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# Energy Dependence of Prompt Fission Neutron Multiplicity in the $^{239}\text{Pu}(n, f)$ Reaction

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## Abstract

Accurate multiplicities of prompt fission neutrons emitted in neutron-induced fission on a large energy range are essential for fundamental and applied nuclear physics. Measuring them to high precision for radioactive fissioning nuclides remains, however, an experimental challenge. In this work, the average prompt-neutron multiplicity emitted in the  $^{239}\text{Pu}(n, f)$  reaction was extracted as a function of the incident-neutron energy, over the range 1-700 MeV, with a novel technique, which allowed to minimize and correct for the main sources of bias and thus achieve unprecedented precision.

At low energies, our data validate for the first time the ENDF/B-VIII.0 nuclear data evaluation with an independent measurement and reduce the evaluated uncertainty by up to 60%. This work opens up the possibility of precisely measuring prompt fission neutron multiplicities on highly radioactive nuclei relevant for an essential component of energy production world-wide.

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Despite the discovery of nuclear fission being 80 years old, a full understanding of this rich quantum phenomenon is still a challenge for experimentalists and theoreticians. Parallel efforts [1–3], pursued worldwide, carry the promise of a renewed

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understanding of this complex phenomenon, and support the development of modern  
5 nuclear technologies for energy production effectively complying with the most re-  
cent requirements on safety, sustainability, economic competitiveness and proliferation  
resistance. From an experimental point of view, the most stringent constraints to the-  
oretical models are expected to come from very precise measurements of observables  
over large energy ranges, as well as from the simultaneous measurement of several ob-  
10 servables highlighting their possible correlations. Among them, the number of prompt  
fission neutrons and their kinetic energy distributions provide valuable information on  
the amount of excitation energy of the heated fissioning system transferred to the pri-  
mary fragments. Moreover, these data, for the fissile  $^{235}\text{U}$  and  $^{239}\text{Pu}$  isotopes and the  
fertile  $^{238}\text{U}$  nuclide, are vital inputs to calculate next-generation nuclear reactor neu-  
15 tronics, which affect projections of the criticality, efficiency, safety, and lifetime of such  
systems. From a theoretical point of view, a model able to describe the fission process  
with the requested accuracy is still lacking, therefore nuclear data applications rely, to  
a large extent, on evaluated data, such as ENDF/B-VIII.0 and JEFF3.3 [2, 3].

Several experimental and evaluation works have been dedicated since the '60-'70s  
20 to produce coherent and precise data and evaluations for the average prompt fission  
neutron multiplicity ( $\bar{\nu}_p$ ) emitted in the neutron-induced fission of  $^{239}\text{Pu}$  in the MeV  
range [4–25]. The importance of these data lies in the fact that the sustainability of the  
nuclear fission chain reaction in a reactor core, the so-called criticality  $k_{\text{eff}}$ , depends  
nearly linearly on the  $\bar{\nu}_p$  of the fissioning nuclide [26] and often has the highest sen-  
25 sitivity to the  $\bar{\nu}_p$  of the main fuel [27]. The precise measurement of  $\bar{\nu}_p$  for a highly  
radioactive nuclide, as  $^{239}\text{Pu}$ , is, however, an experimental challenge as it requires an  
unambiguous identification of fission events from a very intense  $\alpha$ -decay background.  
Moreover, neutrons need to be detected with good efficiency and discriminated from  
 $\gamma$  rays emitted in fission. The current widely accepted reference measurement of J.  
30 Fréhaut et al. [18], carried out in the 1970's, provides the data reported to be most  
precise in the incident-neutron energy region between 1 and 30 MeV, with reported  
uncertainties as low as 0.5% below 15 MeV. Other experimental data [4–25], although  
with larger uncertainties, are all in good agreement with this measurement. The large  
majority and the most precise of these measurements [10, 15–22, 24] were realized

35 detecting neutrons in coincidence with fission events with a close-to- $4\pi$  scintillator detector tank. Other measurements exploited either proportional counters inside paraffin blocks [5, 7–9, 11–14, 23] or the surrogate-reaction technique [25].

