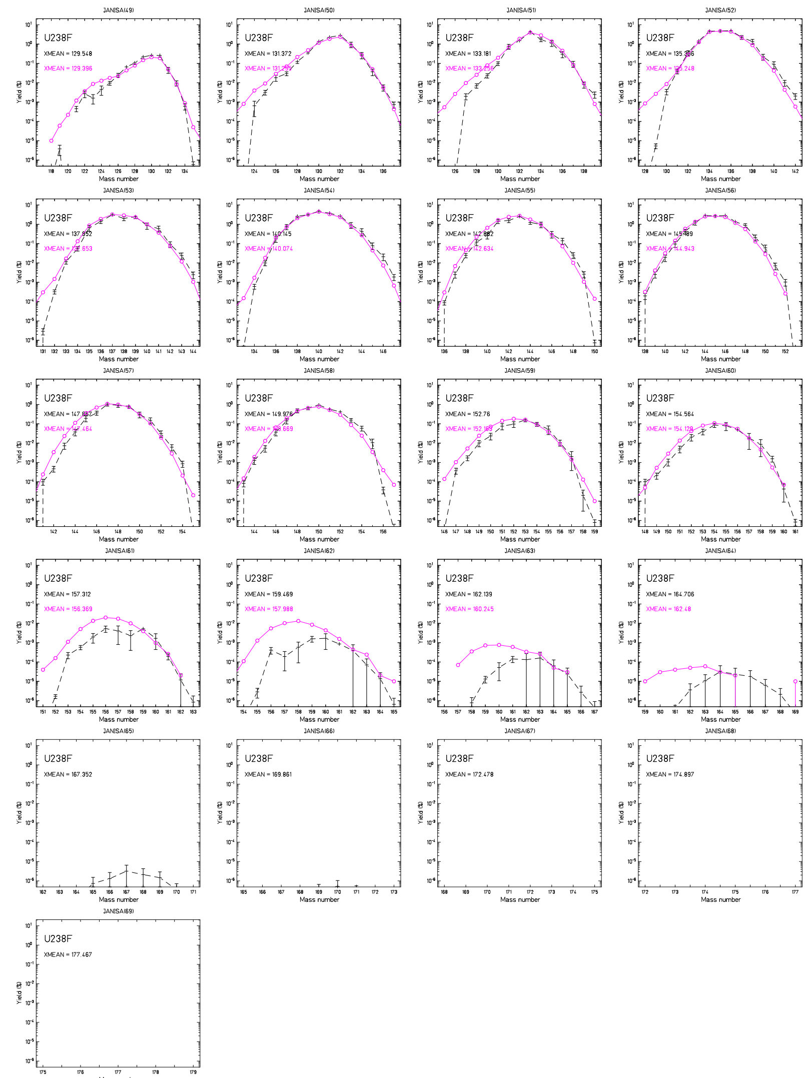

Figure 10: Isotopic distributions of the system ^{238}U(n$_{fast}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

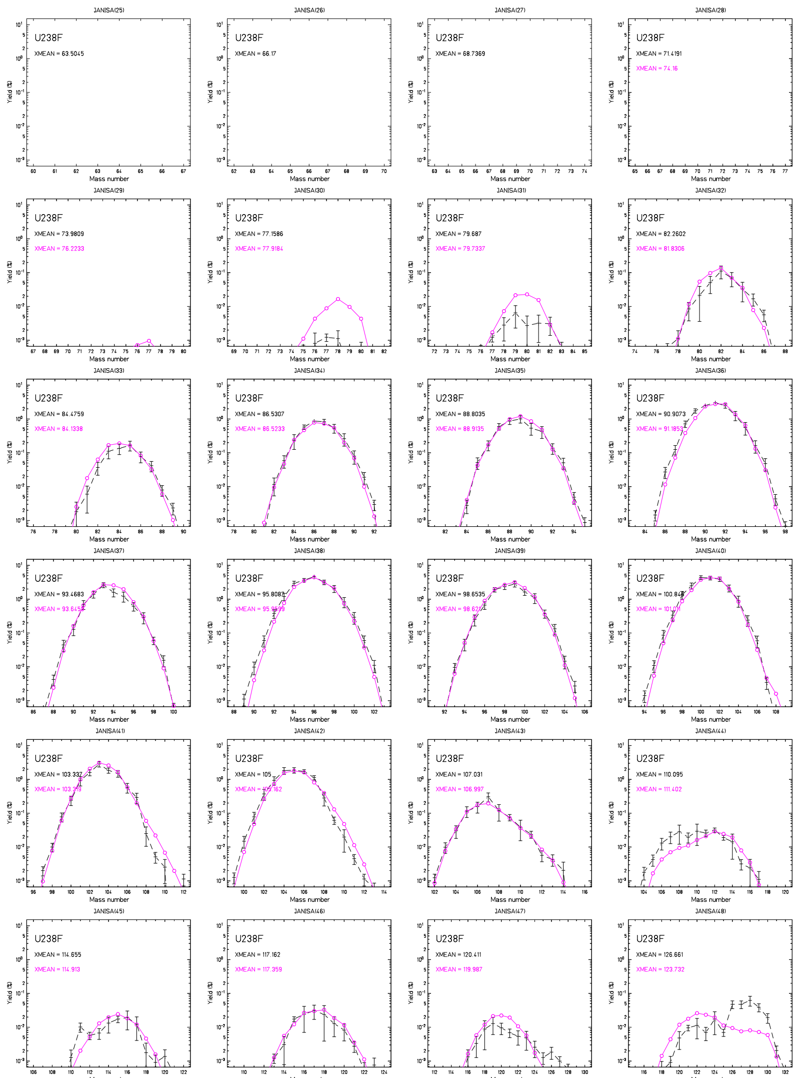

Figure 11: Isotopic distributions of the system ^{238}U(n$_{fast}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

