INTERNATIONAL ATOMIC ENERGY AGENCY

INDC(CCP)-437

Distr.: IE/EL

I N D C INTERNATIONAL NUCLEAR DATA COMMITTEE

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December 2003

IAEA NUCLEAR DATA SECTION, WAGRAMER STRASSE 5, A-1400 VIENNA

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Produced by the IAEA in Austria
December 2003

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Abstract

The model for calculation of the fission neutron multiplicity at energy range from thermal to ~200 MeV was developed. It was verified on the low energy fission data (0 – 20 MeV) that is known with accuracy 1 – 2 % and was extrapolated for multi-chance fission. The calculated results agree inside the error bars with few experimental data in the neutron energy range 20 – 50 MeV for ^{232}Th(n,f), ^{235}U(n,f), ^{238}U(n,f) and ^{238}U(p,f). However, it contradicts to recent evaluation. The difference at ~150 MV is as much as factor ~2.

December 2003

Introduction

To develop main concepts of the accelerator-driven power systems and the corresponding nuclear waste management, it is necessary to know nuclear data for structural materials, fission actinides, and the most important fission products in a very broad energy range from thermal energy to a few hundreds mega-electron-volts [1]. Total fission cross sections were measured in the energy range up to >100 MeV for more important fissile isotopes. This data set allows develop the proper theoretical model [2] and prepare the evaluated data file. However, till now there is no experimental data for neutron multiplicity at neutron energy >50 MeV. Hence, only theoretical model verified at low energy fission can be applied for ν data evaluation.

In this paper we describe the model developed for the calculation of fission neutron multiplicity at energy range from thermal to ~200 MeV. It uses the energy balance approach that was widely applied before at low energies <20 MeV [3,4]. However, the model was modified very much. First of all a chance structure of fission cross section was incorporate in the model. The chance cross sections were calculated in framework of Hauser-Feshbach statistical theory. In an addition, more accurate approach for calculation of the fragment kinetic energy, and the different fission modes contribution were applied. The model was verified in the energy range from thermal energy (spontaneous fission) to 20 MeV. For ^{232}Th, ^{235,238}U the calculated results agree with experimental data with accuracy 1-2% for absolute values and energy dependence.

Finally, energy dependences of ν_{pre}, ν_{post}, and ν_{tot} for ^{232}Th(n,f), ^{235}U(n,f), ^{238}U(n,f), and ^{238}U(p,f) reactions were calculated in the energy range from 20 MeV to 150 MeV.

2. The model description

2.1 Chance fission

At high excitation energy the fission is a multiple process. One may incorporate so named chance of fission and denote it by "*i*". Each chance corresponds to the particular amount of pre-fission neutrons $k=i-1$. "*i*-chance" fission means that *k* pre-fission neutrons were emitted before fission. The residual ($A+1-k$) nucleus has rather low excitation energy U_k, which should be distributed among all post-fission neutrons emitted after the scission of this nucleus to two separate fragments. Due to very different mechanism of neutron emission one should calculate the neutron multiplicity for pre-fission and post-fission processes separately.

Let denote the total fission cross section at incident energy E_0 as:

$$\sigma(E_0) = \sum_{i=1}^{i_{\max}} \sigma_i(E_0) \qquad 1$$

where $\sigma_i(E_0)$ is cross section for *i*-th chance. In this case the multiplicity of pre-fission neutrons is:

$$\nu_{pre}(E_0) = \sigma(E_0)^{-1} \sum_{i=1}^{i_{\max}} (i-1)\sigma_i(E_0) \qquad 2$$

Total amount of post-fission neutrons can be calculated with similar formula:

$$\nu_{post}(E_0) = \sigma(E_0)^{-1} \sum_{i=1}^{i_{\max}} \nu_i(U_{i-1})\sigma_i(E_0)\,, \qquad 3$$

where $\nu_i(U_{i-1})$ is the partial neutron multiplicity corresponding to fission of nucleus with mass number $(A+2-i)$. The CMS energy is $E^*=E_0{\cdot}A/(A+1)$. Notations are collected in table 1.

Chance cross sections were calculated with a modified version of Hauser-Feshbach statistical model code STAPRE [2]. The statistical model of fission cross section assumes fission/evaporation competition during the decay of excited compound nucleus, which is formed after neutron absorption or emission of first pre-equilibrium neutron.

Fission decay widths were calculated within double-humped fission barrier model. Level density systematic, optical potential descriptions and proper references may be found in report [2]. A particular feature of the applied model is dumping of the collective modes at high excitation energy. It allows reduce the fission probability in compare with neutron emission. In an addition, 10% decreasing of the level density parameter at saddle point a_f was applied. This factor not only reduce the fission cross section at E_0~100 MeV but also change very much the fission chance distribution.

2.2 Neutron multiplicity for post-fission emission. Main relations

The partial neutron multiplicity after the emission of k neutrons can be calculated in frame of the traditional model (see [3,4]) based on the law of energy conservation.

$$\nu_{kj} = (U_k + \Delta M_{j,A+1-k} - TKE_j - E_{\gamma 0j})/(<E_{post,kj}> + <B_{kj}> + E_{\gamma 1j}) \;, \qquad 4$$

where $\Delta M_{j,A_k} = M(A_k, Z) - M(A_{lj}, Z_{lj}) - M(A_{hj}, Z_{hj})$ is the energy release, j denote a particular mode corresponding to fission into light and heavy fragments with masses of A_{lj}, A_{hj}, A_k=(A+1-k)=$A_{lj}+A_{hj}$, and charges $Z=Z_{lj}+Z_{hj}$, TKE_j is the total kinetic energy for fragments pair j, $<E_{post,kj}>$ is the average energy of neutron and $<B_{kj}>$ is average binding energy of neutrons emitted from "pair of fragments" j, $<B_{kj}>=0.5{\cdot}(B_{klj}+B_{khj})$. $E_{\gamma 0j}$ and $E_{\gamma 1j}$ are parameters of equation $E_{\gamma j}= E_{\gamma 0j}+\nu\, E_{\gamma 1j}$ for estimation of the energy taken by gamma-rays. So, in our model we do not distribute excitation energy between fragments and do not estimate the neutron multiplicity from light and heavy fragments separately.

The total multiplicity of the post-fission neutrons can be calculated with equation:

$$\nu_k = \sum_j Y_j \nu_{kj} \qquad 5$$

where Y_j is the fragments mass distribution. The real mass distribution has rather complicate shape. Some example for ^{252}Cf(SF) [5] is shown in Fig.1. As one can see, the measured mass distribution can be described as a sum of fission modes that differ of average mass, width parameters and total kinetic energies. The dependences of fission modes parameters on mass of fissile nucleus and incident energy are unknown. Therefore, some reasonable simplifications are required for ν_{kj} calculations in the whole energy range up to 200 MeV.

1. "Two modes" model was used instead of detail description of the fragment mass distribution: symmetric and asymmetric fission. The following values for masses of heavy fragment were used: $A_h=A_k/2+1$ for symmetric fission and A_h=141 for $A+1<233$, A_h=140, for $233<A+1<244$, $140<A_h<144$ for $244<A+1<252$, $144<A_h<142$ for $252<A+1<256$ [6]. Heavy mass value A_h for

asymmetric fission was fixed for all fissile nuclei after pre-fission neutron emission.

2. In paper [7] it was shown that the share of symmetric fission for the ^{238}U neutron induced fission is increasing versus incident energy (Fig.2). For simplification of the calculation the analytic relation (6) was applied:

$$Y_s = \frac{E_0}{1.43E_0 + 75} \qquad 6$$

At energy <20 MeV we used the following extrapolation for any target, that reproduce experimental data from [8] for ^{238}U:

$$Y_s = 0.193 \cdot \exp(-(20\text{-}E_0)^2 \cdot 0.0125),\ E_0 < 20\text{MeV}.$$

3. We assumed only neutrons in the pre-fission emission (charge conservation). Therefore we know the exact mass of fissile nucleus. Charge of fragments were calculated on the basis of equal "charge density" $\rho_k = Z/A_k = Z_{hk}/A_h$, $Z_{lk} = Z\text{-}Z_{hk}$.
4. Four pairs of fragments were selected for the post-fission multiplicity calculation: (A_l,A_h), (A_l-1,A_h+1), (A_l+1,A_h-1), (A_l+2,A_h-2) with equal yield. This assumption seems reasonable due to "flat" shape of the yield near average masses (see Fig.1). We used even number of fragment pairs to avoid the problem with odd-even effects for odd and even targets. In an addition, for each mass A_{hi} (i=1, 2, 3, 4) were calculated ν_{kij} values for three isobars pairs: $N_{hi}+j, Z_{hi}-j$, $N_{li}-j, Z_{li}+j$ (j=0,±1, $N_{hi}+Z_{hi}=A_{hi}$, $N_{li}+Z_{li}=A_{li}$ $Z_{hi}+Z_{li}=Z$, $A_{hi}+A_{li}=A_k$). The averaging throw charge distribution was made with so named "unchanged charge distribution (UCD)" by Unik et al. [9]:

$$P(j) = \frac{1}{\sqrt{c\pi}} \exp\left(-\frac{j^2}{c}\right),\ \ \mathrm{c} = 2(\sigma^2 + \frac{1}{12}),\ \sigma^2 = 0.40 \pm 0.05 \qquad 7$$

So, the average ν_{post} for selected number of pre-fission neutrons k, was calculated with the following equation:

$$\nu_k = \frac{1}{4P_0} \sum_{i=1..4} \sum_{j=0,\pm1} \nu_{kij} P(J),\ \ P_0 = P(1) + P(0) + P(-1) = 0.982 \qquad 8$$

5. $E_{\gamma 0}=0.92 \cdot \langle B_{kj} \rangle$ [MэB] and $E_{\gamma 1}$=0.99 MэB was used for any incident (excitation) energy, chance and fragment mass. The first parameter is differ from value applied in systematic [4]) where $E_{\gamma 0}$=4.42 MeV was constant.

The average ν_{post} at incident energy E_0 was calculated according to eq.3.

2.3 Average energy of the escaped neutrons

The neutrons for pre-fission and post-fission processes are escaped from nucleus due to cascade emission. Therefore, we used the relation estimated in paper [3] to calculate the average kinetic energy of neutrons for both these processes:

$$\langle E \rangle = \frac{4}{3} T \qquad 9$$

For pre-fission emission, the excitation energy and "temperature" is changing throw cascade. So, some simplification was made for T_{pre} calculation:

$$T_{pre} = \left(\frac{U_0 - c\sum_{j=0}^{k-1} B_j}{a} \right)^{1/2}, c = 0.5 \quad 10$$

The dependence of the level density parameter on mass number a=0.11·A_k was adjusted by fitting the model neutron spectrum [3] to the experimental data for prompt fission neutron spectra [10]. The average excitation after emission of k-neutrons, U_k was calculated with formula:

$$U_k = E^* - (\sum_{j=1}^{k-1} B_j + k\frac{4}{3}T_{pre}) \quad 11$$

The temperature for post-fission emission was calculated assuming the thermo - equilibrium between compound and fission fragments:

$$T_{post,kj} = \left(\frac{U_k + \Delta M_{j,A+1-k} - TKE_j}{a} \right)^{1/2} \quad 12$$

The energy release, and binding energy were taken from work [11]. The data missed in the tables were calculated with the Myers-Swiatecki-Lysekill mass formula.

Due to high share of direct (or pre-equilibrium) reaction mechanism, the eq. 9.10 underestimate the average energy of pre-fission neutrons. This factor is a particular important for second chance (k=1). At higher multiplicity only neutrons with small energy can be emitted even in direct reaction. These peculiarities were taken into account applying different relations for second chance:

$$< E_1 >= q(E_0)(E_0 - E_{dir}) + (1 - q(E_0))2\left(\frac{U_0}{a}\right)^{1/2}, \quad 13$$

where $q(E_{in})$ is a share of pre-equilibrium reaction mechanism and E_{dir} is average energy of neutron emitted in this process.

The share of pre-equilibrium process calculated with STAPRE code was described with simple relation:

$$q(E_0) = 1 - \exp(-0.0018(E_0 - 1)^2) \quad 14$$

The average energy taken by neutron scattered with this process can be fitted by linear function:

$$E_{dir} = 0.25E_0 - 1.37, \text{ [MeV]} \quad 15$$

Parameters of equations 14,15 were found by fitting of these simple relations to the STAPRE's calculation.

2.4 TKE dependence on mass and incident energy

The uncertainty δTKE=1% gives (6-10)% errors for the ν_{post} calculations. So, the careful evaluation of the TKE is a crucial point for any model applying for neutron multiplicity calculation. At each stage of neutron emission we know exactly mass and charge of fission fragments pair. Therefore, the total kinetic energy for fixed pair of fragment j was calculated according to following relation:

$$TKE_j = \frac{1.442 Z_{hj} Z_{lj}}{r_0 A_{hj}^{1/3}(1 + \frac{2}{3}\beta_h) + r_0 A_{lj}^{1/3}(1 + \frac{2}{3}\beta_l) + \delta}, \ [TKE] = MeV, \ \ [\delta] = fm \quad 16$$

Parameters r_0=1.16 and $\beta_1=\beta_2$=0.6 was selected following to the paper [5]. As one can see in fig.3, the formula 16 may be successfully applied for description of the complicate dependence of the *TKE* on fragment mass if δ-parameters for each fission mode were fitted to experiment.