Resulting libraries are then validated with respect to integral experiments such as, e.g.,  $k_{\text{eff}}$  experiments [28] that model the behavior of reactor cores on a small scale. 40 This validation step tests the reliability of entire libraries for applications. ENDF/B-VIII.0  $^{239}\text{Pu}(n,f)\bar{\nu}_p$  were obtained from existing experimental data, but the evaluated data had to be adjusted [2] such that simulated and experimental  $k_{\text{eff}}$  were in reasonable agreement for application calculations. To illustrate this point, in Fig.1 we show the relative difference between existing experimental and ENDF/B-VIII.0  $\bar{\nu}_p$  values in 45 the fast neutron energy region, with the data normalized to the current ENDF/B-VIII.0 value of  $^{252}\text{Cf}\bar{\nu}_p$  [29] and not including its uncertainty. For a more readable figure, the uncertainty on the ENDF/B-VIII.0 values was not propagated in the relative difference and is shown as shaded region around the zero value. Discrepancies as high as 2% below 8 MeV are observed, with data systematically lower than the most re- 50 cent ENDF/B-VIII.0 evaluation. A different trend and differences up to 1% are also observed for the JEFF3.3 evaluation. As a comparison, it should be kept in mind that a change in  $\bar{\nu}_p$  by 0.1% in an energy range as small as 100 keV can modify the computed criticality by about 100 pcm, which is about one third of the range between a controlled and an uncontrolled Pu critical assembly [30, 31].

55 In this letter we report on high precision experimental data, obtained with a different and novel technique. They validate, below 5 MeV, the ENDF/B-VIII.0 evaluation with an independent measurement, highlight potential shortcomings in existing data, and reduce the evaluated uncertainty of up to 60% while extending the range of the studied energies from 30 to 700 MeV. The method, used here for  $^{239}\text{Pu}(n,f)\bar{\nu}_p$  measurement 60 for the first time, consists of detecting neutrons with an ensemble of 17.78 cm-diameter liquid scintillator detectors, located on a half-sphere at about 1 meter distance from a fission detector assuring a good energy resolution for the emitted neutrons. Prompt fission neutron spectra (PFNS) are then measured, as a function of the incident-neutron energy, with a double time-of-flight technique [32]. Values of  $\bar{\nu}_p$  are finally extracted 65 from the integration of PFNS. As opposed to tank experiments [10, 15–22, 24], these

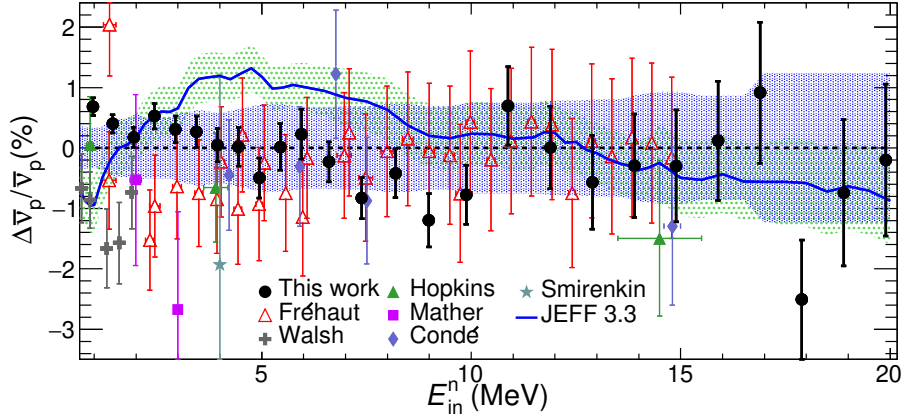


Figure 1: (Color online) Relative difference between experimental and ENDF/B-VIII.0  $\bar{\nu}_p$  values from this work and some previous experiments [10, 13, 15–18]. The difference with the JEFF3.3 evaluation [3] is also shown.

kinds of measurements suffer from statistics limitations, due to the limited detector angular coverage, and from the presence of a background due to neutron scattering on surrounding materials. However, they present two main advantages. First, while scintillator tanks are, at most, roughly segmented, the high segmentation of the neutron detector array allows to measure the neutron angular distribution, and therefore to precisely correct for the contribution of regions not covered by the detector. Second, PFNS are precisely measured and an energy-dependent efficiency curve, typically determined with respect to a  $^{252}\text{Cf}$  source, can be used. This is not the case in tank experiments, where only the difference in the mean energy of the  $^{252}\text{Cf}$  and  $^{239}\text{Pu}$  PFNS could be accounted for, based on an empirical parametrization [33], insufficient by today's standards. These two effects lead to systematic biases in the existing  $\bar{\nu}_p$  measurements not properly corrected for, thus enlarging further the level of uncertainty on  $\bar{\nu}_p$ . On the contrary, in our experiment the availability of a high-intensity, pulsed and well-collimated white neutron source, and the described novel technique allowed for the first time to effectively minimize and estimate the sources of possible bias while collecting high counting statistics and providing an independent measurement.