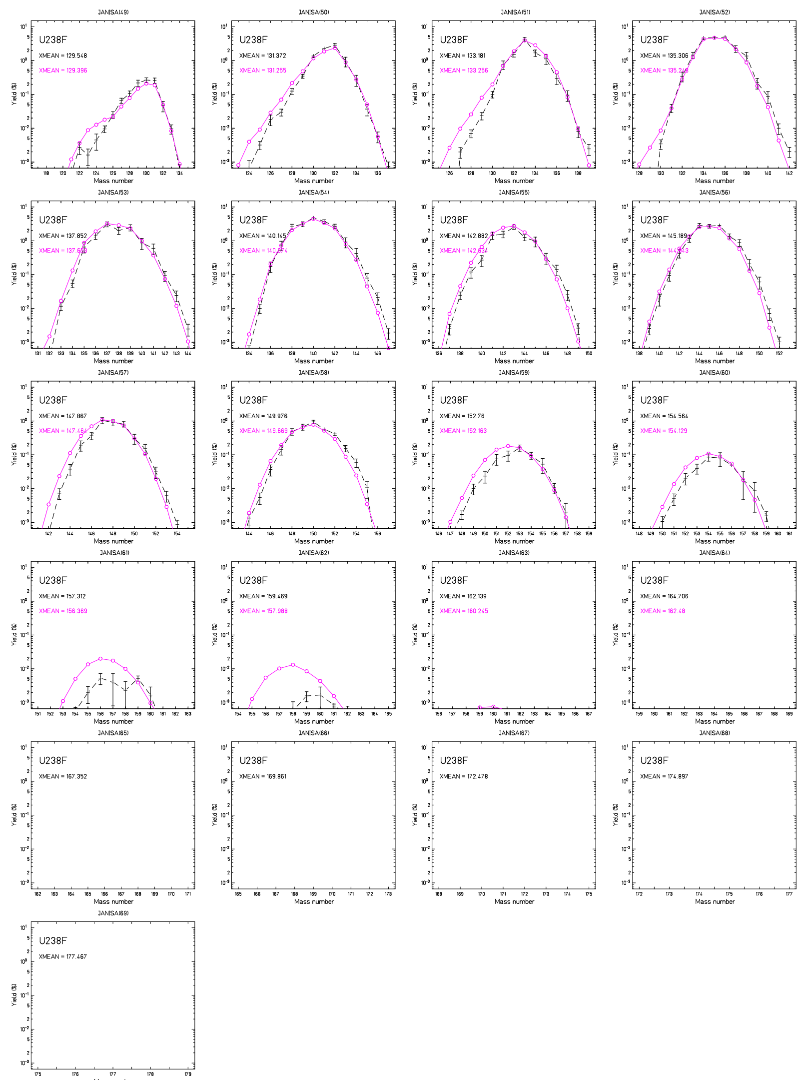

Figure 12: Isotopic distributions of the system ^{238}U(n$_{fast}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

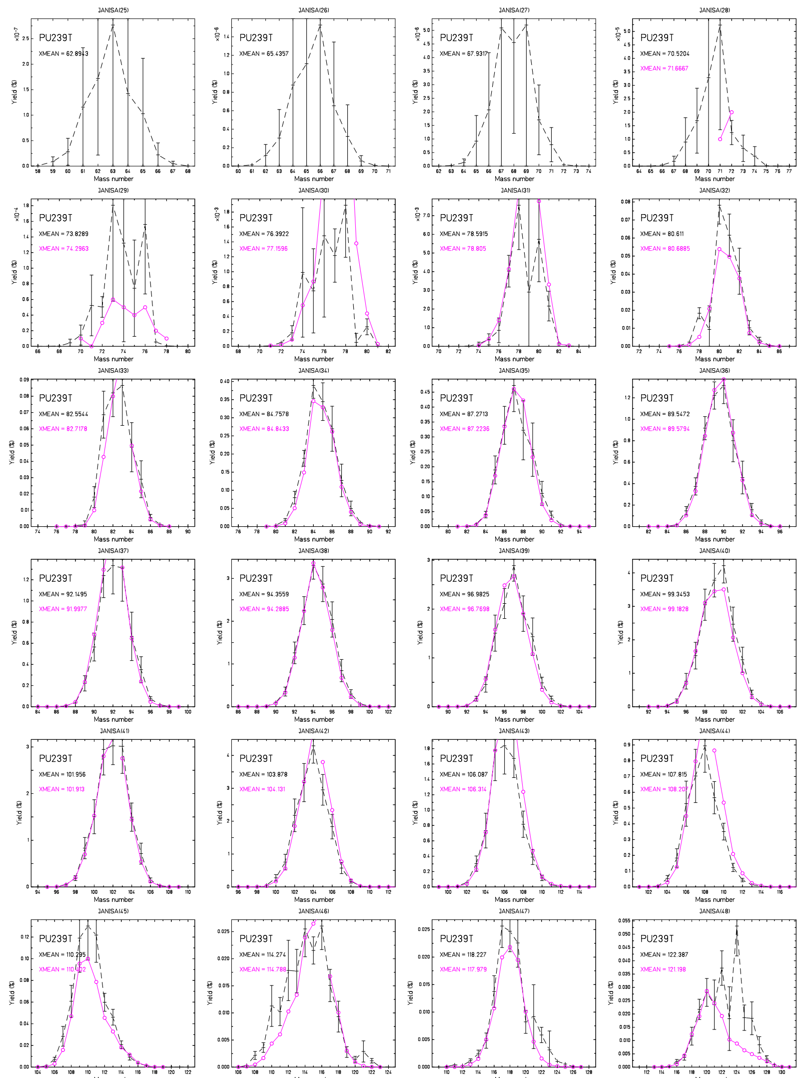

Figure 13: Isotopic distributions of the system ^{239}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, linear scale.

