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ON THE CONTRADICTION BETWEEN MICROSCOPIC AND MACROSCOPIC DATA FOR ^{235}U FISSION NEUTRON SPECTRUM AT THERMAL ENERGY

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Abstract

It was shown that already existing microscopic experimental data for spectrum of the ^{235}U prompt fission neutron at thermal point allow us to estimate the spectrum shape with high accuracy. The average neutron energy calculated on the basis of experimental data 1.977±0.008 contradicts to values from ENDF/B-VI and ABBN-93 libraries. It was emphasized that the "old" contradiction between microscopic and macroscopic experimental data is not solved till now.

Introduction

The ^{235}U is a most important nucleus for practical applications. So this explain a particular interest to measurement and evaluation of the ^{235}U neutron data. The prompt fission neutron spectrum (PFNS) for ^{235}U at thermal point have been investigated in many works, but some problems still exist. The PFNS may be investigated in a several kind of the experiments. The direct information is extracted from microscopic experiment in which the spectrum shape is measured at fixed neutron incident energy. The detector efficiency is the only function which required for spectrum shape estimation from these experiments. The average cross section measured in integral experiment also may be used for PFNS evaluation. However, in this case one should know not only the reaction cross section but the real shape of the spectrum exposed the investigated sample. In benchmark experiments the reaction rates are measuring in various type of the reactors and critical assemblies. The difference between experimental and calculated results (if it exists) may be applied for PFNS correction. However, the final result will depend very much on the neutron data accuracy and the accuracy of the codes and model that were used for these calculations.

All recent ^{235}U PFNS evaluations ([1-3]) were based on the experimental data however, they give very different spectrum shape (>15%) and different average energy of the fission neutrons 1.964±0.019MeV [1], 2.027MeV [2], 2.033MeV[3]. In paper [1], we used only microscopic data for PFNS evaluation. The authors of [2] took into account all set of data: microscopic, integral and benchmark data to find the parameters of the Watt distribution. As a result, the low energy part of the spectrum was mainly based on the microscopic data but the PFNS shape in the high energy region was constructed to describe the average cross sections and benchmark experiments [4]. It seems that the parameters of the Madland-Nix model [3] were also adjusted to compromise the microscopic and integral data.

The low average energy 1.97±0.02MeV was reported in many experimental works. The authors [2] pointed out this value however, they were obliged to increase to ~3% the average energy to describe the results of integral experiments and benchmark data. They concluded that may exist another sources of the discrepancy, however the large uncertainties for the microscopic PFNS at high energy allowed them to correct neutron spectrum and include such data in ABBN-93[5].

Have we enough the microscopic data to carry out the correct PFNS evaluation for ^{235}U and find the average energy with reasonable accuracy supporting the choice between 1.97MeV and 2.03MeV? It seems that analysis of the experimental data collected in [1] gave the positive answer. But the results of this evaluation and the final conclusion depends on the model simplification in particular for the extrapolation to high energy region (>10MeV) of the spectrum and for the comparison of the spectra measured at different incident energies. However, this analysis shown us that we have enough data at thermal point which cover the energy range from ~0.03MeV to ~14MeV to carry out the non-model evaluation of the spectrum and to estimate the average energy of the fission neutrons with accuracy <0.5%. Mentioned above problems stimulated this investigation and determine the main goal of this paper.

Recent evaluation of the microscopic data and average cross sections.

The following assumptions were used in our systematic of the experimental data and PFNS calculation reported in [1]:

1. The PFN spectra may be described as a sum of two Watt distributions for light and heavy fragments with equal contribution:

$$S(E,E_0) = 0.5\sum_{i=1}^{2} W_i(E,E_0,T_i^x(E_0),\alpha) \qquad (1)$$

where T_i^x are the temperature parameters for nucleus x and light and heavy fragments (i=1,2). E_0 is the incident neutron energy, α is the ratio of the total kinetic energy (TKE) at the moment of the neutron emission to full acceleration value.