The experiment was performed at the Weapons Nuclear Research facility [34, 35] of Los Alamos Neutron Science Center at the Los Alamos National Laboratory. The

neutron beam was produced by spallation and bombarded a high-purity  $^{239}\text{Pu}$  target  
85 after a flight path of about 21.5 m. A newly-developed, high-efficiency, light-weight,  
fast fission chamber, with an improved discrimination capability between fission and  
 $\alpha$ -decay events [36], was coupled to 54 EJ-309 [37] liquid scintillators from the Chi-  
Nu array [38] to detect neutrons emitted in fission events. The fission chamber housed  
47 mg of  $^{239}\text{Pu}$  arranged in twenty-two deposits and eleven readout channels, with  
90 an  $\alpha$ -activity of about 10 MBq per channel, to be compared to a fission rate of about  
15 events/s. A fission-fragment detection efficiency of 95% was nevertheless achieved  
[36]. Such a feature is crucial to avoid any bias of the data associated with the selection  
of a particular range in angle or kinetic energy of the detected fragments. Neutrons and  
 $\gamma$  rays were detected in coincidence with a fission-chamber signal in the scintillator  
95 cells and identified via the pulse shape discrimination technique down to 200 keV and  
up to about 14 MeV. The neutron detectors covered nine angles, from  $30^\circ$  to  $150^\circ$ .  
The use of digital Fast Acquisition SysTEM for nuclEAR Research [39] allowed the near  
complete avoidance of numerical dead time. A detailed description of the experimental  
setup can be found in [36, 38, 40, 41].

100 The combined setup and the high recorded statistics lead to a precise reconstruction  
of the PFNS as a function of the incident-neutron energy  $E_{in}^n$ , from 0.7 to 700 MeV.  
We stress that the data presented here were collected in the same experiment and un-  
der the same experimental conditions as the PFNS data discussed in [40]. The ex-  
periment allowed us to access both the PFNS and  $\bar{\nu}_p$  observables, the latter with an  
105 expanded analysis, as relevant systematic uncertainties are different. The first step to  
extract  $\bar{\nu}_p$  values is therefore common to the two analysis, and is described in Ref.  
[40], where the PFNS experimental data and the associated uncertainties are reported.  
Here we only recall that neutron detector efficiencies were obtained by measuring the  
PFNS of the  $^{252}\text{Cf}$  spontaneous fission reaction in the same experimental conditions  
110 and with the same analysis procedure as the  $^{239}\text{Pu}$ . For each detector, the measured  
 $^{252}\text{Cf}(sf)$  PFNS was divided by the evaluated PFNS standard [42], normalized to the  
evaluated ENDF/B-VIII.0  $\bar{\nu}_p$  for  $^{252}\text{Cf}$  of  $(3.759 \pm 0.42\%)$  [2], and used to evaluate the  
efficiency of every EJ-309 detector. The bias associated with this procedure was care-  
fully evaluated via GEANT4 simulations [43] and found to be negligible. The prompt

115 fission neutron spectrum for each of the eighty-six  $E_{in}^n$  bins studied was obtained by combining all the detector spectra corrected for their efficiency. As each of them was corrected by its neutron detector efficiency, the integral of the PFNS is the average number of prompt neutrons emitted per fission ( $\bar{\nu}_p$ ). The so-extracted values are, however, affected by systematic biases which have to be accounted for with a more complex  
 120 analysis to obtain high-precision data. In the following, results are presented with the absolute statistical and systematic uncertainties, propagated through the data analysis. The latter includes the uncertainty on the evaluated  $^{252}\text{Cf}$  PFNS, while the uncertainty of 0.42% on the  $^{252}\text{Cf}\bar{\nu}_p$  is not included. This will allow to easier account for more precise future measurements of  $^{252}\text{Cf}\bar{\nu}_p$ . Tabulated data are provided as supplemental  
 125 material to the present work.

The main breakthrough with respect to previous measurements is the possibility of effectively estimating the sources of possible systematic bias. Data were corrected for four different experimental biases: the neutron detection energy range, the presence of a slower incident neutron background (wrap-around) [44], the limited detector angular  
 130 coverage and the detector dead time. The correction on the  $\bar{\nu}_p$  values related to each of these physical effects ( $\epsilon_{\bar{\nu}_p}$ ), as well as the uncertainty introduced on the final  $\bar{\nu}_p$  value by each correction ( $\sigma_{\bar{\nu}_p}$ ), are plotted in Figs. 2a and b, respectively, as a function of  $E_{in}^n$ .