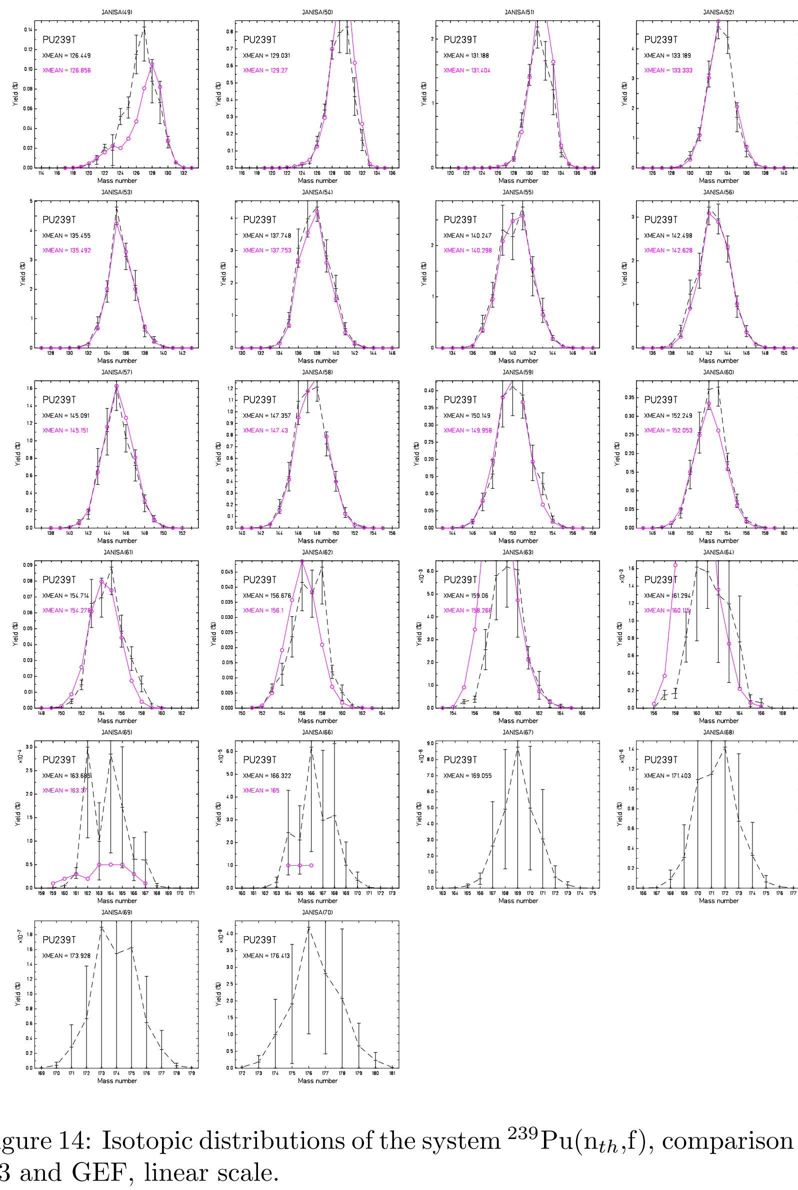

Figure 14: Isotopic distributions of the system ^{239}Pu(n_{th},f), comparison of JEFF 3.3 and GEF, linear scale.

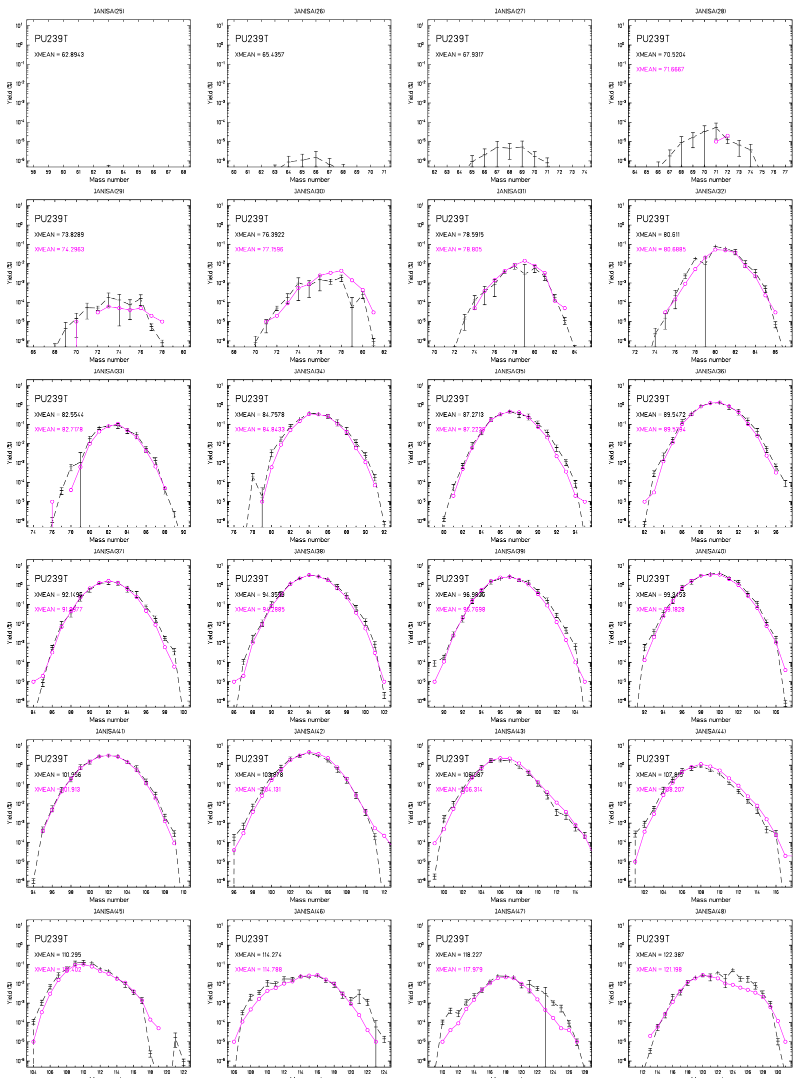

Figure 15: Isotopic distributions of the system ^{239}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