2. Temperature parameters for any fissile system were calculated with ^{252}Cf data according to the following formula:

$$T_{l,h}^{x} = T_{l,h}^{Cf}\sqrt{\frac{E_x^* A^{Cf}}{E_{Cf}^* A^x}} \qquad (2)$$

where $E^*=E_r+B_n+E_0$-TKE, E_r - energy release, B_n - binding neutron energy, E_0 - incident neutron energy, A - mass number of fissile nucleus. The ratio of the T_l/T_h=1.248 does not depends on fissile nucleus and incident energy.

3. There is the only free parameter α was fitted to the experimental data [9-11] for incident neutron energy <6 MeV.

The experimental data for ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{237}Np and ^{239}Pu (24 spectra) have been described in the framework of this model inside the experimental errors. The conclusion was made that the average energy for ^{235}U fission neutron at thermal energy is known now with accuracy <1% (<E>=1.964±0.019MeV). Omitting the details of this evaluation we show here only average cross sections for ^{252}Cf and ^{235}U neutron spectra. The ratio of the experimental data to calculated ones are presented in Fig 1,2.

The spectrum shape estimated in [1] for ^{252}Cf does not contradict to the macroscopic experimental data. In the same time for ^{235}U the best agreement was found for ENDF/B-VI evaluation. The ratio of the ^{235}U neutron spectra from ENDF/B-VI and ABBN-93 libraries which agree reasonable well with macroscopic data, to the spectrum calculated in [1] (Fig.3) confirms that very different spectrum shape and average neutron energy are required to describe the microscopic [1] and macroscopic [5] data.

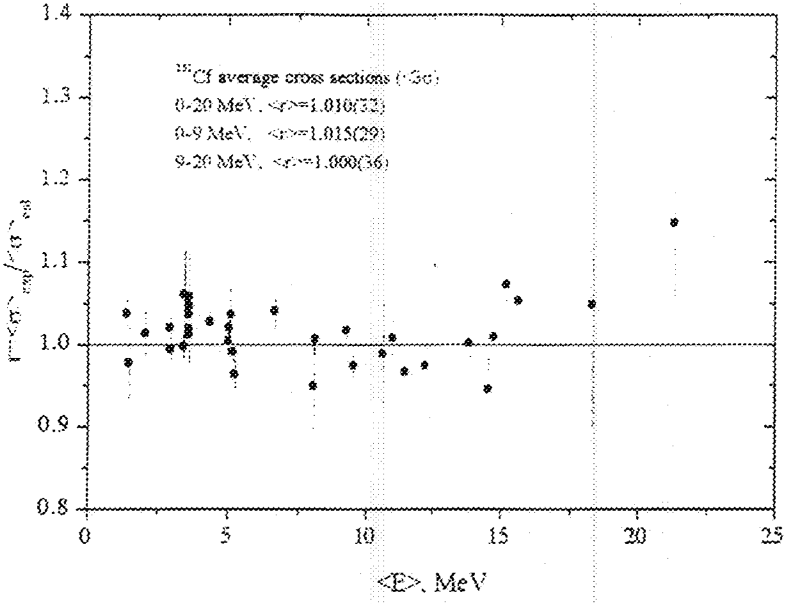

Fig 1. Ratio of the experimental and calculated cross sections averaged over ^{252}Cf spectrum versus average energy of the reaction response. Experimental data were taken from [6- 11]