First, the detection limits of 0.2 and 14 MeV for the fission neutrons were consid-  
 135 ered. The lower limit was set by the threshold for discriminating neutrons from  $\gamma$ -rays, while the high-energy one was related to the dynamic range of the electronics. For corrections needed by these detection limits, the two regions were handled separately. The contribution to  $\bar{\nu}_p$  of neutrons below the 200 keV detection limit was estimated assuming a simple theoretical description of the low-energy region of the PFNS based on  
 140 a Maxwellian spectrum [45, 46] and found to be as high as 1%, as shown in Fig. 2a (red dots). The measured spectra were therefore extrapolated at energies from 200 keV downwards and  $\bar{\nu}_p$  corrected for it. The bias introduced by the arbitrary choice of the fitting range on the extracted  $\bar{\nu}_p$  found to be smaller than 0.2% (cyan stars in Fig. 2a). The uncertainty introduced on the  $\bar{\nu}_p$  values by this procedure is negligible with respect  
 145 to the statistical and systematic uncertainty of the uncorrected value (compare red dots

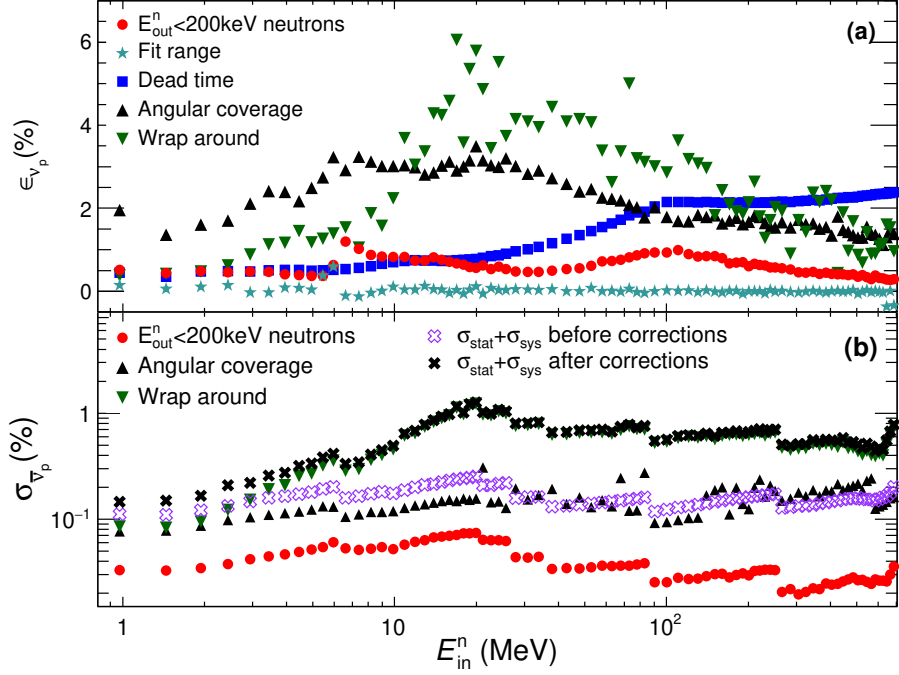


Figure 2: (Color online) (a) Bias of  $\bar{v}_p$  due to different experimental effects. (b) Uncertainty on  $\bar{v}_p$  ( $\sigma_{\bar{v}_p}$ ) introduced by the correction of the experimental bias and the sum of the  $\sigma_{\bar{v}_p}$  before and after the corrections. The “fit range” and the “dead time” corrections  $\sigma_{\bar{v}_p}$  are negligible (see text).

and open crosses in Fig. 2b). For the high-energy limit, we can reasonably expect neutrons above 14 MeV to be emitted during a pre-equilibrium, pre-fission process for incident energies above about 24 MeV. A TALYS calculation [47] estimates their contribution to be about 0.9% of  $\bar{v}_p$  at this  $E_{in}^n$ . It should be noted that this process can contribute significantly to  $\bar{v}_p$ , but it cannot be estimated quantitatively as available pre-equilibrium emission models have been validated on limited experimental data [48]. Therefore,  $\bar{v}_p$  values for  $E_{in}^n$  above 24 MeV should be considered as a lower limit.