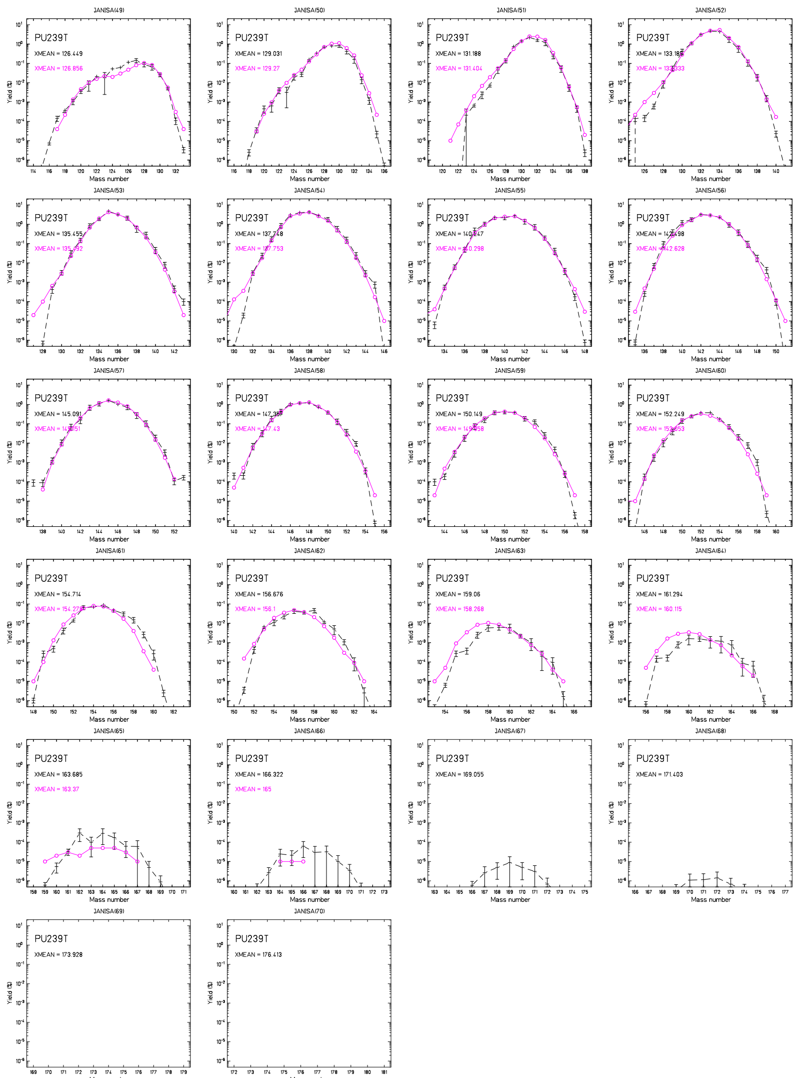

Figure 16: Isotopic distributions of the system ^{239}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

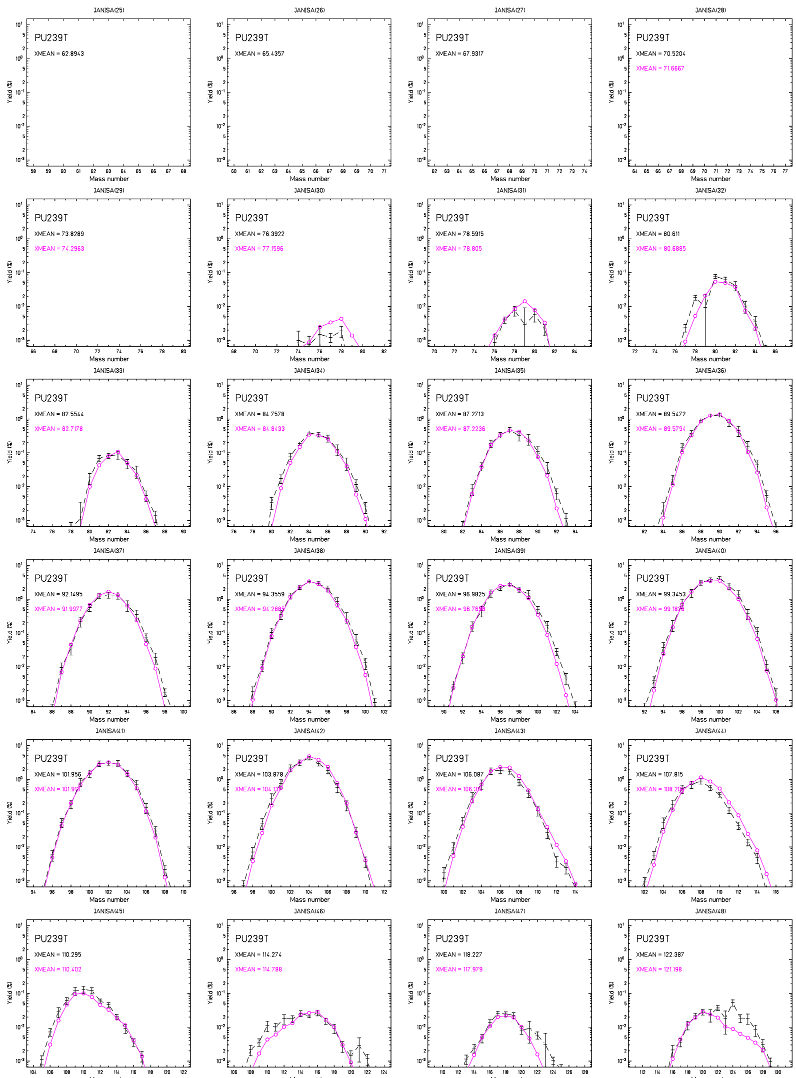

Figure 17: Isotopic distributions of the system ^{239}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