We used this partial *TKE* to calculate partial ν_{ij} for fixed compound and fragment pair. Sake for the comparison of the calculated *TKE* values and experimental data we used equations similar to eqs. 3,8. So, the fragment kinetic energy at incident energy of neutrons E_0 is:

$$TKE_i = \frac{1}{4P_0}\sum_{m=1..4}\sum_{j=0,\pm1} TKE_{mj}P(J), \quad TKE(E_0) = \sigma^{-1}\sum_{i=1}^{i_{max}} TKE_i\sigma_i(E_0) \qquad 17$$

Parameters δ_{asym}=1.55 fm and δ_{sym}=2.63 fm was fitted to the Zoller's experimental data for ^{238}U [7]. In the following calculations for any isotopes we conserve this ratio $\delta_{sym}/\delta_{asym}$ but absolute value for δ_{asym} was calculated from systematic [4] for neutron energy 5MeV. In same cases, an additional correction for TKE data was applied to agree with ν-experimental data that was measured with accuracy <1%. Eqs. 16,17 predict the independence of *TKE* on incident energy for asymmetric fission or some increase for symmetric fission (see Fig.4) due to the inverse dependence on mass number. This fact contradicting to the experimental data may be connected with charge particle emission before fission, any else effects or even systematic errors of work [7]. However, we conserve the experimental dependence incorporating the small energy increase of δ-parameters on incident energy: $\delta = \delta_0 + \frac{d\delta}{dE}E$, with $\frac{d\delta}{dE} = 0.002\frac{fm}{MeV}$.

3. Validation of the model for low energy (<20MeV) fission

For many isotopes ν data was measured with accuracy ~1% for spontaneous fission and neutron induced fission from thermal energy to ~20MeV. Any model should describe these experimental data to be successfully extrapolated to higher input energy. First of all we compare the direct *TKE* experimental data with *TKE* values fitted to describe the ν experimental data. The best known data for $^{233,235}U(n_{th},f)$, $^{239}Pu(n_{th},f)$ and $^{252}Cf(sf)$ reactions and calculated result is shown in Table 2.

The similar results for all available isotopes from Th to Cf are presented in Fig. 5 together with global *TKE* systematic from works [4,14]. So, one may conclude that self-consistent model was developed. There are no any systematic contradictions between fitted *TKE* values and results of direct experiments.

The more complicate dependence of TKE on mass of fissile nucleus is visible in compare with data evaluated by Viola ($TKE=(0.1189\pm0.0011)Z^2/A^{1/3}+(7.3\pm1.5)$) and Malinovskij. Hence, one may apply any global systematic of *TKE* for ν evaluation however, the accuracy of this data will not be less than (5-10)%. If the ν-data at some energy points is known with higher accuracy, minor correction (<1%) for *TKE* is required.

The experimental *TKE* for ^{232}Th target versus input neutron energy and its enrgy dependence used in the model calculation are depicted in Fig. 6. The results of ν-calculations for $^{232}Th(n,f)$, $^{235}U(n,f)$ and $^{238}U(n,f)$ reactions are given in Fig. 7-9.

One should highlight that *TKE* data input in the model are in agreement with direct experimental data. Again, one should make the same conclusion: if *TKE* dependence is known, our model can reproduce energy dependence and absolute value of the neutron multiplicity inside the experimental errors. The results presented in this section allow us conclude that our model has a good basis and can be applied for ν-evaluation in the higher energy range.

4. Neutron multiplicity on the basis of Heavy Ions (HI) systematic

In an addition to model that was discussed above we used also the data from heavy ions reaction. The experimental data for pre- and post-fission neutron multiplicity available from heavy ions experiments were collected in work [29]. For reaction A_1+A_2=>A=>fission with low mass "heavy ions" A_2<30 it was found:

$$\nu^0_{pre}(A,U_0) = 1.98 - 0.0133A - 0.0376U_0 + 0.00042AU_0 \qquad 18$$

$$U_0 = E_0 \frac{A_1}{A_1 + A_2} + B_0$$

In the following paper [30] this equation was corrected to take into account the deviation of compound from valley of beta stability.

$$\nu_{pre}(A,U_0) = \nu^0_{pre}(A,U_0) + 0.071\xi - 0.0055\xi^2 + 0.30 \qquad 19$$

In this equation the $\nu^0_{pre}(A,U_0)$ function is given by eq. 18. The correction ξ is ξ=A-A_β. The mass of nucleus along beta stability valley can be calculated with formula:

$$A_\beta - 2Z = \frac{0.4A_\beta^2}{A_\beta + 200} \qquad 20$$

$$A_\beta = \left((Z-100) + \sqrt{(Z-100)^2 + 240Z}\right)/0.6$$

The number of post-fission neutrons can be calculated with relation:

$$\nu_{post}(A,U_0) = -4.52 - 0.0017A + 0.0705U_0 + 0.00155A^2 - 0.000216AU_0 \qquad 21$$

The different reaction mechanism is the main problem for the application of heavy ions systematic for neutron-induced fission. In neutron fission the share of direct (pre-equilibrium) reaction is ~98% at incident energy ~50 MeV. Taking into account this peculiarity the pre- and post- fission neutron multiplicity can be calculated applying effective excitation:

$$E_{eff} = (1 - q(E_0))U_0 + q(E_0)(E_0 - E_{dir}) \qquad 22$$

These two approaches with total available energy as in Eq. 18 and reduced energy according to Eq. 22 were used for estimation of upper and low limits of neutron multiplicity for neutron-induced reactions on the basis of heavy ions data. In an addition, one should have in mind the experimental problems for correct estimation of the pre- and post-fission neutrons in heavy ions experiments.

5. Neutron multiplicity in the energy range <150MeV

Only two experiments [20,23] were carried out at the neutron energy range 20-50 MeV. In this energy range our calculation does not contradict to experimental data.

At higher energy our model predicts higher neutron multiplicity than it was predicted by heavy ions data. In an addition, our result demonstrates more complicate shape than simple linear dependence expected from the HI data.

For ^{238}U our evaluation is essentially higher data that was recommended recently in work [31] and ν-values that were calculated on the basis of HI systematic with reduced excitation energy according to eq. 22. At the same time, the HI systematic data without any energy correction agree with our result with accuracy <20%.

In the following we investigate some factors that may change the calculated result.

As it was mentioned above the *TKE* of fission fragments is the crucial value for ν_{post} calculation. Only new experiments can confirm the reality of the energy (or isotopic) dependence of the *TKE* in the energy range >50 MeV. According to Fig.4 the expected difference in the *TKE* at ~200MeV is ~5MeV. Having in mind, that ~9 MeV of energy is required for emission of 1 neutron it may changes of ν value less than to 0.5. The Fig.10 shows that the influence of different *TKE* dependences - according to experimental data and predicted by Eq. 16 ($d\delta/dE$=0) on the calculated ν-values are small.

In eq.10 we assumed average "temperature" for the calculation of pre-fission neutron energy. If one take c=0 instead of c=0.5, the ν_{post} will be reduced to $\Delta\nu_{post}$ =0.25 at E_0=100 MeV

The uncertainty may be connected with bad known of the contribution of different fission modes (symmetric/asymmetric fission). However, according to data presented in Fig. 13 the difference in ν-value that is visible at low energy reduced very much and can not bring much troubles for ν calculations at E_0>100 MeV.

We have no experimental cross sections for selected fission chance. Our results are based on theoretical calculations only and chance distribution may be overloaded with systematic mistakes. The chance distributions for E_0=100 MeV calculated for two variants of level density on fission barrier a_f=1.0a and a_f=0.9a are depicted in Fig. 14. This factor changes the average ν_{pre} very much. As a result, ν_{post} changes also, but in such a way that total ν_{tot} is practically constant. This peculiarity can be explained if one plots the dependence of ν_{pre} and ν_{post} on mass of fissile nucleus (or chance number). These functions (see Fig.16) have the same slope but opposite sign. Hence, if the average neutron multiplicity (ν_{pre}) will be changed due to changing of chance distribution, the calculated ν_{post} will be changed to the same value into opposite direction. So, the unknown chance distribution cannot provide the strong influence on calculated ν_{tot}-values.

Charge particles emission may also disturb the result. The following cross sections were estimated for ^{238}U target at E_0=100 MeV on the basis of the theoretical model [31]: ^{238}U(n,n)→^{238}U(xf)→fission~1100 mb, ^{238}U(n,p)→^{238}Pa(xf)~200 mb, ^{238}U(n,xα)~40 mb. The experimental fission cross section is ^{238}U(n,f)~1400 mb. So, one may neglect the α-particle emission at a pre-fission stage. The fission of protactinium isotopes after the proton emission give ~20% of the neutron emission fission. The ν_{pre}(100)=7.2. The proton emission will reduce this value to ν_{pre}(100 MeV)=6.2. So, the average pre-fission neutron multiplicity is 7.0 instead of 7.2. The difference of neutron and proton binding energies is small ~3 MeV in compare with total energy taken for emission of 1 neutrons in fission. So, one may assume that ^{238}U and ^{238}Pa have the same excitation energy. The model calculation gives very close numbers for post-fission multiplicity: ν_{post}(^{238}U, E_0=100 MeV)=7.2, ν_{post}(^{238}Pa, E_0=100 MeV)=7.8. The comparison of all these figures allow us to conclude that we cannot expect the uncertainty much higher than $\Delta\nu$~1 due to leaving out of the charge particle emission.

In addition to results for neutron induced fission it is interesting to analyze the data for proton induced fission. In the energy range up to 150 MeV two experiments were carried out for ^{238}U(p,f) reaction [32,33]. In both works the similar experimental set up was applied. The neutron detectors and two pairs of fission fragment detectors were placed in a plane perpendicular to the proton beam. Neutron spectra were measured by time of flight method. The neutron multiplicity and the separation of the pre- and post-fission neutrons were estimated from measured neutron energy-angular distribution relative fragment direction at the same angle (90-deg) relative proton beam.

Experimental and calculated results are presented in Fig. 17-19. Our result for total neutron multiplicity without any additional correction is in very good agreement with data measured in work [33]. However, some disagreement is visible for partial multiplicities for a_f=0.9a. Our model underestimates the post-fission multiplicity and overestimates the pre-fission data at higher input energies. However, all data can be described inside the error bars without any correction for the level density parameter (a_f=1.0a).

More strong contradiction exists for 150 MeV data [32]. If the ν_{post} values agree reasonable, the difference for ν_{pre} is in factor ~2.

First of all one can demonstrate the global problem of this work. They applied plastic scintillator (no γ-discrimination) as a neutron detector placed on 35 cm flight path. As was mentioned before, the ν_{post}, ν_{pre} neutron multiplicities were estimated from neutron spectra measurements. However, in this experimental condition these data may be overload with strong systematic errors. In addition there is the inside contradiction between experimental data of work [32] - low number and low average of the pre-fission neutrons.

According to our calculation (a_f=0.9a), the pre-fission neutrons should take away ~114 MeV at E_0=150 MeV to provide ν_{post}=6.6 that agrees with experimental value ν_{post}=5.1. If the experimental data for ν_{pre}=5.8 is true, each pre-fission neutron should take ~20 MeV energy. The binding energy is ~7 MeV. So, average kinetic energy of pre-fission neutrons should be ~13 MeV. This value contradicts very much to experimental data [32] $<E_{pre}>$=2.42 MeV for pre-fission neutrons which agree with 2.8 MeV estimated in our model for c=0.5. One should highlight that neutrons with such high average energy cannot be measured in the experiment [32] at all.

Due to high contribution of the pre-equilibrium (direct) reaction mechanism, the input proton cannot be absorbed by the nucleus and the energy available for fission reaction is rather small (eq. 14,15,22). So, only ~75 MeV should be distribute among the ν_{pre}=5.8. The neutron average kinetic energy in this case is ~2 time smaller, but it is ~6.2 MeV still very high in compare with experimental value.

In an addition a big difference between the average energy of pre-fission neutrons should be found for (p,n) and (n,f) reactions applying this argument. The first neutron should be included in measured ν_{pre}=5.8+1. And average energy may be estimated as $<E_{pre}>$=(37.4+5.8*6.2)/6.8=10.8 MeV. So, one may conclude that our model reproduces also the (p,f) experimental results except 150 MeV point that should be used with great care.

6. Conclusion

The self-consistent model on the basis of energy balance with the incorporation of chance structure of fission was developed. It was verified with the low energy fission data (0-20 MeV) for which the neutron multiplicity is known with accuracy 1-2% and was applied for higher energies. The calculated results agree inside error bars with few experimental data in the neutron energy range 20-50 MeV for ^{232}Th, ^{235}U, ^{238}U. However, the recent evaluation [31] being in good agreement with our result and experimental data in the range <50 MeV disagree with our prediction at ~150 MeV as much as a factor ~2.