Second, the obtained values of  $\bar{v}_p$  were corrected for neutrons emitted in fissions induced by slower-than-measured neutrons, the wrap-around background [44]. The fraction of wrap-around background,  $k_{WA}$ , in each  $E_{in}^n$  bin could be analytically determined from the time-of-flight spectra of incident neutrons as described in [40]. The procedure was here validated by the observation of dips in the evolution of  $k_{WA}$  with



$E_{in}^n$  at energies corresponding to absorption resonances in  $^{16}\text{O}$ ,  $^{14}\text{N}$  (i.e. air) and  $^{11}\text{B}$  (boron material present in the beam hardener). The  $k_{WA}$  fraction varies from about  
 160 10% to about 3% below 20 MeV and above 200 MeV, respectively, of the impinging  
 neutron flux and modifies the  $\bar{v}_p$  value up to 6%, pointing out its importance (green  
 triangles in Fig. 2a). The relative uncertainty introduced on the  $\bar{v}_p$  values by the cor-  
 rection of this effect, which reaches up to 1%, arises from the statistics available for the  
 estimation of  $k_{WA}$  (green triangles in Fig. 2b).

165 Third, the limited detector angular coverage was considered. The high segmenta-  
 tion of the Chi-Nu array allowed for the reconstruction of the  $\bar{v}_p$  angular distribution  
 and the correction for those angles that were not covered by detectors. Nine spectra,  
 one for each measured  $\theta_{lab}$ , were obtained by combining the spectra from the six de-  
 tectors at the considered angle and  $\bar{v}_p(\theta, E_{in})$  extracted. Their uncertainty is close to  
 170 0.3%. The angular distributions,  $\bar{v}_p(\theta, E_{in})$  vs  $\cos(\theta)$ , exhibit two main characteris-  
 tics: first, they are not isotropic, even at low incident energies, with a  $\bar{v}_p(0^\circ)/\bar{v}_p(90^\circ)$   
 of about 1.05 below 10 MeV, and a trend similar to the one observed in the data for  
 fission-fragment anisotropy [49–51]. Second, they are characterized by a certain de-  
 gree of forward/backward asymmetry which increases with  $E_{in}^n$ , reflecting the increase  
 175 in the kinematical boost and the pre-equilibrium emission. Angular distributions were  
 fitted with up to 4<sup>th</sup>-order polynomial functions and  $\bar{v}_p(E_{in})$  was taken as the sum of  
 the experimental values and the values deduced from the fitted distributions, for those  
 angles that were not covered by detectors during the experiment. The systematic un-  
 certainty on  $\bar{v}_p$  due to the arbitrary choice of the functions was found to be negligible  
 180 with respect to its final uncertainty. Accounting for the neutron angular distribution  
 modifies up to 4% the  $\bar{v}_p$  values and it mainly arises from the contribution of the most  
 forward/backward angles (black triangles in Fig. 2a). This implies that the assump-  
 tion of a flat angular distribution or a non-accurate knowledge of it likely leads, even  
 at low energies, to an underestimation of  $\bar{v}_p$ . Interestingly, existing literature data are  
 185 generally lower than the present results, and this could be a source of discrepancy (see  
 Figs.1 and 3). The uncertainty on the  $\bar{v}_p$  values introduced by the described correction  
 is shown as black triangles in Fig.2b.