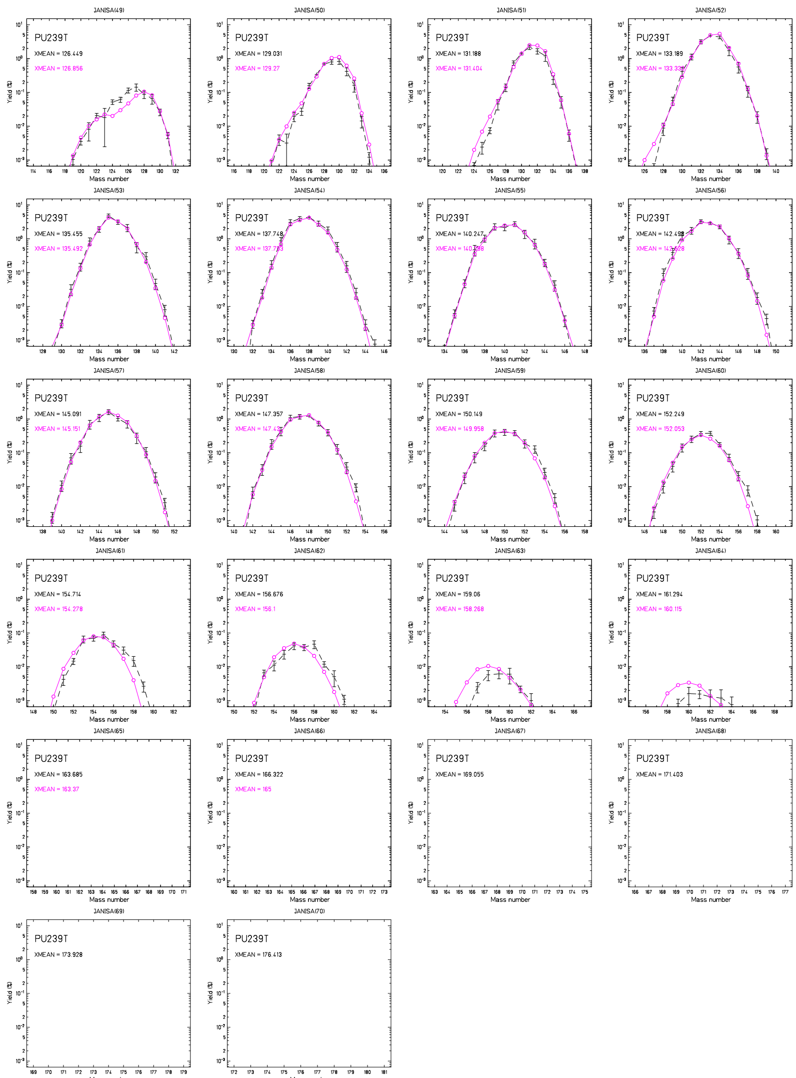

Figure 18: Isotopic distributions of the system ^{239}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

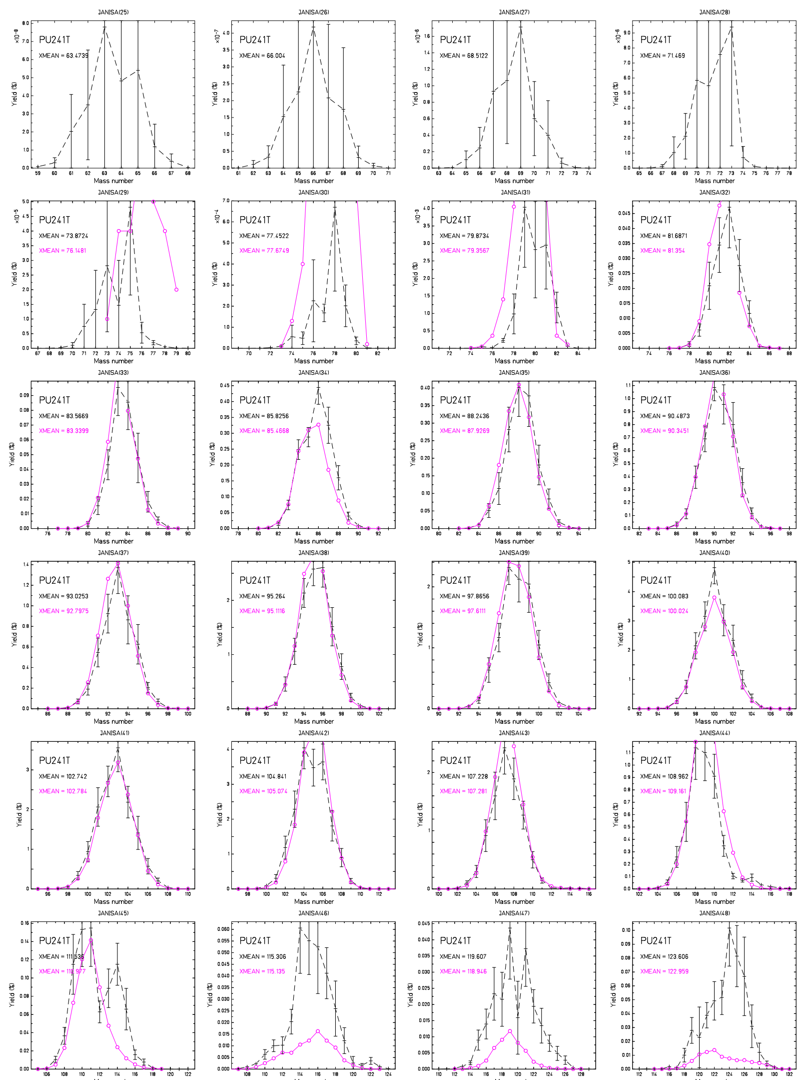

Figure 19: Isotopic distributions of the system ^{241}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, linear scale.