Some factors that may change the result at high energies were investigated. It was not found any arguments for strong decreasing of the total neutron multiplicity. Hence, new experiments at E_0~100 MeV are urgent necessary to solve this contradiction. In addition, new experiments for (p,f) neutron multiplicity in the energy range 50-150 MeV are also required.

The separate measurements for ν_{pre} and ν_{post} for both (n,f) and (p,f) reactions are very important from point of view of basic science for correct understanding of the fission process at high excitation energy and adjusting of model parameters. Besides, the more realistic calculations of average energy for pre-fission neutrons should be carried out for the final conclusion concerning neutron multiplicity at high input energy for (n,f) and (p,f) reactions.

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Table 1. List of notations.

Fissile nuclei	chance number	pre-fission neutrons	Binding energy	Escaped energy $E_{pre}(k)$ for k pre.-fission neutrons.	Average excitation after emission of k-neutrons
A+1	1	0	$B_{A+1}=B_0$	0	$U_0=E^*+B_0$
A	2	1	$B_A=B_1$	$E_{pre}(1)=<E_{11}>$	$U_1= E^*-E_{pre}(1)$
A-1	3	2	$B_{A-1}=B_2$	$E_{pre}(2)=<E_{21}>+<E_{22}>+B_1$	$U_2= E^*-E_{pre}(2)$
A-2	4	3	$B_{A-2}=B_3$	$E_{pre}(2)=<E_{31}>+<E_{32}>+<E_{33}>+B_1+B_2$	$U_3= E^*-E_{pre}(3)$
…	…	…	…	…	…
A-k	i	k	$B_{A-k}=B_k$	$E_{pre}(k)=\sum_{j=1}^{k}< E_{kj} > + \sum_{j=1}^{k-1} B_j$	$U_k= E^*-E_{pre}(k)$

Table 2 Experimental and calculated *TKE* and *v* data.

reaction	TKE_{exp}, MeV [12]	ν_{exp}, [13]	TKE_{cal}, MeV	ν_{cal}
$^{233}U(n_{th},f)$	170.1±0.5	2.488±0.004	170.06	2.488
$^{235}U(n_{th},f)$	170.5±0.5	2.416±0.004	169.91	2.417
$^{239}Pu(n_{th},f)$	177.9+0.5	2.876±0.006	177.39	2.876
$^{252}Cf(sf)$	184.1±1.3	3.756±0.005	184.20	3.755

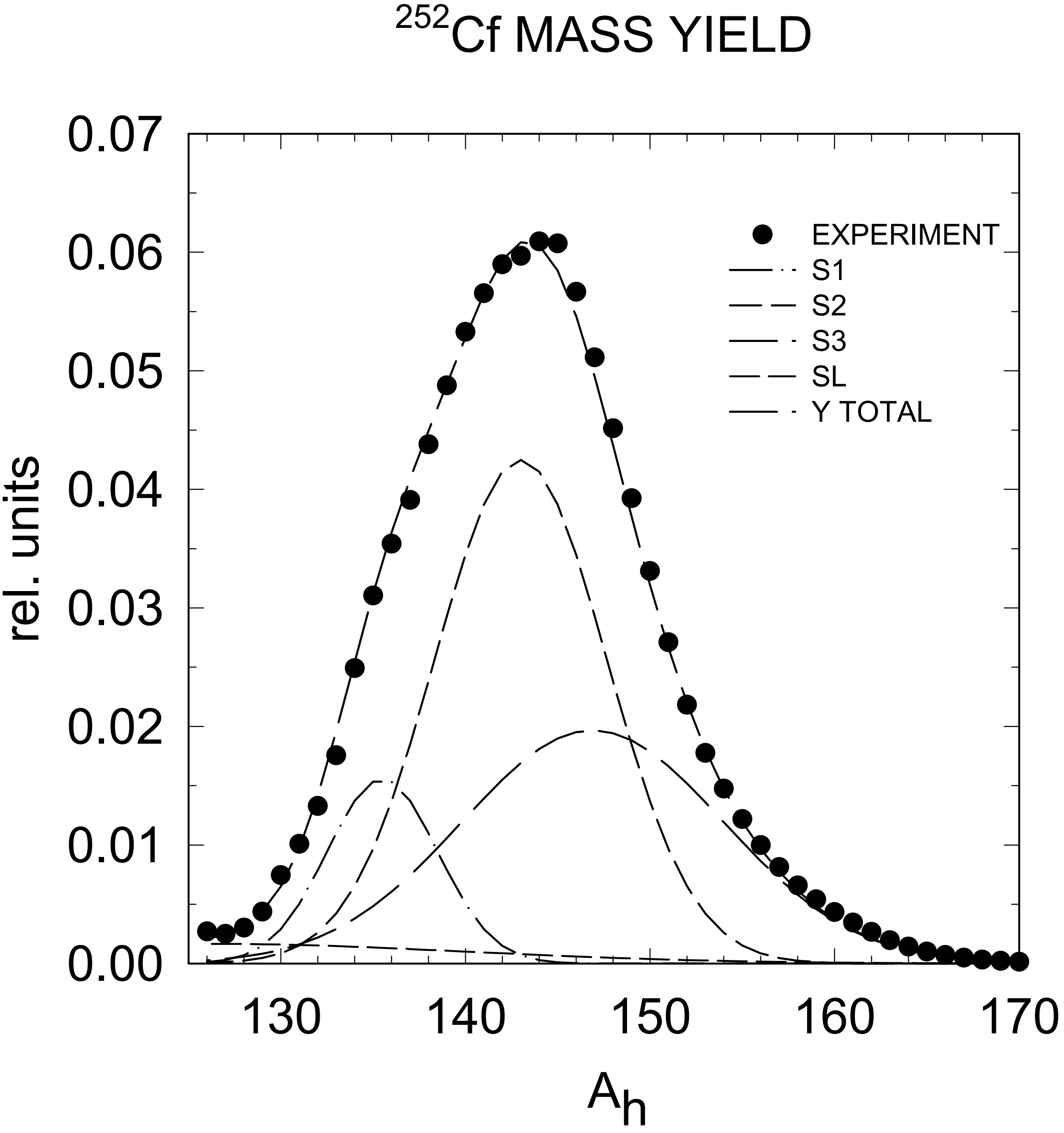

Fig. 1. Experimental mass distribution for ^{252}Cf [5] and its description with four Gauss functions that correspond to different fission modes.

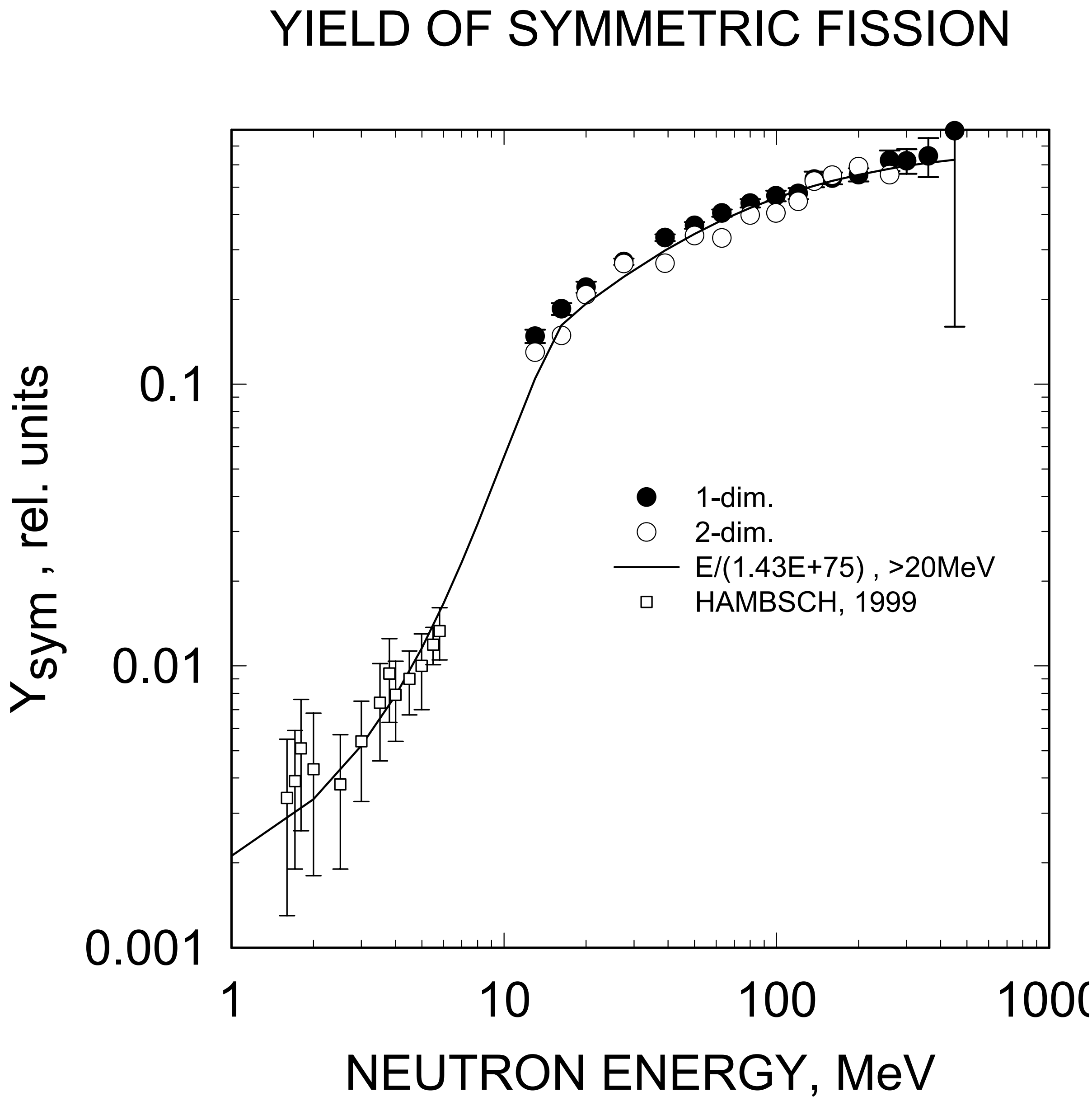

Fig.2 Yield of the symmetric fission. Circles are taken from work [7] and represent values determined via two-dimensional and one-dimensional fits to the experimental data. Solid line shows the simple analytical approach (eq. 6).

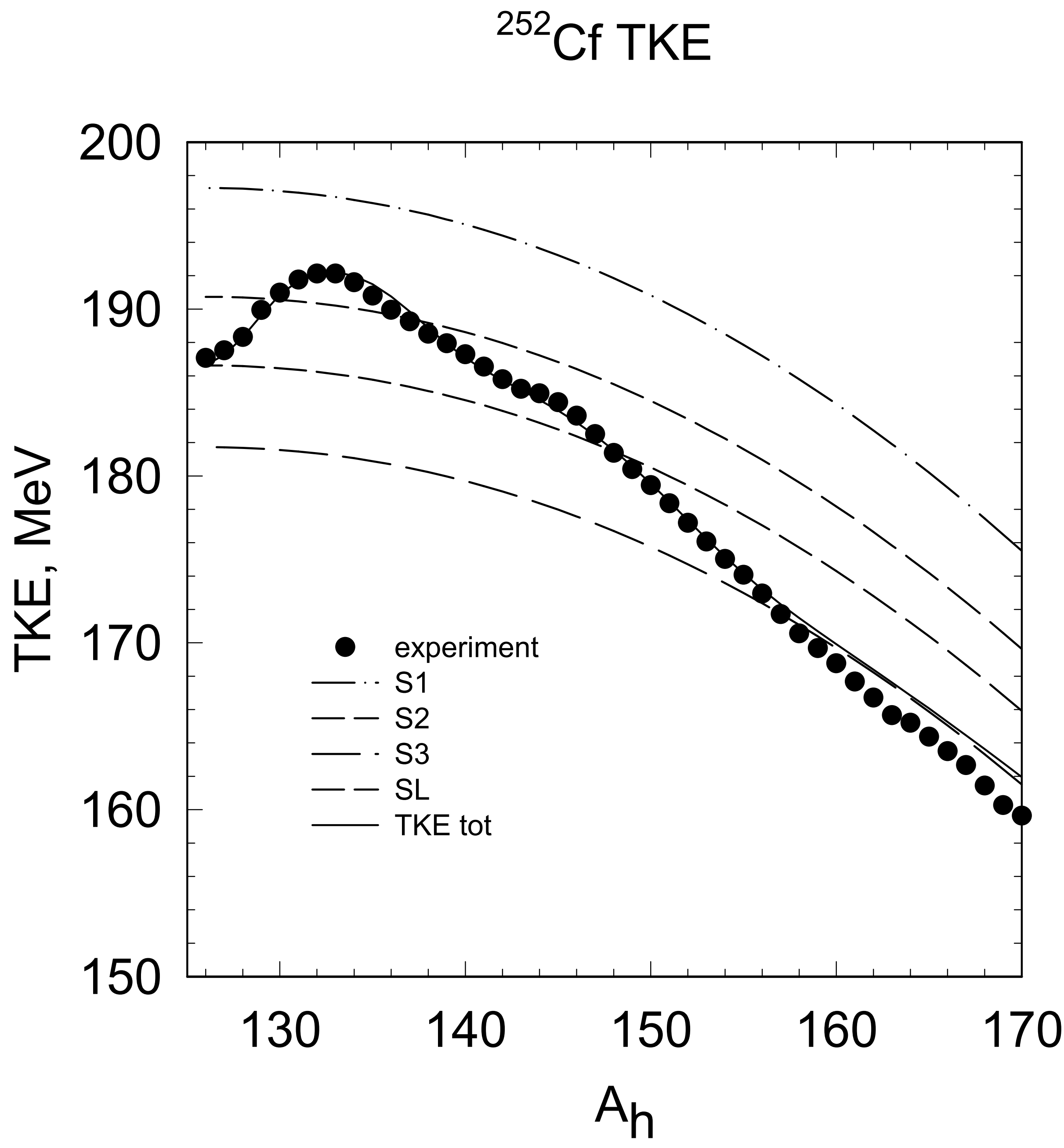

Fig.3 Experimental dependence of *TKE* on heavy fragment mass [5]. Lines show *TKE* dependence for selected fission modes with δ-parameters fitted to average partial <*TKE*>. Solid line is total dependence for mode contributions presented in fig.1