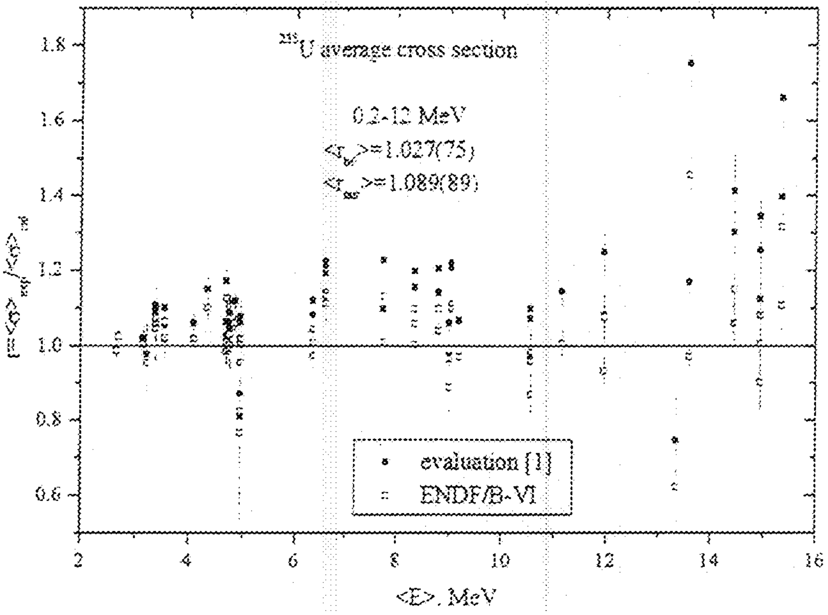

Fig 2. Ratio of the experimental and calculated cross sections averaged over ^{235}U spectrum versus average energy of the reaction response. Experimental data were taken from [12-24].

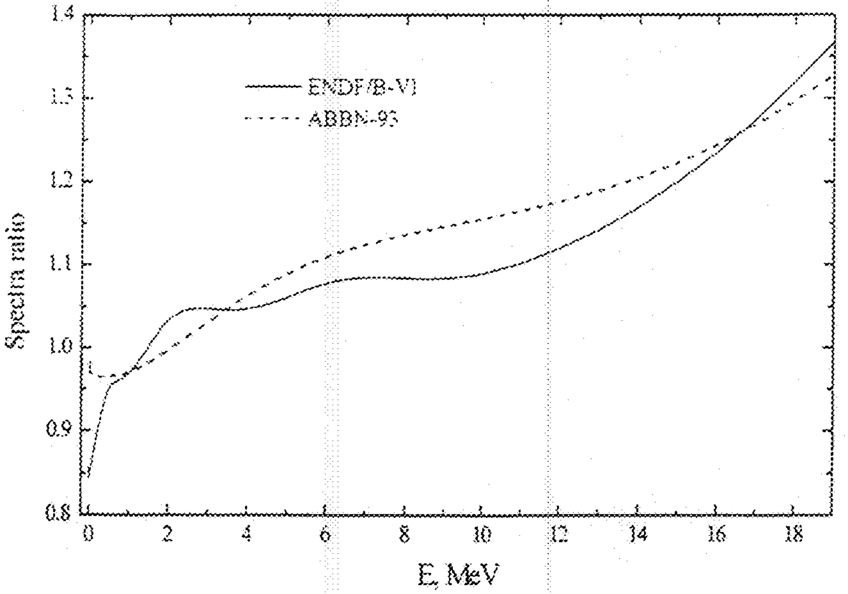

Fig 3. The ratio of the ^{235}U PFNS according to ENDF/B-VI [3] and ABBN-93 [5] to the spectrum from [1].