Finally, the impact of the neutron detector dead time was investigated. Once a

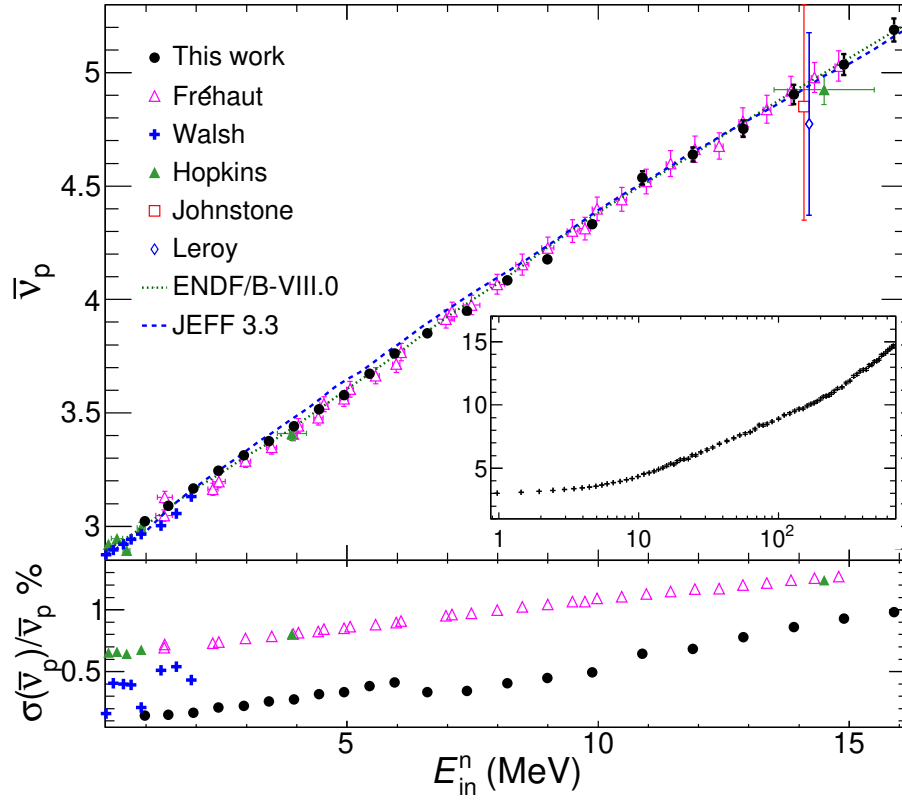


Figure 3: (Color online) Measured  $\bar{\nu}_p$  and its uncertainty as a function of incident neutron energy up to 16 MeV. Some data from previous experiments are also shown [11, 13–15, 18]. The  $^{252}\text{Cf}$   $\bar{\nu}_p$  uncertainty was removed from existing data. Dotted and dashed lines are ENDF/B-VIII.0 and JEFF3.3 evaluations, respectively. The insert shows the measured  $\bar{\nu}_p$  over the whole studied  $E_{in}^n$  energy range.

particle (neutron or  $\gamma$  ray) fires a scintillator detector of the Chi-Nu array, a charge-  
 190 integration window of 200 ns is opened, during which any other impinging particle is  
 not recorded separately, but its charge signal adds to that of the first one. Therefore  
 particles impinging with a time difference smaller than 200 ns in the same detector can  
 be mis-identified and neutrons can be “lost” or “gained”. The net amount of “lost” neu-  
 trons was estimated with a full Monte Carlo simulation based on experimental distribu-  
 195 tions. Measured neutron and  $\gamma$ -ray multiplicities, as well as time-of-flight distributions  
 for each  $E_{in}^n$  bin were sampled and used as input. A similar procedure was undertaken

for the fast-to-total signal charge ratio vs total signal charge correlation of each detector. The same simulation, with the appropriate inputs, was run for the  $^{252}\text{Cf}(sf)$  data, as part of the detector dead time distortion is accounted for when correcting the PFNS  
 200 for the detector efficiency. The net correction varies from  $\sim 0.5\%$  to above  $2\%$  for energies below 10 MeV and above 100 MeV, respectively (squares in Fig. 2a), due to the increase of  $\gamma$  and neutron multiplicities as the incident-neutron energy increases. The number of simulated events is high enough so that the statistical uncertainty introduced by this correction is negligible.

205 The data corrected as described above are shown as a function of  $E_{in}^n$  in Figs. 1 and 3. Our data exhibit the expected constant increase up to 700 MeV with no obvious structure. As mentioned,  $\bar{\nu}_p$  values for energies above about 24 MeV, where the contribution of high-energy ( $> 14\text{MeV}$ ) pre-equilibrium neutrons becomes non negligible, should be considered as a lower limit. Below about 14 MeV,  $\bar{\nu}_p$  exhibits a linear  
 210 dependence with the neutron energy. A linear extrapolation below 3 MeV provides an estimated value of  $\bar{\nu}_p$  at thermal neutron energies of  $(2.879 \pm 0.010)$  neutrons/fission, in agreement with the evaluated value of  $(2.868 \pm 0.012)$  [2] and with comparable uncertainty.

The obtained  $\bar{\nu}_p$  total uncertainties (excluding the  $0.42\%$  uncertainty associated to  
 215 the reference data  $^{252}\text{Cf}(s.f.) \bar{\nu}_p$  [2]) span from  $0.15$  to  $1.3\%$ , and are smaller than  $1\%$  below 14 MeV  $E_{in}^n$  (see Figs. 2b and 3). Such low uncertainties on a broad energy range were never reached before, not even with different experimental techniques ([15–24] and [5, 9, 13]) as shown in the bottom panel of Fig. 3. The relative difference between our data and ENDF/B-VIII.0 values is shown in Fig. 1. At low  $E_{in}^n$  our data show a  
 220 different trend than the reference experimental data of J. Fréhaut et al. [18], but the difference between our data and the recent ENDF/B-VIII.0 evaluation [2], averaged over the points measured below 5 MeV, is of  $0.3\%$ . A significant discrepancy is observed at the opening of the second-chance fission. The observed overall agreement with the ENDF/B-VIII.0 evaluation shows that the data presented here agree with the general  
 225 trend of the bulk of the data considered to be reliable enough for the evaluation.