^{238}U, TKE FROM ZOLLER'S EXPERIMENT

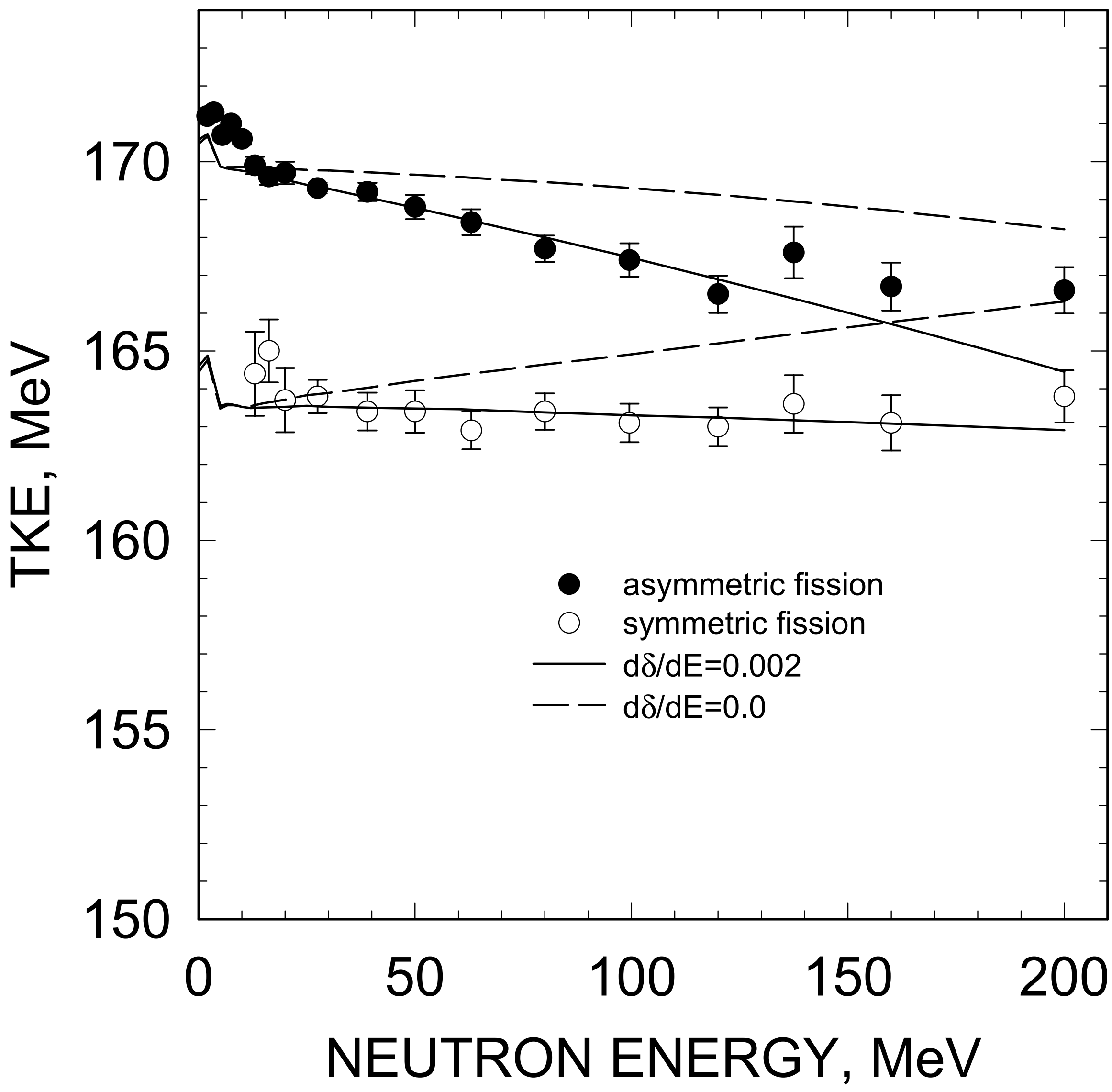

Fig. 4 Average *TKE* for symmetric and asymmetric fission according to data of work [7]. Points give the experimental results, lines are model dependences with eq. 16,17.

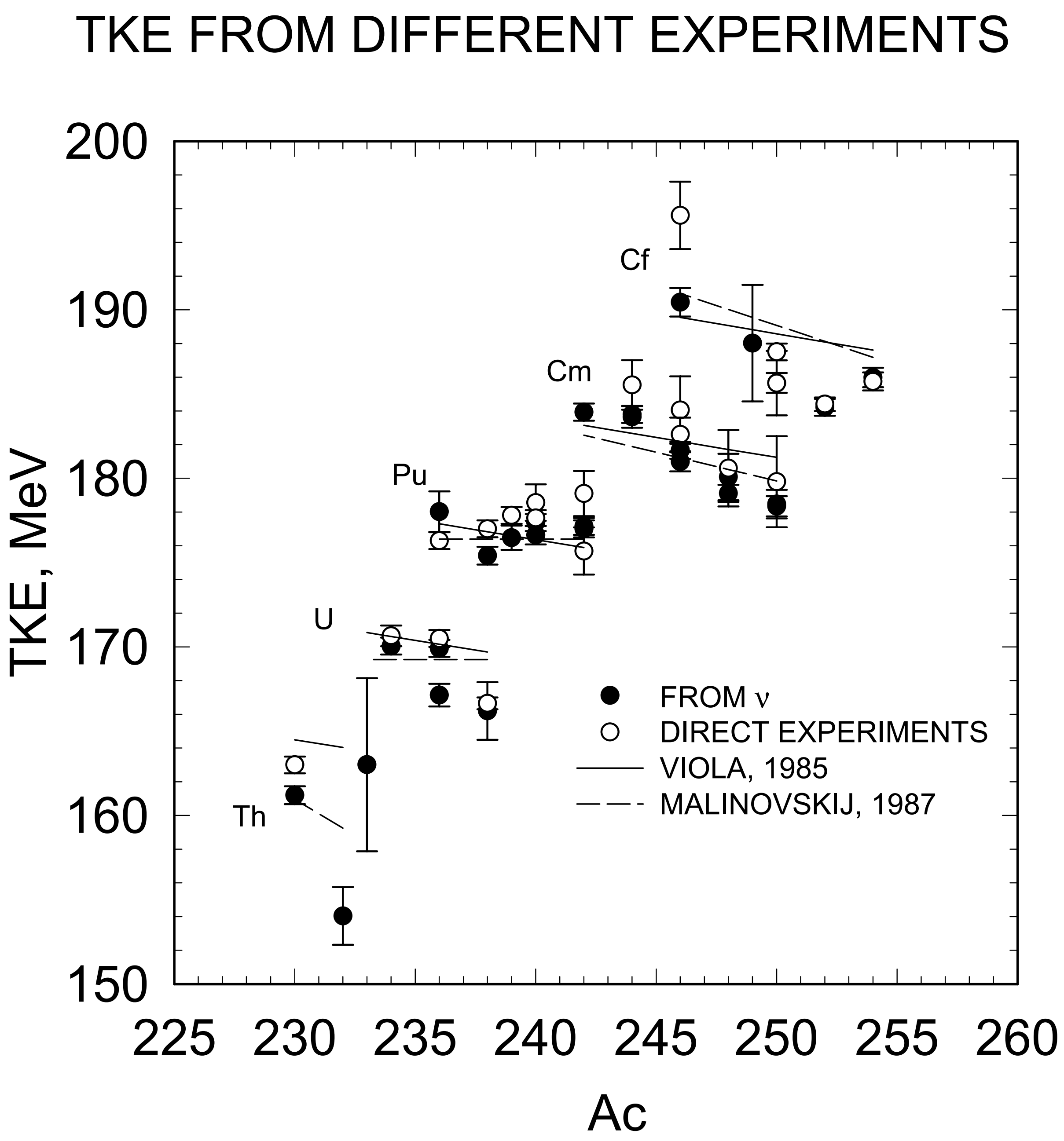

Fig.5 Isotopic dependence of TKE estimated from ν-data and results of direct measurements collected in [6]. Evaluated data by Viola [14] and Malinoskij [4] are given with solid and dashed lines.

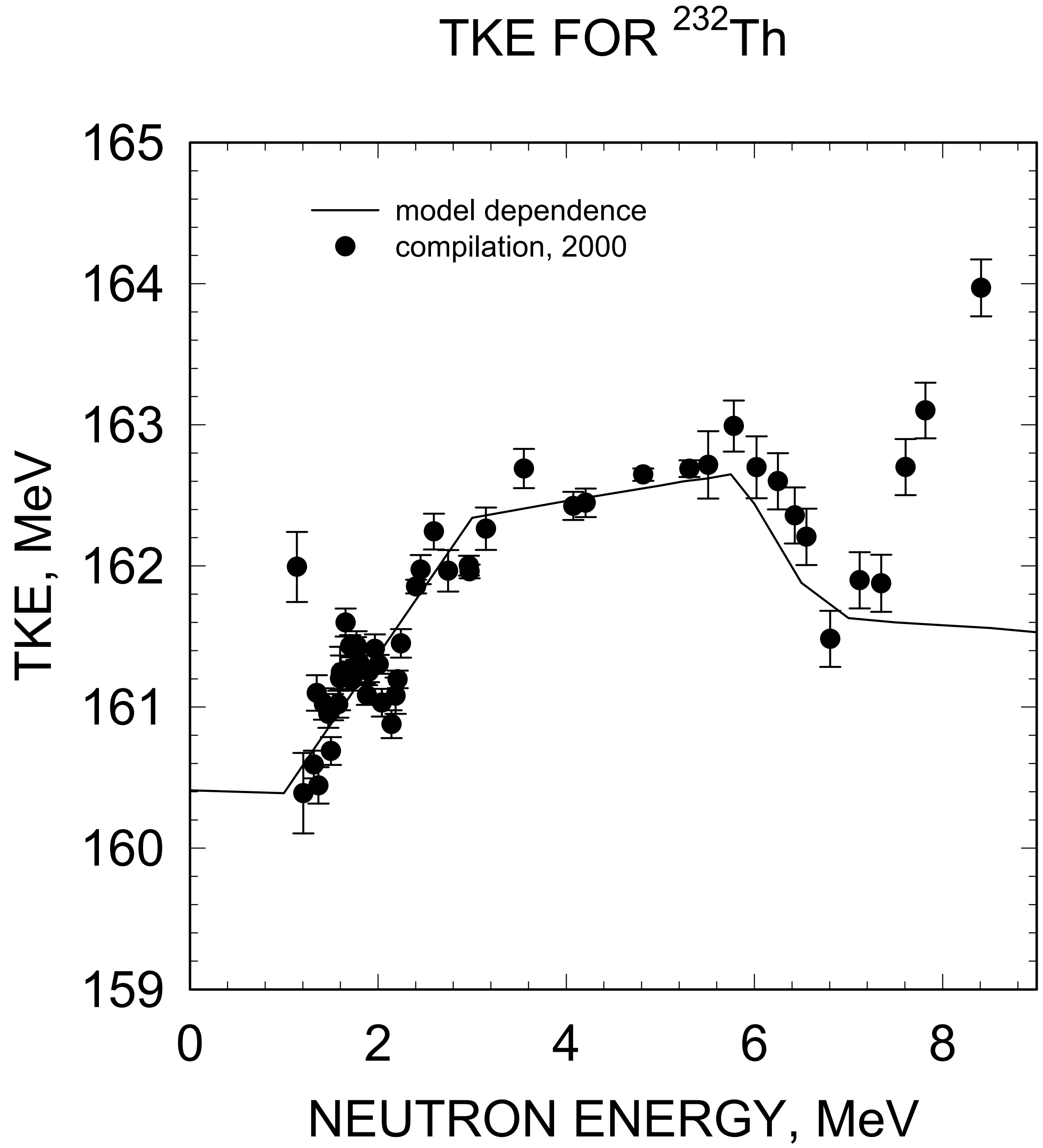

Fig. 6 *TKE* versus input energy for ^{232}Th(n,f) reaction. Line shows the dependence that was used in our model for ν calculation presented in Fig. 7. The normalized experimental data was taken from compilation [6].