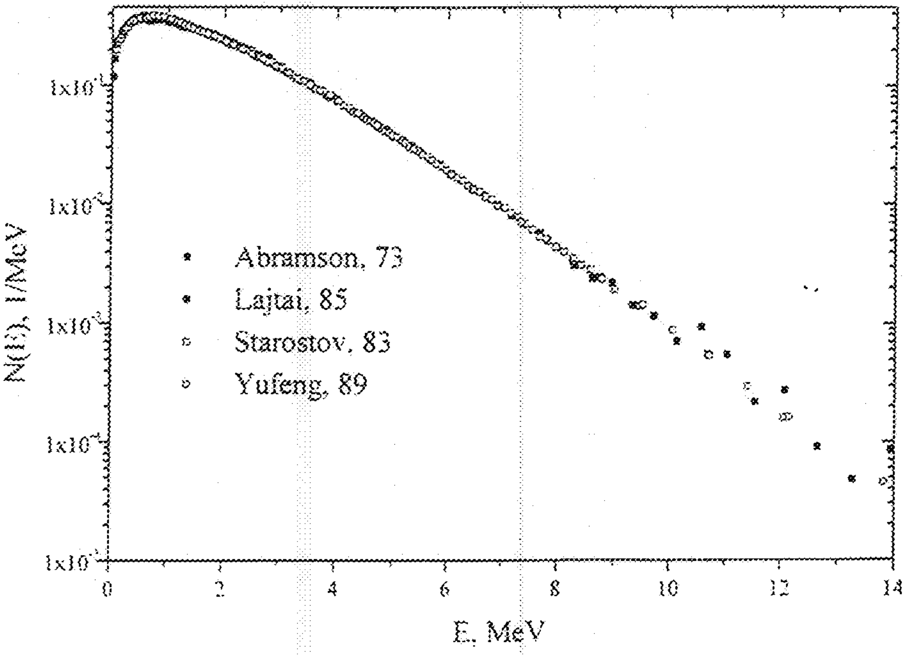

Fig.4 The normalized experimental data from works [25-28].