Complex phenomenological fission models [52–54] are nowadays available, which allow for a reasonable and cross-dependent description of many fission observables.

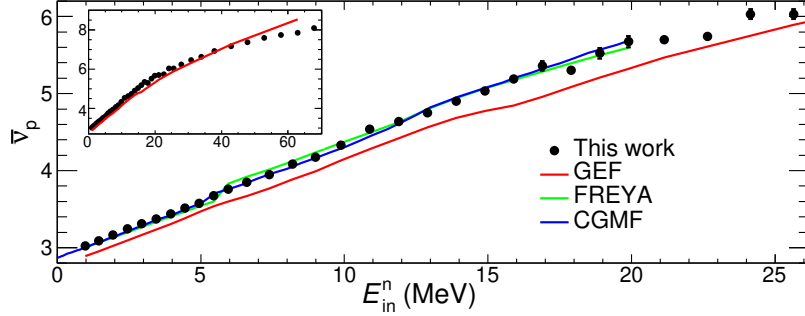


Figure 4: (Color online) Comparison of our data to GEF [55], FREYA [53] and CGMF [52] predictions.

Accurate values of  $\bar{\nu}_p$  are essential constraints to these models. Notably, the sharing of energy between kinetic and excitation energy together with the energy sharing between the two fragments are crucial components of the models sensitive to  $\bar{\nu}_p$ . However, it should be noted that  $\bar{\nu}_p$  alone cannot constrain the models. Our data are compared to the semi-empirical model GEF [55] in Fig.4. We observe that GEF predictions reproduce our  $\bar{\nu}_p$  values within 0.15 (4.5%) and 0.4 (8%) neutrons per fission below 8 MeV and over the full energy range [1 – 25] MeV, respectively. The observed difference of 0.15 (0.4) neutrons per fission corresponds, in the GEF model, to a “wrong” sharing between fission-fragment excitation and kinetic energies of about 1 (2.8) MeV, to be compared to about 200 MeV released in fission. Although these model results are too far from experimental data to be used in evaluations, it should be noted that GEF is not tuned to these experimental data. Our data are also compared to the fission-event generators FREYA [53] and CGMF [52], up to 20 MeV, which is the limit of the models [52, 56]. FREYA and CGMF values systematically underestimate our data below 5 MeV, with differences up to 1.5% and 1%, respectively. While this deviation is smaller than for GEF values, it should be noted that for FREYA and CGMF results the fission-fragment total kinetic energy is adjusted to reproduce available  $\bar{\nu}_p$  data. The obtained values are therefore not  $\bar{\nu}_p$  predictions. Moreover, structures commensurate with second- and third-chance fission can be seen in all model values and our experimental data; however, model and experimental values do not fully agree on the  $E_{in}^n$  where multiple-chance fission structures are observed. This is the case because these struc-