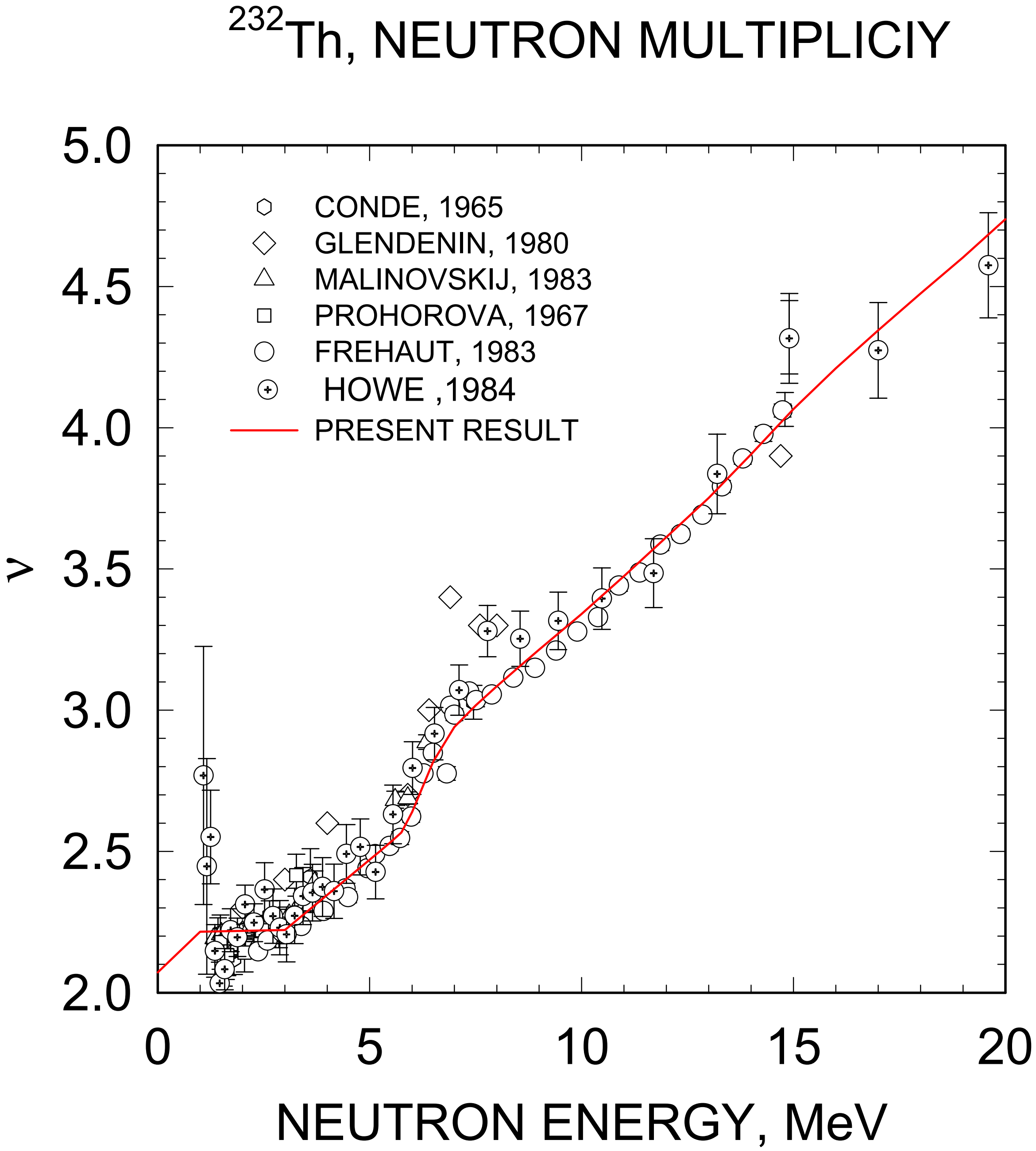

Fig.7 Experimental ν(E) and calculated result for ^{232}Th(n,f) reaction at low energy. Experimental data were taken from [15-19].

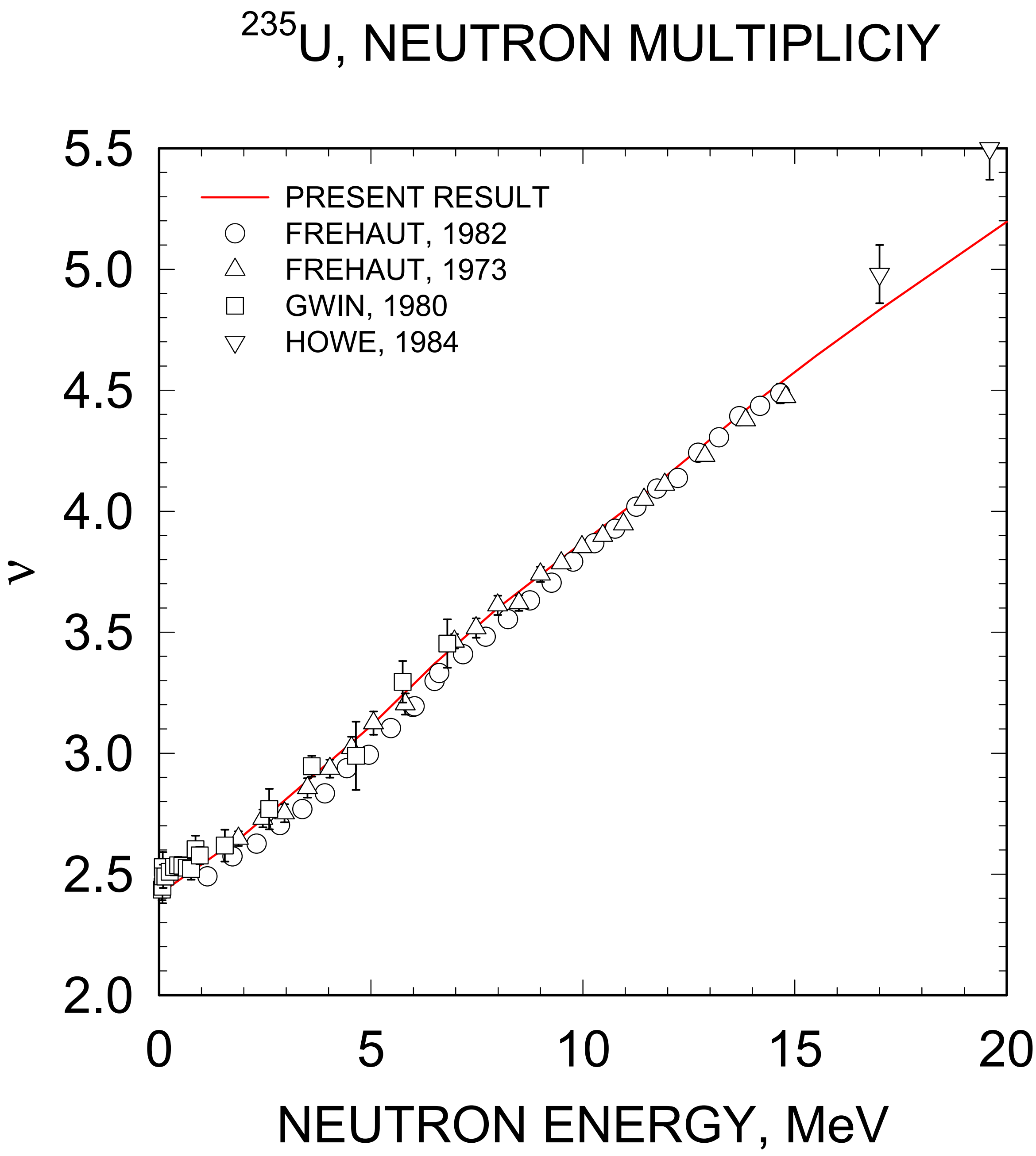

Fig.8 The same as in fig. 7 for ^{235}U(n,f). The experimental data were taken from [20-23].

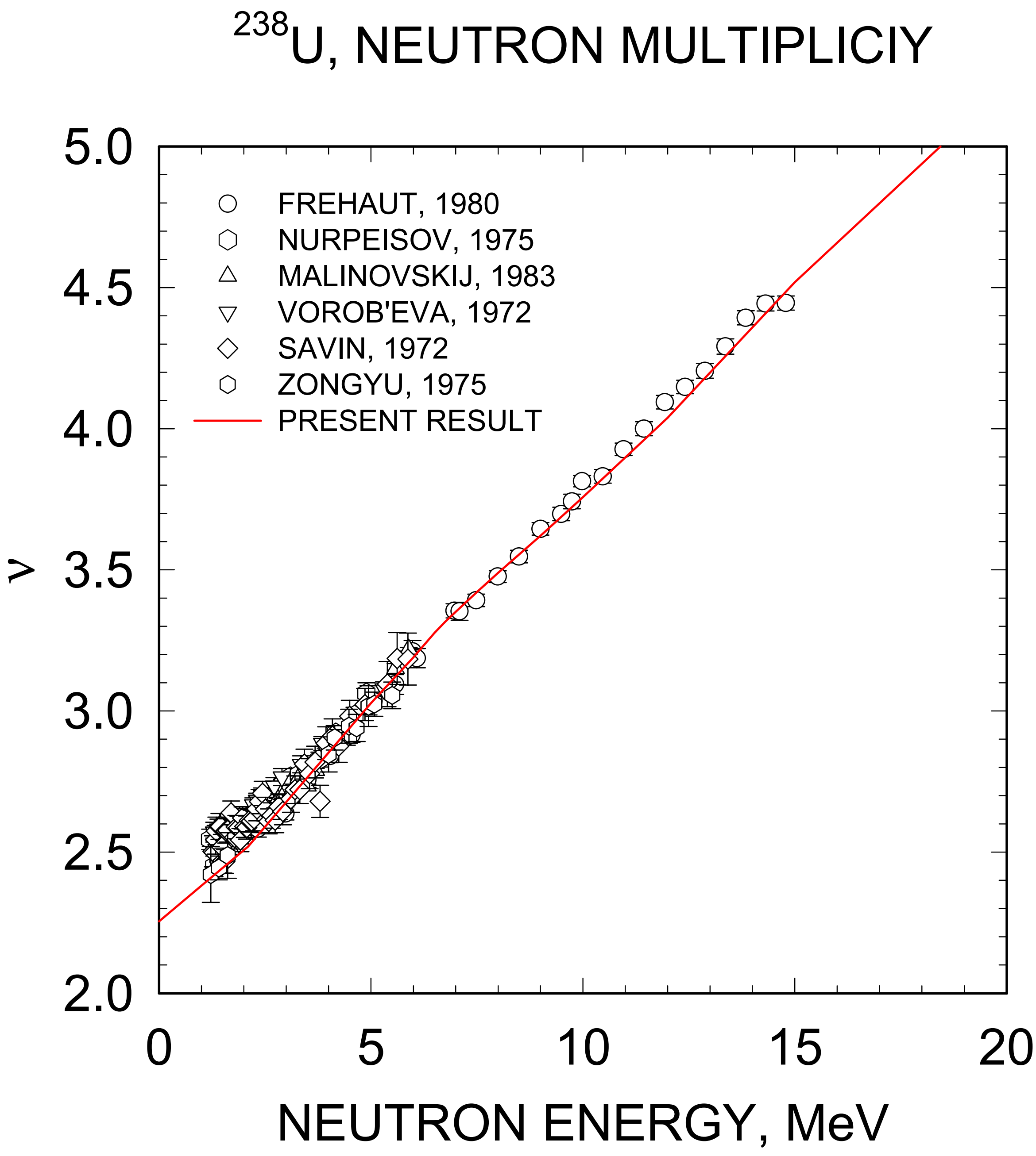

Fig.9 The same as in fig. 7 for ^{238}U(n,f). The experimental data were taken from [24-28].