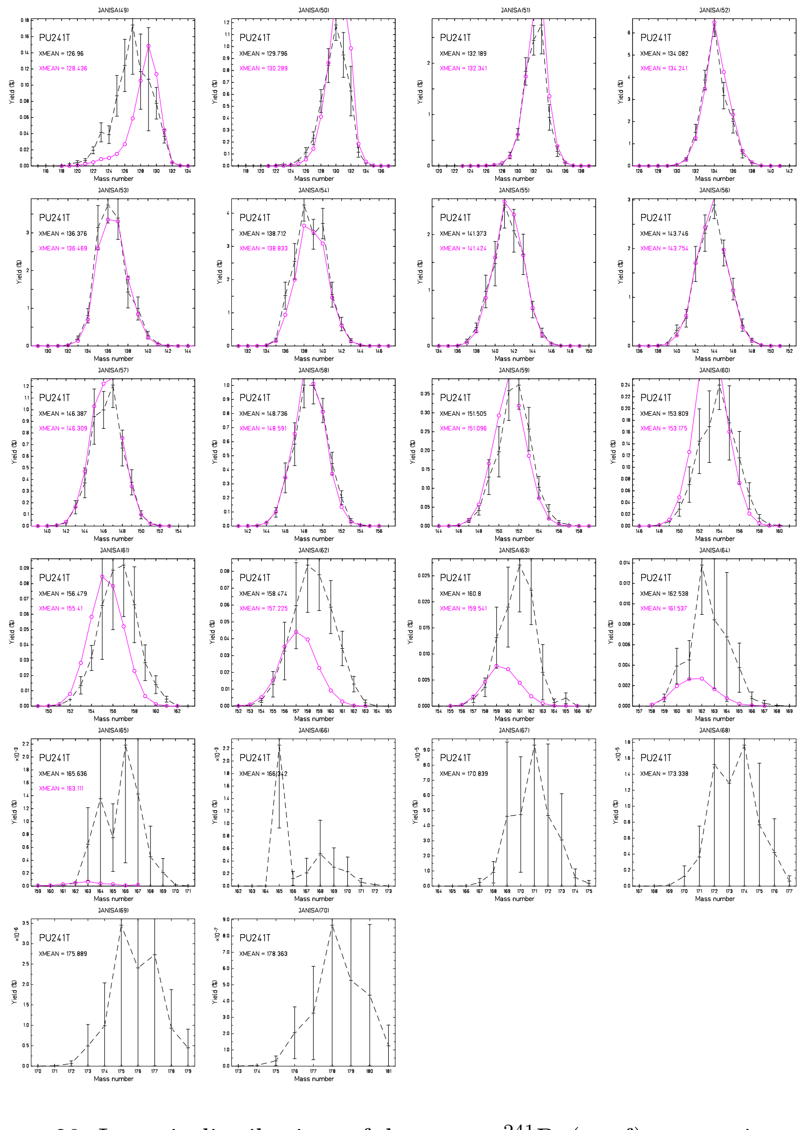

Figure 20: Isotopic distributions of the system ^{241}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, linear scale.

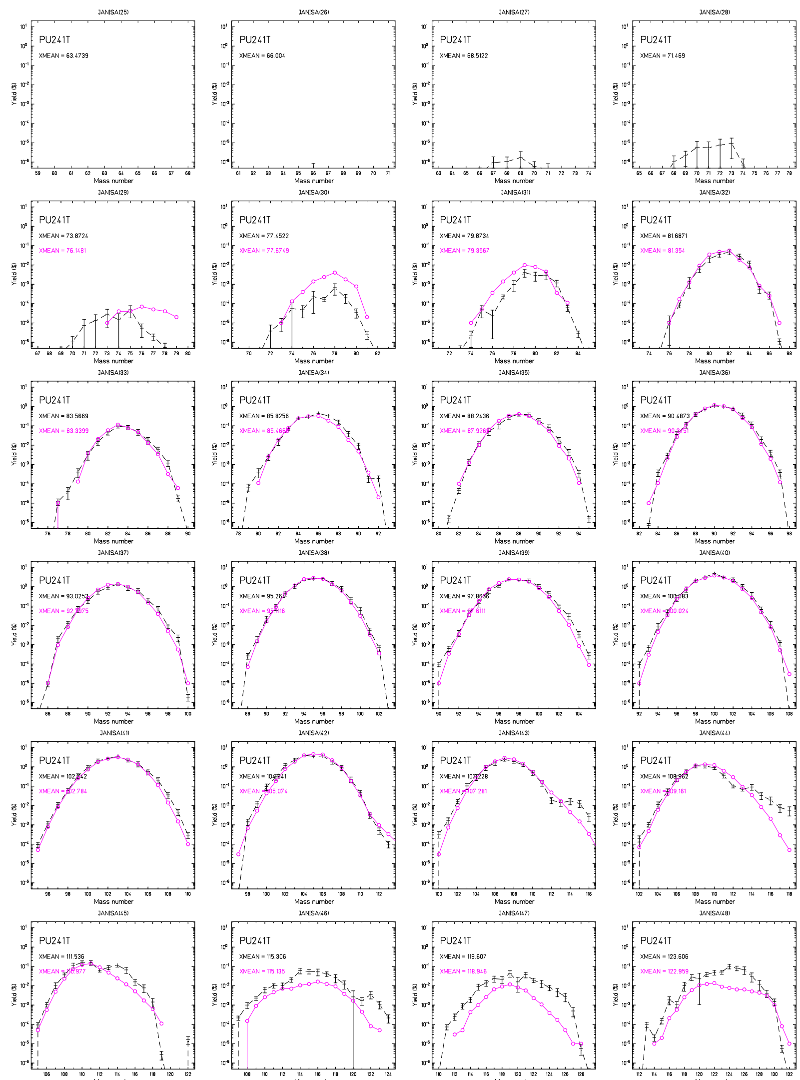

Figure 21: Isotopic distributions of the system ^{241}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

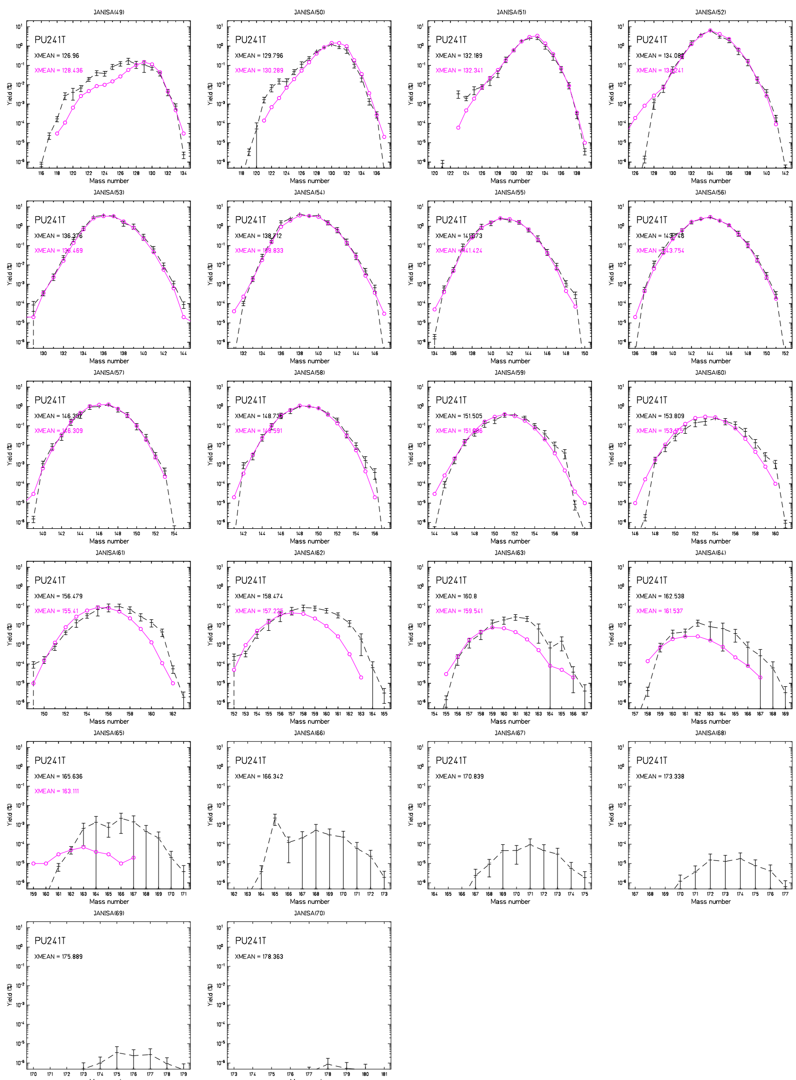

Figure 22: Isotopic distributions of the system ^{241}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, large range.