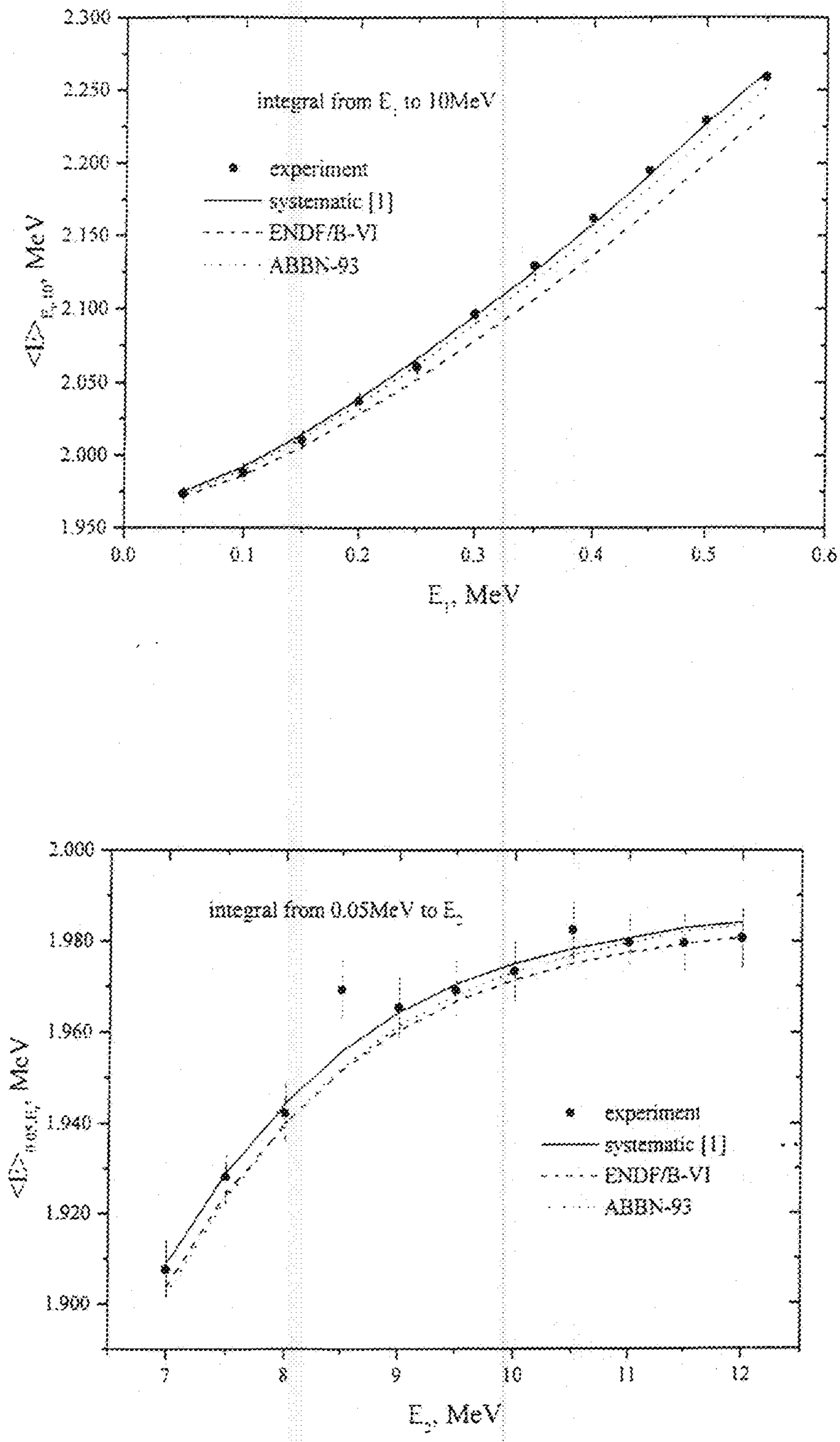

Fig.5. Average neutron energy versus low E_1 and high E_2 limits. Points shows the experimental data. Solid line - calculated values after normalization to <r>. Results for ENDF/B-VI and ABBN-93 were normalized to $\langle E\rangle_{exp}/\langle E\rangle_{cal}$ (Table 1).

Non-model evaluation of the PFN spectrum for ^{235}U.

There exist four experiments investigated the neutron spectra for ^{235}U for incident neutron energy <30keV results of which are available throw EXFOR library [25-28]. The original data have a different normalization therefore these data were re- normalized applying the spectrum shape suggested in [1]. The total data set after the normalization is shown in Fig.4. As one can see, the data of different experiments does not contradict to each other and may be used as a single whole to estimate the average neutron energy and spectrum shape in the energy range from ~30keV to 14MeV. Two percent error was added to the original values of work [28]. All 294 points were suggested as independent ones.

First of all this data were fitted with mentioned above expression (1) (χ^2 =1.1). It was found that α=0.945±0.002 and <E>=1.971±0.002MeV. This value agree very well with <E>=1.97±0.015MeV presented in [29]. The lower value α=0.936 in [1] was estimated if the data for incident energies up to 5MeV were taken into account.

To avoid the uncertainties due to large data spread at low and high limits we used the following procedure for average energy calculation. Average energies and ratios $r_{E1,E2}$ were calculated for various low E_1 and high E_2 limits:

$$r_{E_1,E_2} = \frac{<E>^{exp}_{E_1,E_2}}{<E>^{cal}_{E_1,E_2}}, \qquad <E>_{E_1,E_2} = \frac{\int_{E_1}^{E_2} EN(E)dE}{\int_{E_1}^{E_2} N(E)dE}$$

The *N(E)* denotes the experimental or calculated specra with fitted parameter α=0.945. The average <*r*>=1.0029±0.0019 was used to calculate the experimental average neutron energy $<E>^{exp}_{0,\infty} = <r><E>^{cal}_{0,\infty}$. As one can see in Fig.5 the energy dependencies agree inside the errors with experimental data and only small absolute correction is required.

As a next step the ratio of the experimental data to Maxwellian distribution M(E,T) (T=1.314MeV=(1.971/1.5) MeV) was calculated. The deviation of the experimental points from the Maxwellian was described by power expansion (χ^2=0.87):

$$N(E) = (0.95342 - 0.4909 \cdot 10^{-1} E - 0.92331 \cdot 10^{-2} E^2 - 0.24973 \cdot 10^{-3} E^3)\, M(E,1.314)$$

Table 1. Average neutron energy for ^{235}U.

No.	<E>, MeV	comments
1	2.033	ENDF/B-VI, [3]
2	2.027	ABBN-93, [2]
3	1.964±0.019	α=0.936±0.027, [1]
4	1.977±0.008	experiment
5	1.971±0.002	α=0.945±0.002, this work
6	1.971	power fit

The deviations of the experimental and calculated spectra from Maxwellian distribution are shown in Fig. 6. As one can see the ENDF/B-VI and ABBA-93 are going out of the experimental error. The average energies for the ^{235}U fission neutron spectrum at thermal energy estimated with various approaches are collected in the Table 1. The systematic error of <*r*> calculation (3.6keV) and the error for calculation of $<E>_{E1,E2}$ (6.6keV) give the total error for the experimental average energy.

Conclusion.