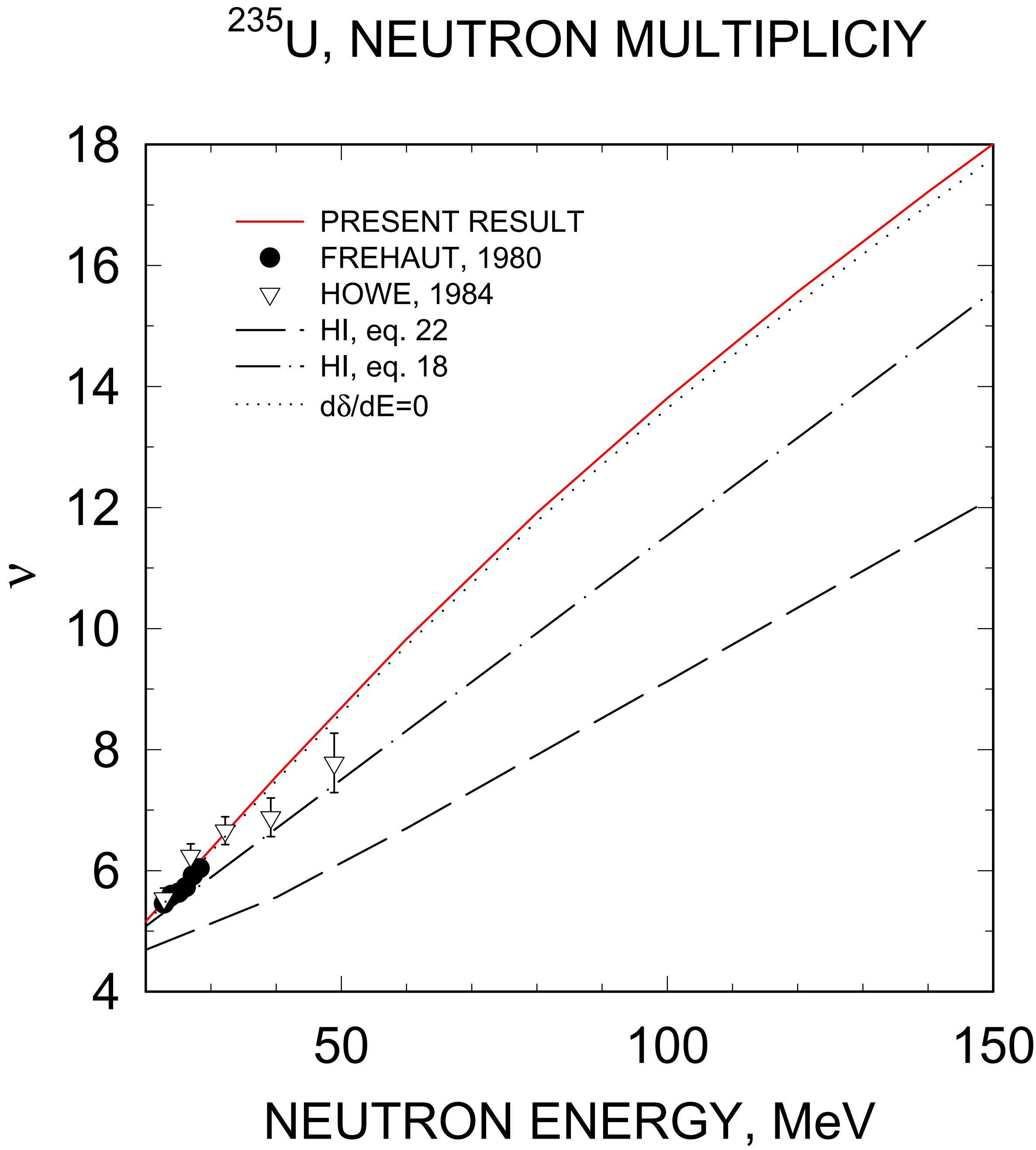

Fig.10. Experimental data [20,23] and calculated results of the ^{235}U neutron multiplicity at the incident energy range 20-150MeV. Dot-dashed and dashed lines present result for HI systematic with total excitation energy according to eq. 18 and eq.22 correspondently. Dotted line is the dependence of ν for dδ/dE=0.

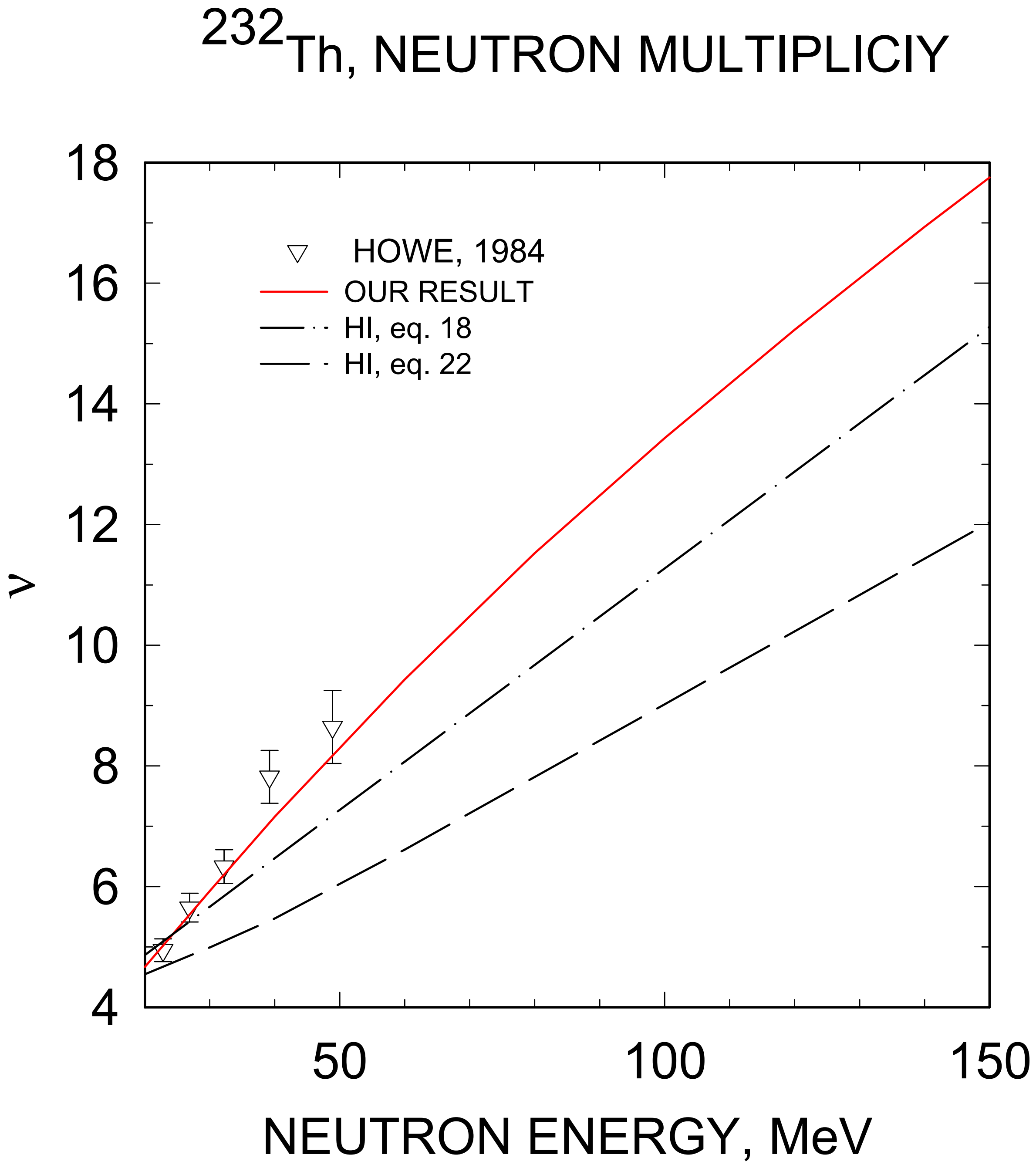

Fig.11 The same as in fig.10 for ^{232}Th. Experimental points were calculated on the basis of ν_{232}/ν_{235} ratio from [20] and our absolute value for ^{235}U.

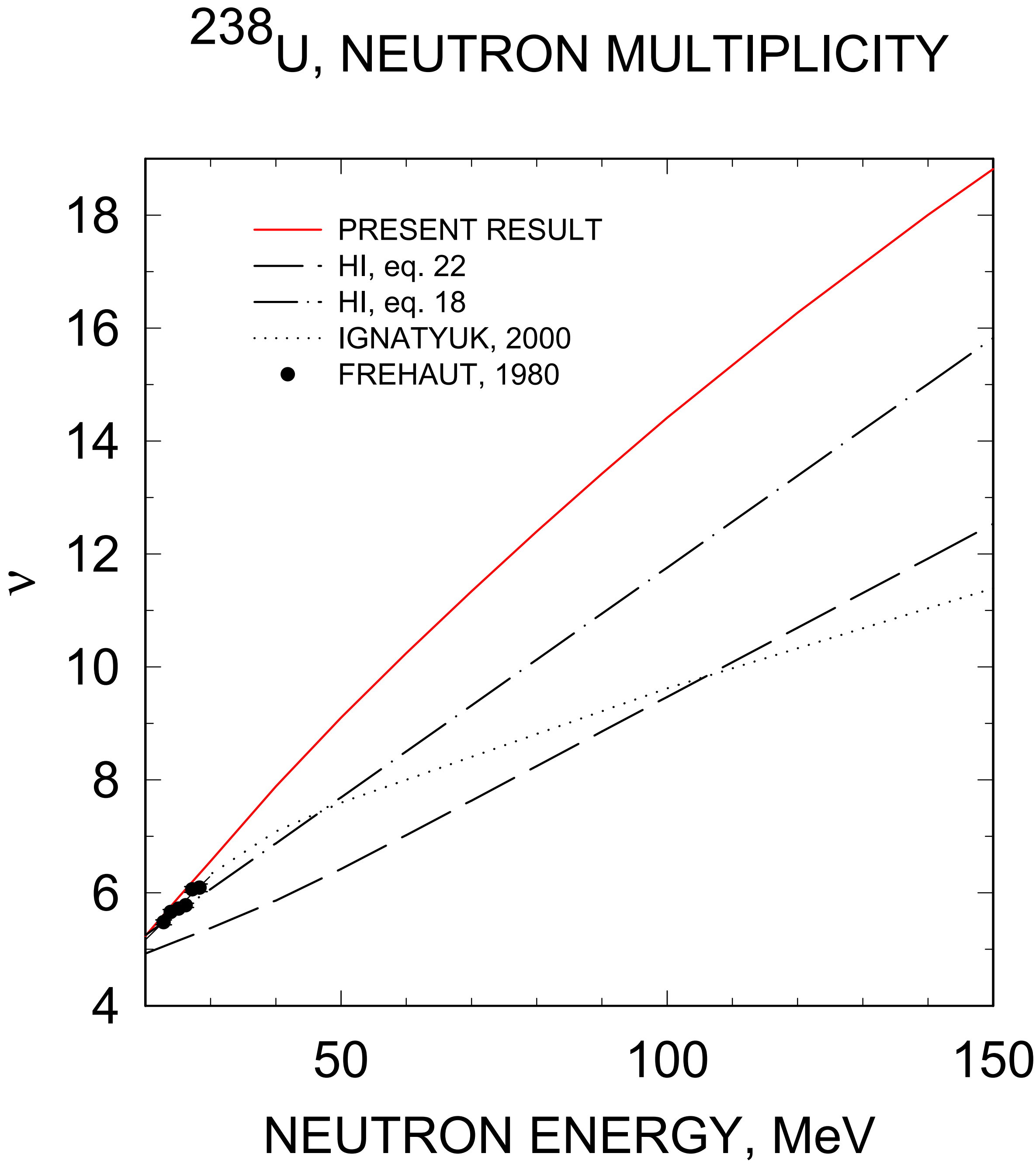

Fig.12 The same as in fig.10 for ^{238}U. Experimental points were taken from [23]. Recommended dependence from work [31] is shown by dotted line.