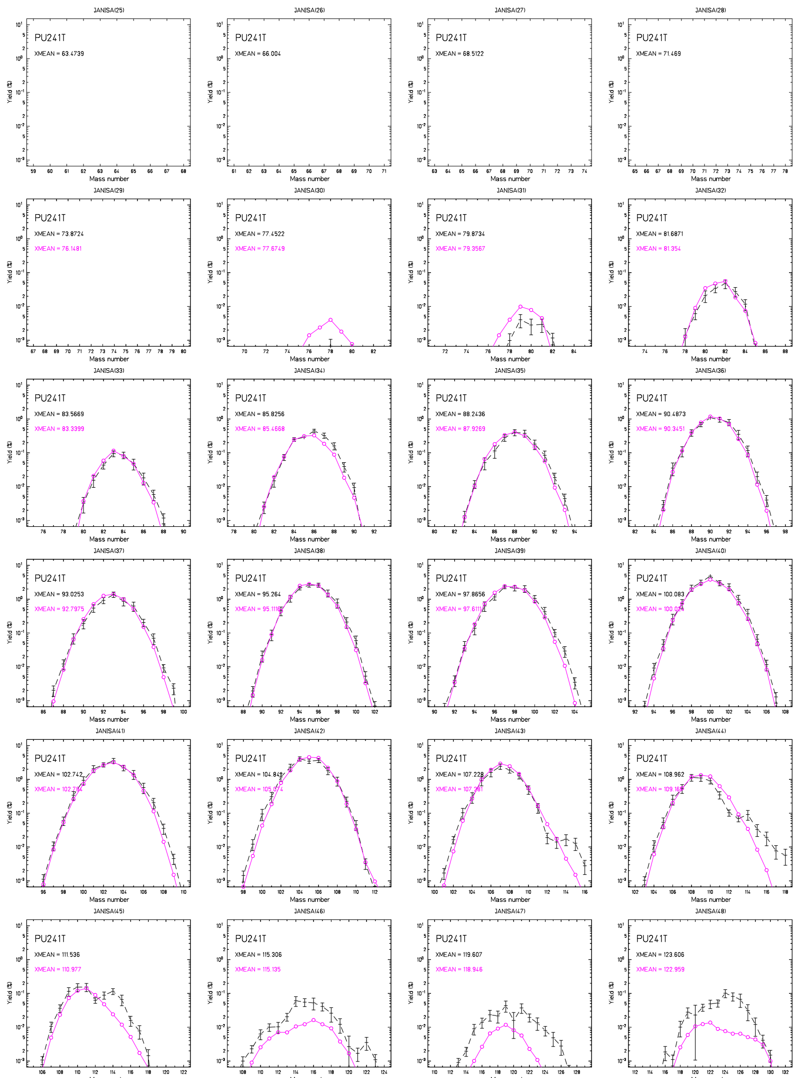

Figure 23: Isotopic distributions of the system ^{241}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

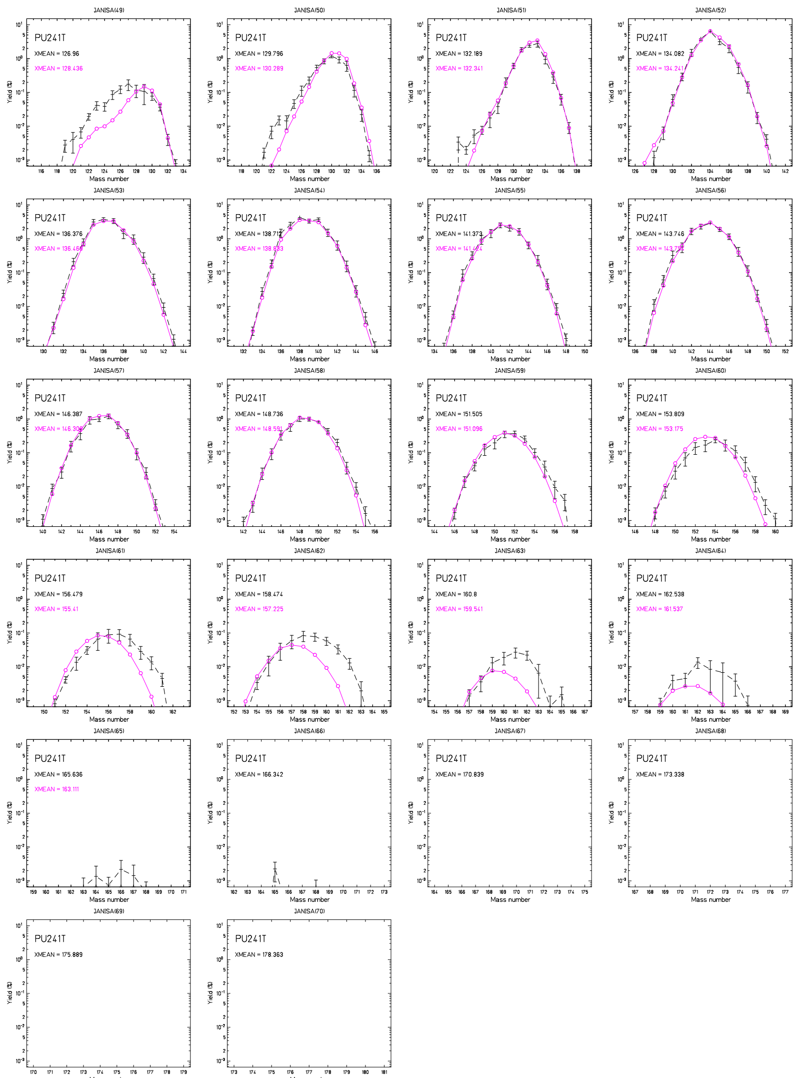

Figure 24: Isotopic distributions of the system ^{241}Pu(n$_{th}$,f), comparison of JEFF 3.3 and GEF, logarithmic scale, small range.