tures could not be observed in many other experimental data before given that a high  
 250 precision is needed to resolve them. Hence, the data presented here can inform com-  
 plex fission models on the absolute value and shape of  $\bar{\nu}_p$  more conclusively. Indeed,  
 our data were used as an input to an evaluation with the CGMF model [52]. In this  
 case, they could be fitted well within the small experimental uncertainties. However, it  
 should be noted that parameters underlying these models need to be constrained and/or  
 255 validated with respect to precise experimental data to be able to provide precise enough  
 nuclear data to meet the requirements demanded by nuclear energy applications. As  
 mentioned before, above 25 MeV the contribution of neutrons with energies above  
 14 MeV becomes significant, making of the measured  $\bar{\nu}_p$  values a lower limit. For  
 $E_{in}^n$  greater than 60 MeV, the GEF pre-equilibrium neutron spectra become unphysical.  
 260 To assess the impact of our data compared to existing data sets, we performed two  
 new evaluations of  $^{239}\text{Pu} \bar{\nu}_p$ , with ( $E_V^{w/this\ work}$ ) and without the data presented here  
 ( $E_V^{w/o\ this\ work}$ ), using the same methodology. The uncertainties of the all data [8, 9, 13,  
 15–22, 24] were carefully reviewed and increased according to [57] in cases where  
 uncertainties were missing. Our data reduce the ENDF/B-VIII.0 and  $E_V^{w/o\ this\ work}$   
 265  $\bar{\nu}_p$  evaluated relative uncertainty,  $\sigma_{\bar{\nu}_p}^{ev}$ , by up to 50% and 60%, respectively, in the 1  
 to 15 MeV range (see dashed lines in Fig.5). This is of high importance for nuclear  
 applications as it reduces the uncertainties and increases the predictive power of neu-  
 tronics calculations. In addition to the high-impact due to low uncertainties, our data  
 offer two additional benefits. Below 5 MeV the  $\bar{\nu}_p$  evaluated mean value,  $\bar{\nu}_p^{ev}$ , is only  
 270 slightly modified ( $< 0.15\%$ ) by our data (Fig. 5 green full line), which therefore val-  
 idate an evaluation obtained by an average over previous data measured all by the  
 same-but different than here technique. That is of high importance, given that this vali-  
 dation was missing so far. Furthermore, above 5 MeV, where no integral data exist and  
 experimental data are scarce, our results modify ENDF/B-VIII.0 and  $E_V^{w/o\ this\ work} \bar{\nu}_p^{ev}$   
 275 by up to 0.7% and 0.9%, respectively. This is consistent with an increasing importance  
 of physics effects leading to biases as  $E_{in}^n$  increases, which were carefully accounted  
 for in this work. Our data provide therefore a more solid ground for future evaluations.

In conclusion, previously unattained precise and accurate new data on  $^{239}\text{Pu} \bar{\nu}_p$  are  
 reported, which extend the studied range from 1 up to 700 MeV. The data were obtained

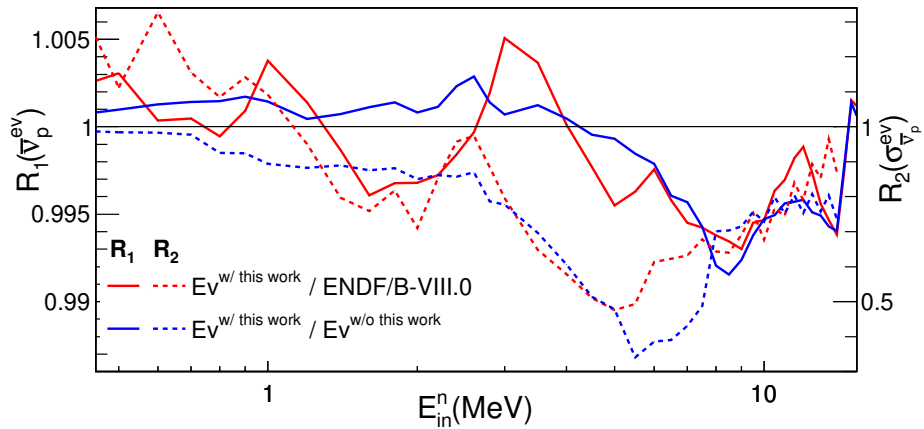


Figure 5: (Color online) Ratio of  $\bar{\nu}_p$  evaluated mean value ( $R_1$ , full lines, left axis) and relative uncertainty ( $R_2$ , dashed lines, right axis) for different evaluations (see text).

280 with the double time-of-flight technique and an innovative setup. It allowed to explicitly account for experimental systematic bias, which have hampered the precision and accuracy of existing experimental results, thus providing more reliable-than-existing data. Below 5 MeV a good agreement with the recent ENDF/B-VIII.0 evaluation is observed validating it, for the very first time, with an independent measurement. A  
 285 new evaluation performed here with these data shows that they significantly reduce the uncertainty on evaluated nuclear-data libraries for a nuclide, the  $^{239}\text{Pu}$ , crucial for nuclear energy applications.

With this measurement the experimental challenge of precisely measuring prompt fission-neutron multiplicity on highly radioactive nuclei has been taken up thanks to the  
 290 innovative setup and experimental technique. New high-precision  $^{239}\text{Pu}$   $\bar{\nu}_p$  measurements could be realized at incident-neutron energies from 200 keV to 2 MeV, where existing data are highly spread, and even down to 1 keV where no data exist. Moreover these results open up the possibility of precisely investigating other high-activity actinide nuclei to contribute to a better understanding of the fission process while providing key  
 295 elements for the development of new technologies relevant for society.

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