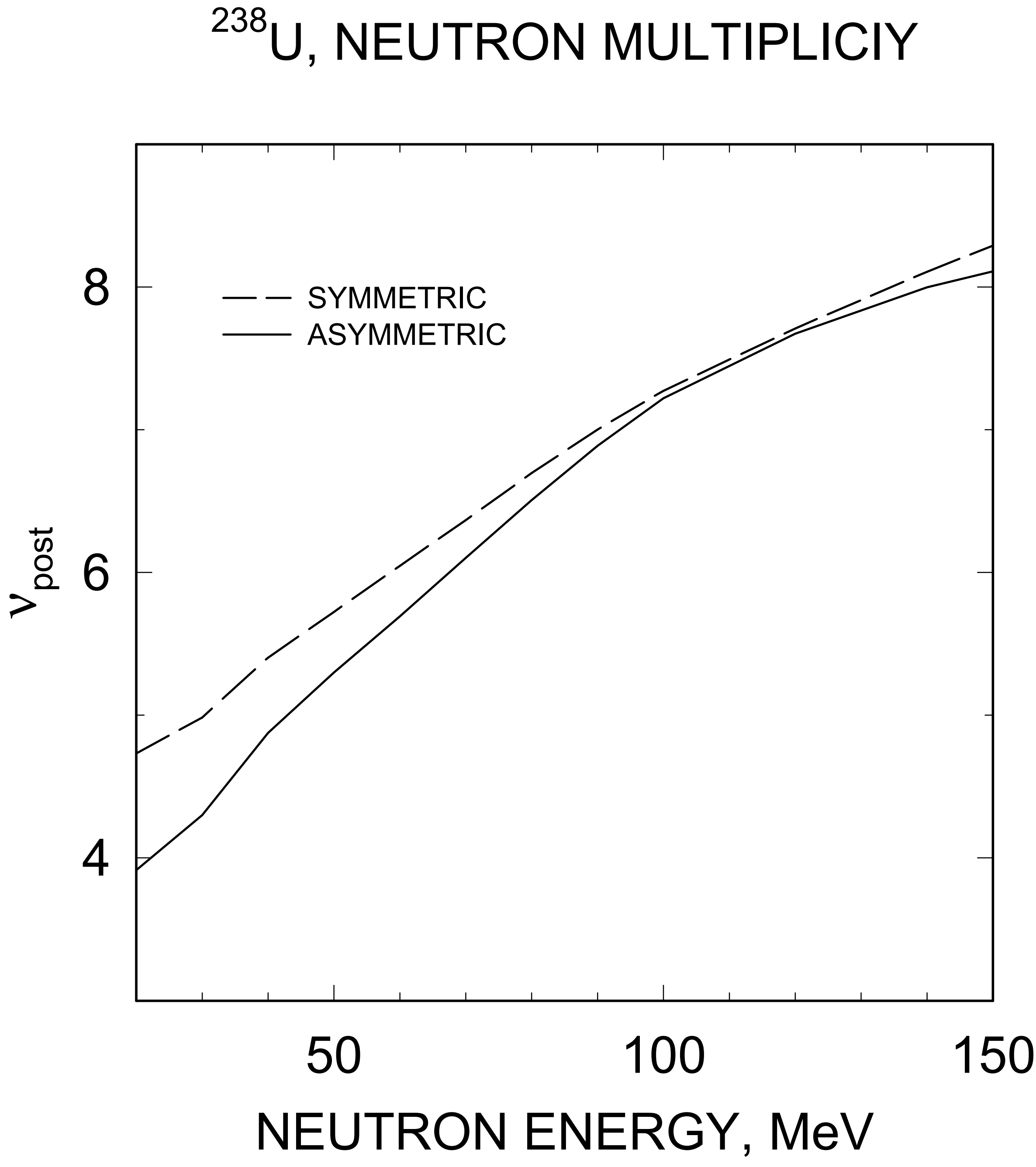

Fig. 13. The partial neutron multiplicity for asymmetric and symmetric fission modes as function of the incident energy for ^{238}U.

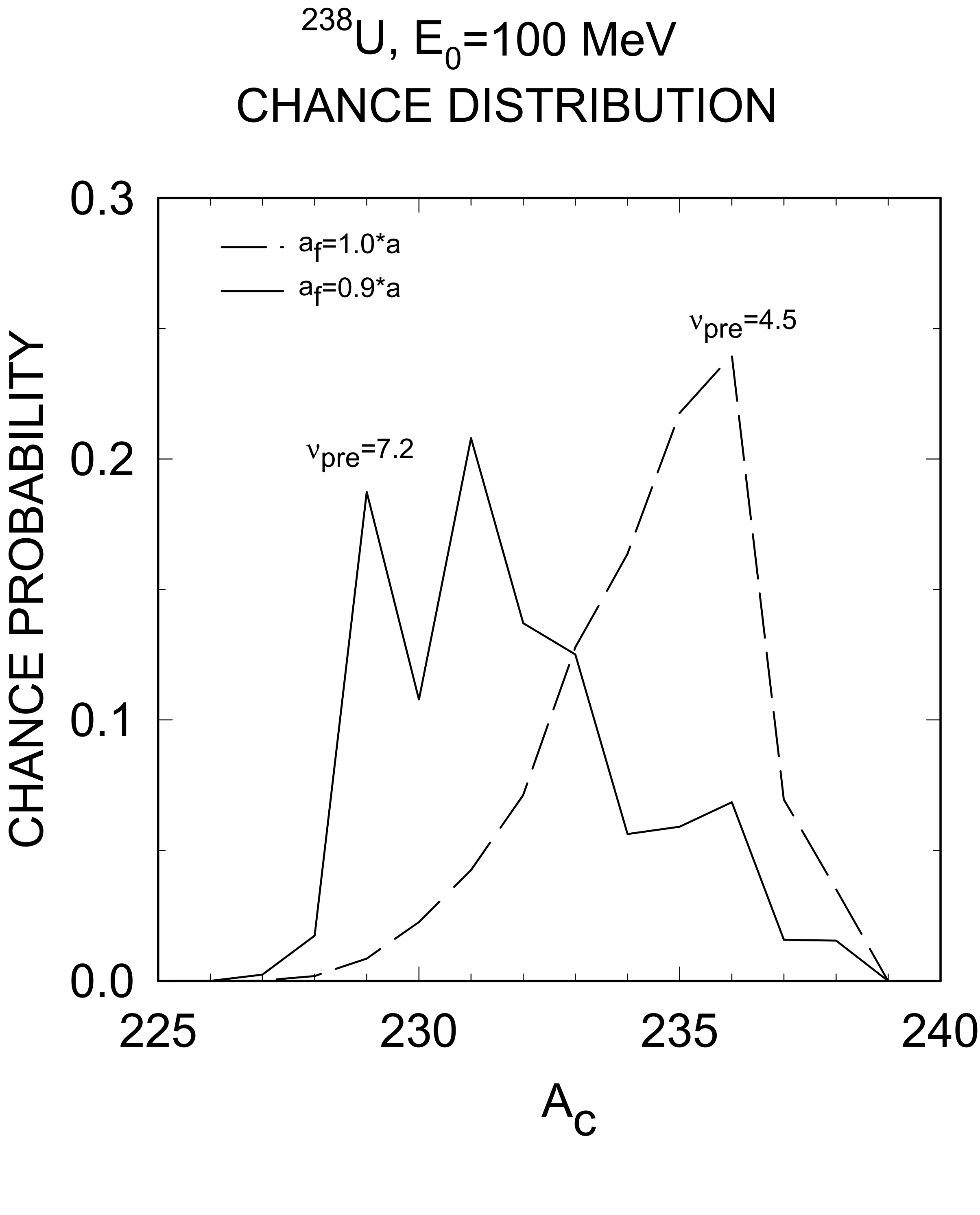

Fig. 14. Fission chance distribution for two level density parameters on fission barrier.

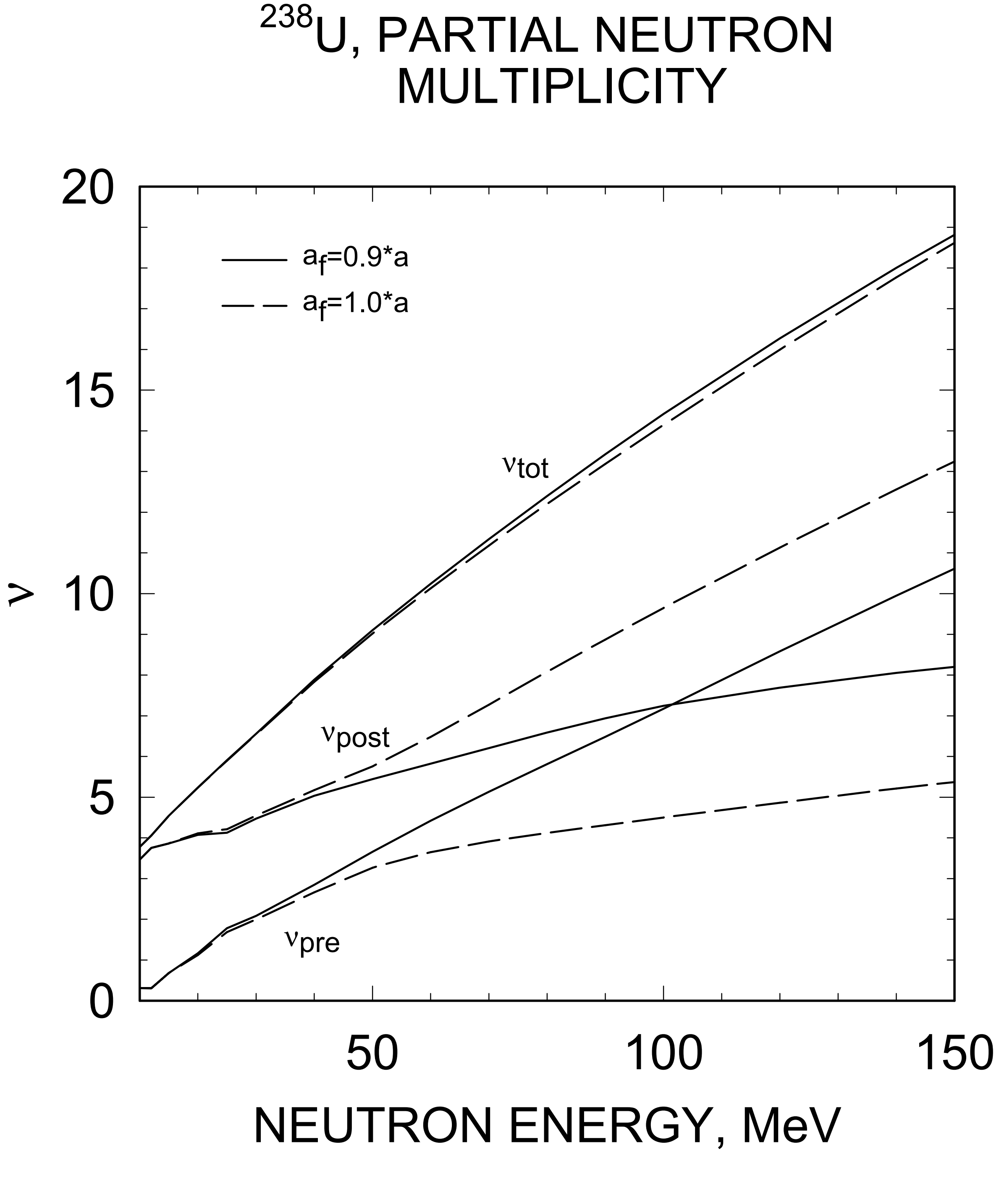

Fig. 15. Neutron multiplicity versus incident energy for different level density parameters.

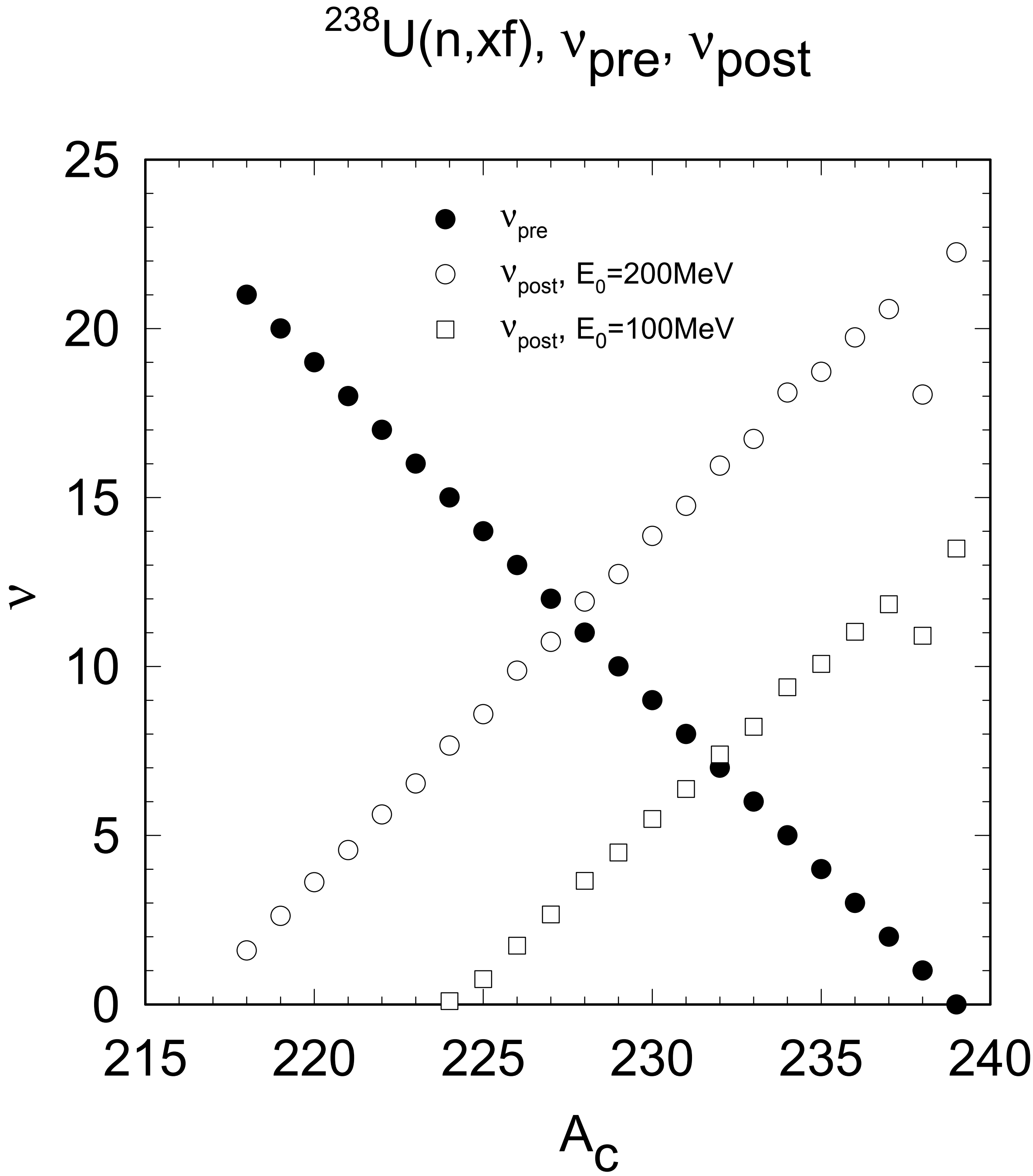

Fig.16. ν_{pre} and ν_{post} dependences on mass of fissile nucleus. Post-fission neutron multiplicity is shown for two incident energies.