Observations

Four systems were selected for a detailed comparison of the independent yields from the JEFF 3.3 evaluation and the GEF results. These systems are contributing most strongly to the anti-neutrino production in presently operated fission reactors.

^{235}U(n$_{th}$,f)

^{235}U(n$_{th}$,f) is the most intensively studied system. Thus, the evaluated independent yields are expected to be the most reliable. Figures 1 to 6 show almost perfect agreement between JEFF 3.3 and GEF for the elements with peak yields above 1 %. There are some issues in the most asymmetric wings, where the super-asymmetric (S3) mode contributes. Severe discrepancies appear for $Z < 32$ and $Z > 60$. In both cases, the yields are overestimated; in the second case, the isotopic distributions are shifted towards lighter isotopes in addition. The distributions near symmetry are rather well reproduced. However, the shape of the distribution of the $Z = 48$ isotopic yields is not correct: the height of the right peak is strongly underestimated. It is known that the symmetric mode is characterized by a small charge polarization and a low TKE, corresponding to a large prompt-neutron multiplicity, while the asymmetric modes (S1 and S2) in this Z range are characterized by a large charge polarization, favouring the production of neutron-rich isotopes at scission, and a high TKE, corresponding to a small prompt-neutron multiplicity. With this information, one can attribute the left peak in the isotopic distribution of $Z = 48$ to the symmetric mode and the right peak to the asymmetric component, consisting of the S1 and S2 fission channels. Thus the contribution of the symmetric mode to the $Z = 48$ yield is correctly calculated by GEF, while the contribution of the asymmetric component is underestimated. In view of the good reproduction of the distributions of $Z = 50$ and higher, which fixes the shape of the heavy part of the asymmetric component, the shape of the distribution of $Z = 48$ indicates the presence of a further-reaching tail of the asymmetric component towards symmetry. This problem is already visible in the distributions from $Z = 45$ to $Z = 47$. However, the almost constant intensity of the right side-peak in these distributions from JEFF 3.3 is very difficult to reconcile with the inherent regularities of the GEF model. The solution of this problem is not obvious. Our previous study [1] on fragment yields from fission at higher excitation energies revealed the very same problem in the isotopic distribution of $Z = 49$ for the electromagnetic-induced fission of ^{238}U.

In summary, the isotopic distributions with peak yields above 0.1 % are fairly or well reproduced, except the problem near symmetry. There is a need for re-considering the S3 fission mode and the competition between symmetric and asymmetric fission modes for $Z = 48$. Attempts for solving these problems were not yet successful, because GEF is not a direct fit to the fission yields. The inherent regularities of the GEF model and the reproduction of other kind of data, for example the mass-dependent prompt-neutron multiplicities, see ref.

[2], impose additional constraints. Finally, one must always be aware that some evaluated yields might be erroneous, in particular in the low-yield regions.

^{238}U(n$_{fast}$,f)

In figures 7 to 12 that show the isotopic distributions of the system ^{238}U(n$_{fast}$,f), one observes about the same features as found for ^{235}U(n$_{th}$,f). There is some additional erratic scattering, which may be attributed to the lower quality of the evaluated data for this system. In addition, there are some indications for a slight systematic shift of the isotopic distributions from GEF towards the neutron-rich side in the light group and to the neutron-deficient side in the heavy group. This might indicate an underestimated charge polarization or an overestimated amount of energy sorting at scission.

^{239}Pu(n$_{th}$,f)

In the isotopic distributions of the system ^{239}Pu(n$_{th}$,f) shown in figures 13 to 18, the distributions with peak yields above 1 % are at least fairly well reproduced, except the problems near symmetry. One observes an increased erratic scattering and larger error bars in the evaluated data than in the uranium cases discussed above. Most of the discrepancies between the evaluation and the GEF results are not systematic. The problems found for the uranium cases in the asymmetric wings does not appear clearly for ^{239}Pu(n$_{th}$,f), except the shift to the neutron-deficient side in the heavy wing. The problem in the transition from the symmetric component to the heavy asymmetric component, here appearing for $Z = 47$ and $Z = 48$ is again clearly visible.

^{241}Pu(n$_{th}$,f)

The isotopic distributions of the system ^{241}Pu(n$_{th}$,f) show strong discrepancies between the evaluation and the GEF results. Most of these discrepancies are related to the serious problems found in the mass yields of this system, see figs. 101 and 102 of the main document. These problems do not allow to make a more detailed discussion of the isotopic distributions.

Summary

The comparison of the isotopic distributions from the JEFF 3.3 evaluation with the results of the GEF code reveals a rather good, often almost perfect, agreement for the yields of the strongly populated elements with yields above 1 %. There are problems in the isotopic distributions in the extreme asymmetric wings of the fission-fragment distribution and in the transition from the symmetric to the heavy peak of the asymmetric component. The first problem may be cured by an improved description of the S3 fission mode, while the second one seems to indicate the presence of a tail in the distribution of the heavy asymmetric component towards symmetry, which is not represented by the adjustment to the higher yields.

The comparison of the fission yields from JEFF 3.3 with the GEF results reveals the exceptionally good quality of the empirical data for the system ^{235}U(n$_{th}$,f) by the small amount of erratic fluctuations in the discrepancies, compared to the other systems.

As a critical conclusion, it is clear that the GEF model has some deficiencies in certain regions of low yields of the fission-fragment distributions. But there is also an encouraging message: Many discrepancies between evaluated data and GEF results found for the different systems are consistent and hint to the same underlying problems. As a practical consequence, the comparisons shown in the preceding sections allow to apply some empirical corrections to the independent yields from GEF, resulting in a revised evaluation with essentially improved quality.

References

[1] Ch. Schmitt, K.-H. Schmidt, B. Jurado, Phys. Rev. C 98 (2018) 044605.

[2] J. Terrell, Phys. Rev. 127 (1962) 880.