1. The shape of the ^{235}U PFNS at thermal point is known with accuracy ~3% (the maximum difference between model and power fit calculations in the energy range 0.03-9 MeV) and the

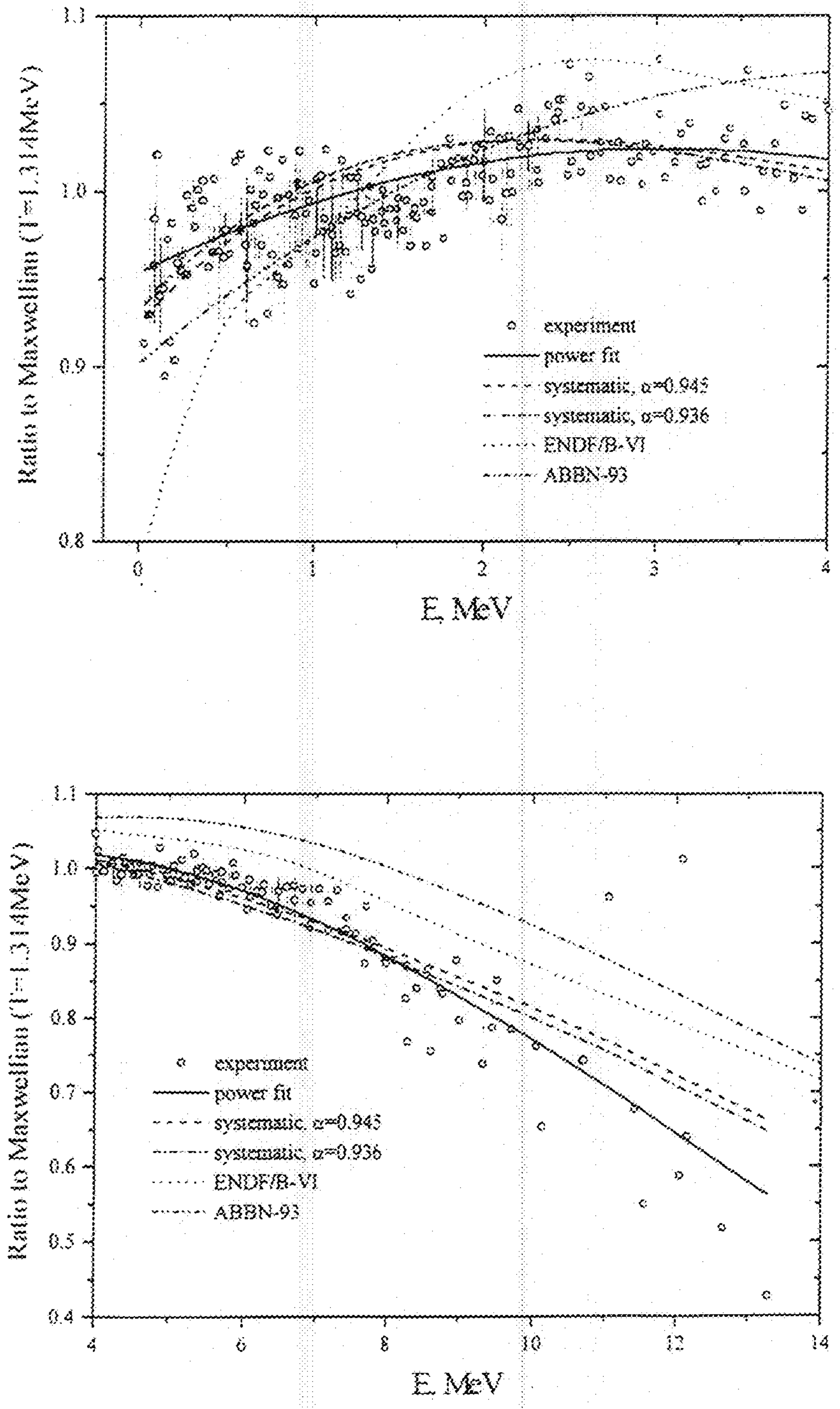

Fig. 6. Ratio of the experimental data (symbols) and calculated spectra to the Maxwellian.

average energy with the accuracy ~0.4%. *This fact does not allow to change arbitrary the spectrum shape beyond of these uncertainties.*

2. There still exist the contradiction between microscopic and macroscopic data. It seems that one can not explain this fact due to uncertaities of the microscopic data. *So, new efforts are required to increase the accuracy of the macroscopic experimental data and to check the benchmark calculation.*

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