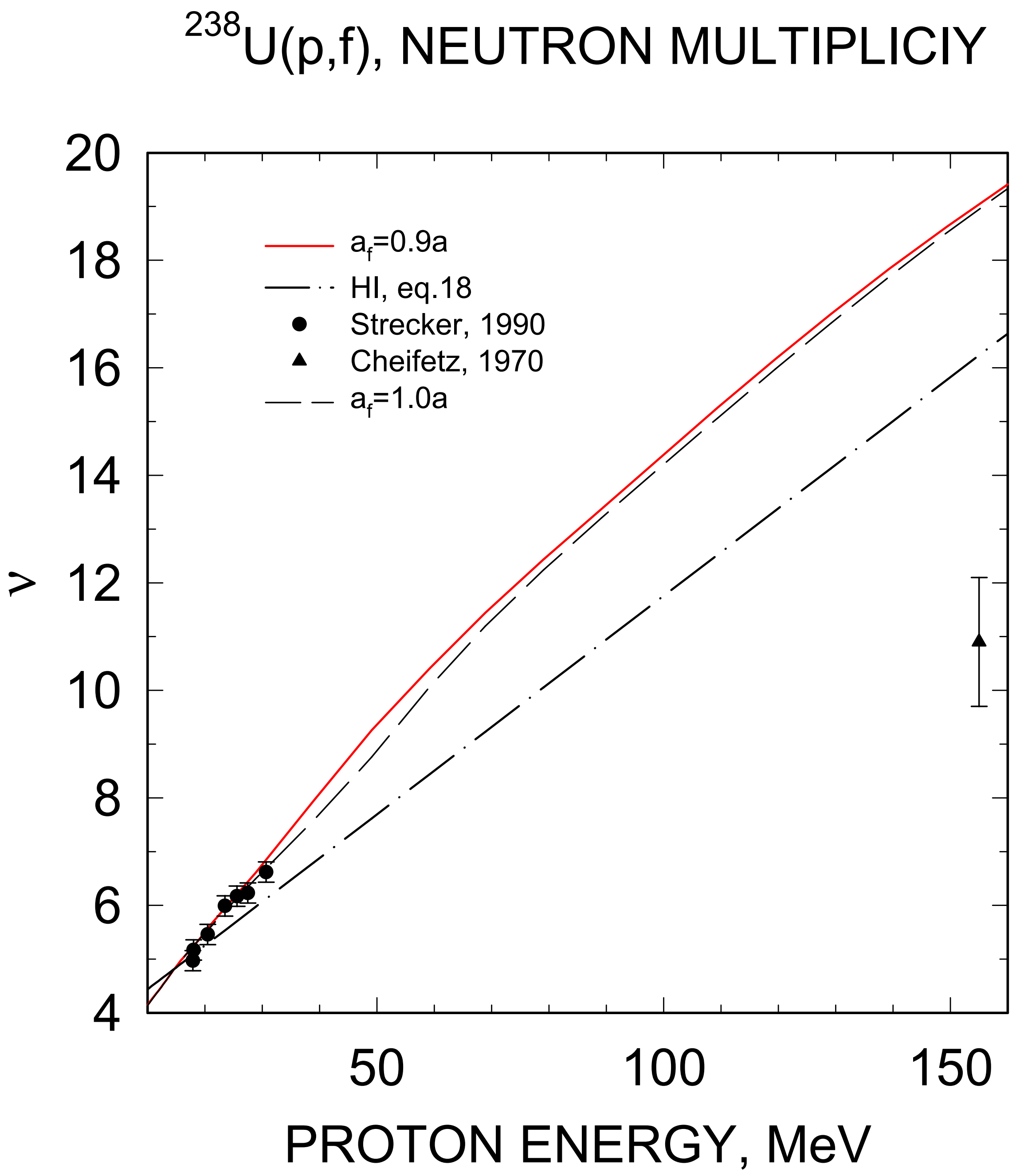

Fig. 17. Experimental data [32,33] and calculated results of the ^{238}U(p,f) total neutron multiplicity at the incident energy range 10-150MeV. Dot-dashed line presents result for HI systematic with total excitation energy according to eq. 18.

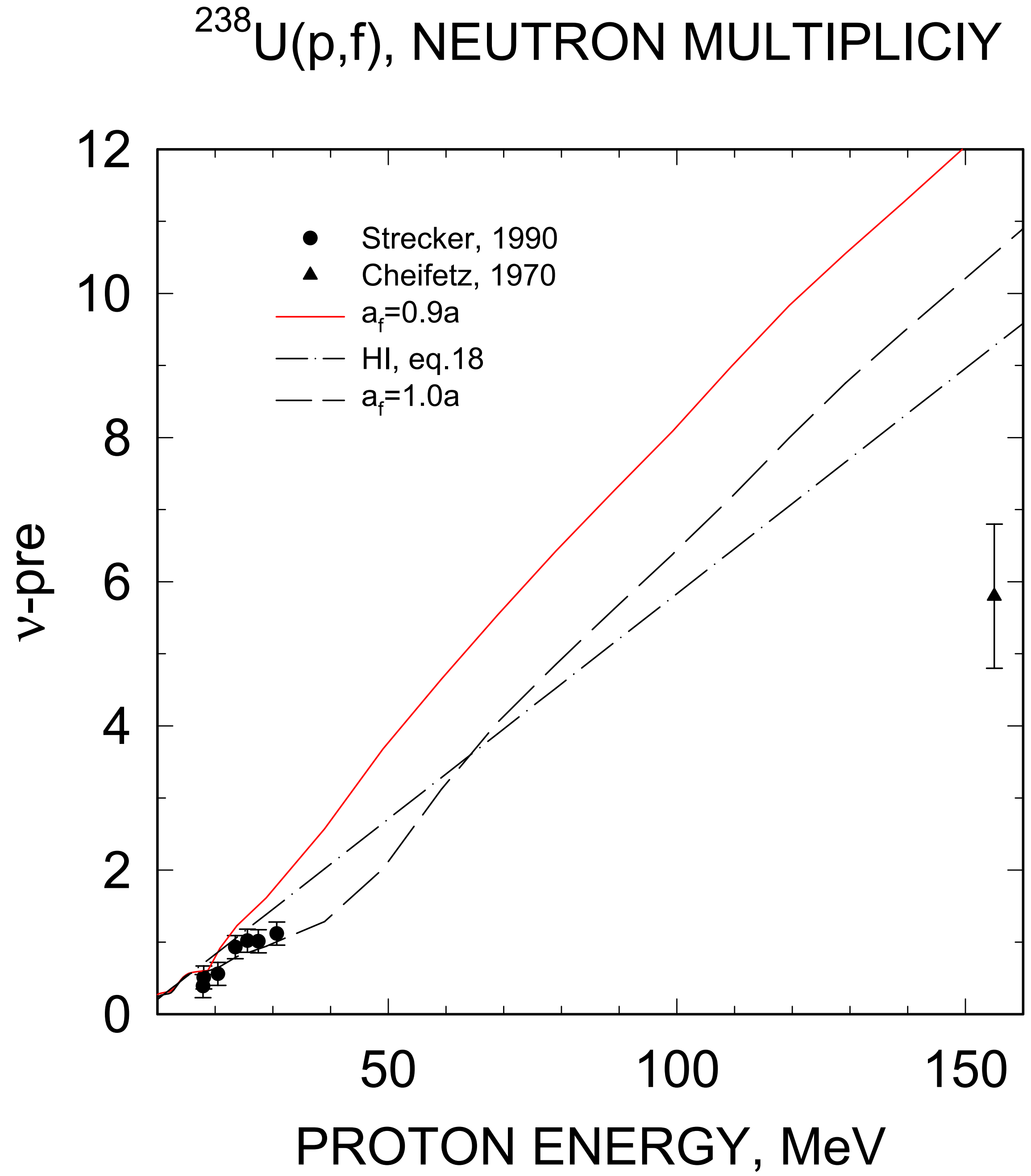

Fig. 18. The same as in Fig 17 for pre-fission neutron multiplicity. The total number of scission neutrons ν_{sc}=0.36 [10] was applied for a calculation of the pre-fission multiplicity from isotropic component measured in work [33] $\nu_{pre}=\nu_{iso}-\nu_{sc}$.

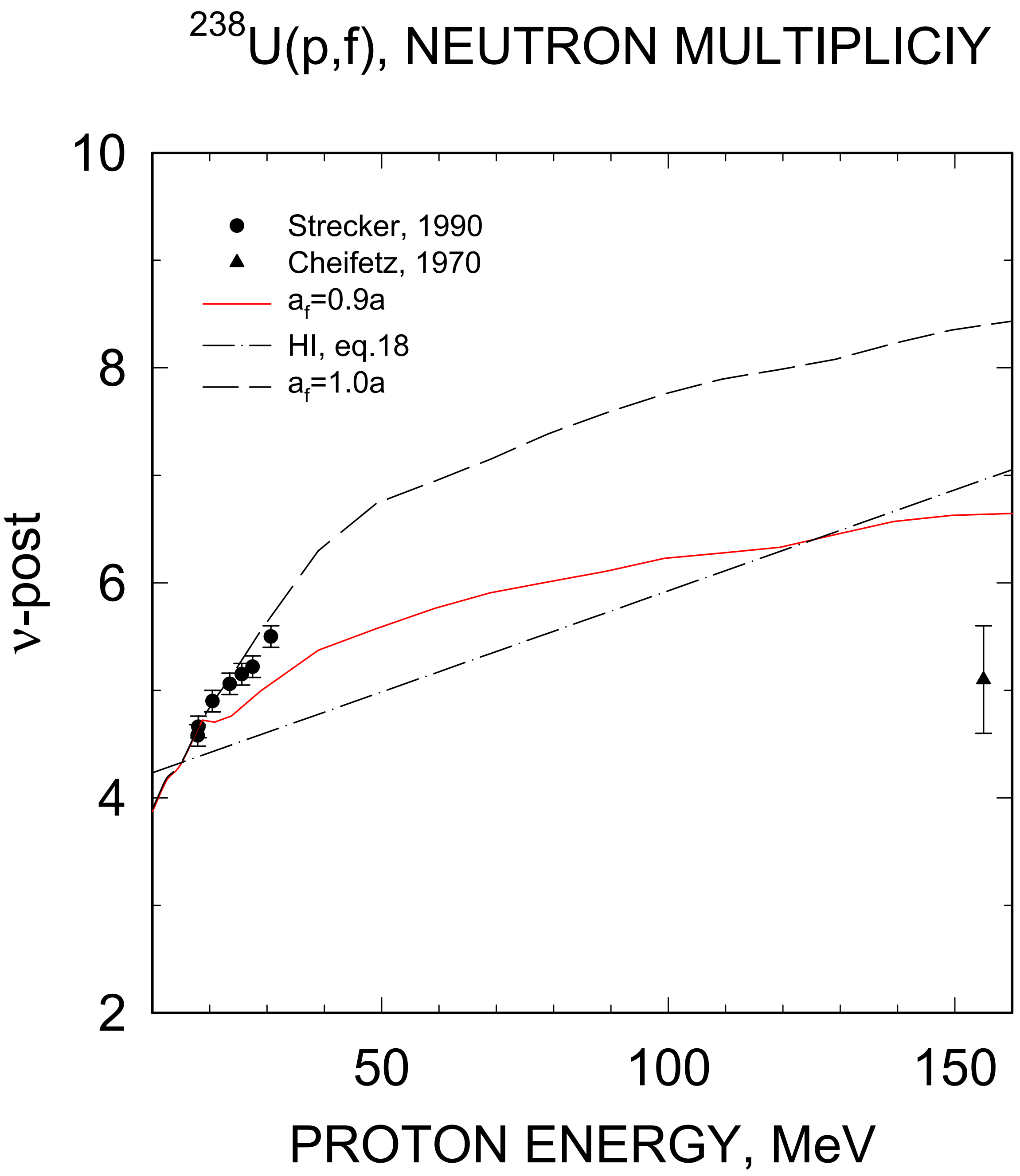

Fig. 19. The same as in Fig. 18 for post-fission neutron multiplicity. The experimental data [33] was corrected according to the following equation $\nu_{post}=\nu_{post\ exp}+\nu_{sc}$.

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