THE COMPARATIVE ANALYSIS OF DIFFERENT METHODS FOR SCISSION-NEUTRON COMPONENT EXTRACTION

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It is known that both spontaneous and slow neutron induced fissions are accompanied by the emission of prompt neutrons. Well established that most of them are evaporated from the fragments fully accelerated due to Coulomb interaction. However, some neutrons can appear directly at the moment of nucleus scission. It is shown that the quantitative estimation of the last component contribution may depend on the method of the experimental data processing.

The experimental data obtained in the process of n-f angular correlations study [1-4] are in a good agreement with the hypothesis of neutron evaporation from fully accelerated fragments. First of all this is confirmed by a strong correlation of the neutron's movement along fission axis as it is expected from kinematic consideration. The predominant registration of prompt fission neutrons in the direction of motion of light or heavy fragments certainly indicates that significant part, if not all of them, evaporates from fully accelerated fragments. Moreover, the neutron energy spectra, measured for different angles with respect to the direction of light fragment motion, correspond to this hypothesis also. Nevertheless, some neutrons can appear directly at scission of nucleus. There is a real difficulty to separate them experimentally from the post-acceleration component, because contrary to light-charged particles, scission neutrons are not focused by the Coulomb field of the nascent fragments. To distinguish them from the neutrons emitted after fully acceleration of fission fragments, the difference in the angular and energy distributions is normally used.

In the article [4] it is possible to see the example of experimental data obtained in slow neutron induced fission for ^{235}U and ^{233}U targets. The figure 4 of this paper shows the neutron yields as a function of the angle between neutron flight direction and the direction of motion of the light fragment. It means the direction of light fragment motion corresponds to 0°. For this direction a part of neutrons emitted from the heavy fragment is very small and total spectrum is quite close to the neutron spectrum produced by the light fragment. On the other hand at 180° the contribution of neutrons from the light fragment is negligible and the neutron spectrum is shaped by the heavy fragment (see figure 2 from [4]).

Since the contribution of neutrons, which come from the complementary fragment at 0˚ and at 180˚ in laboratory system, is so small, the entire spectrum of neutrons for each of these directions can be attributed in a first approximation to one fragment. It is possible to convert both these energy spectra to the center-of-mass (CM) system for light and heavy fragment, respectively, using Jacobian of transformation.

Then, if we consider a small fraction of neutrons detected from the complementary fragment, these spectra can be defined more precisely due to an iterative process. One can introduce also an anisotropic angular evaporation of neutrons in the CM system for each fragment. This anisotropy is connected with a large fragment spin, which appears close to the breaking point [5–7]. The result of the model calculation for the energy dependence of this anisotropy on energy of evaporated neutron is presented in [8].

On the basis of neutron spectra obtained in the fragment CM systems one can calculate neutron spectrum for any angle θ_{lab} in the laboratory system of reference:

$$N(E_{lab},\mu_{lab}) = N_L(E_{lab},\mu_{lab}) + N_H(E_{lab},\mu_{lab}), \qquad (1)$$

where the neutron spectra for light and heavy fragments separately can be written as:

$$N_{L(H)}(E_{lab},\mu_{lab}) = \varphi_{L(H)}(\mu_{cm}) \cdot \Phi_{L(H)}(E_{cm}) \cdot D, \qquad (2)$$

here E_{lab} – the neutron energy measured in laboratory system of reference,

$\mu_{lab} = \cos(\theta_{lab})$ and $\mu_{cm} = \cos(\theta_{cm})$;

$\Phi_{L(H)}(E_{cm})$ – the energy spectrum of neutrons in the reference frame for fragment CM;

$\varphi_{L(H)}(\mu_{cm}) = (1 + bP_2(\mu_{cm}))$ – the angular distribution of neutrons in the fragment CM-system;

D – Jacobian of transformation.

Let E_V be kinetic energy per nucleon for the fission fragment, then we get the relations:

$$\mu_{cm} = \frac{\mu_{lab}\sqrt{E_{lab}} - \sqrt{E_V}}{\sqrt{E_{cm}}} \qquad (3) \qquad\qquad E_{cm} = E_{lab} + E_V - 2\mu_{lab}\sqrt{E_{lab}E_V} \qquad (4)$$

The mass distribution of fission fragments has peculiar form that allows to speak about well distinguished two groups - light and heavy. If during experimental data processing we apply approximation and use for each of these groups the average weight and fixed final velocity of the fragments, the Jacobian takes a very simple form:

$$D = \begin{vmatrix} \dfrac{\partial E_{cm}}{\partial E_{lab}} & \dfrac{\partial E_{cm}}{\partial \mu_{lab}} \\ \dfrac{\partial \mu_{cm}}{\partial E_{lab}} & \dfrac{\partial \mu_{cm}}{\partial \mu_{lab}} \end{vmatrix} = \sqrt{\frac{E_{lab}}{E_{cm}}} \qquad (5)$$

The estimations show that this approximation is quite reasonable and greatly simplifies the calculations [9, 10].

In such a way (1) calculated spectrum can be compared with the experimentally measured spectrum corresponding to the same angle. Integral amount of neutrons for each angle of measurement can be also calculated and compared with experimental data too.

It turns out that neutron yields and neutron spectra calculated in this way for different angles are in a good agreement with experimental data. Nevertheless, it is necessary to mention that in the region close to 90° there is some excess of experimentally registered neutrons in comparison with calculated neutron yields. Such a discrepancy is usually explained by the presence of an additional component, which is associated with the neutrons emitted at the moment of nucleus rupture. The large velocity of fission fragments does not influence on this part of neutrons and to a first approximation they can be considered as isotropically distributed in the laboratory frame of reference.

For a finding of the scission neutrons contribution in a fission process not only the neutron-fragment angular correlations is possible to use but also neutron-neutron coincidences can be applied to determine the conditions of prompt fission neutrons emission [11-13]. Recently in

PNPI was performed a precise measurement of the angular dependence of n-n coincidence count rate in spontaneous fission of ^{252}Cf [14]. This experiment is certainly credible, because here the analysis of experimental data was particularly careful performed.

Evidently, to get true parameters of scission neutrons it is extremely important to obtain the experimental angular distributions free from systematic errors. The special attention in this work was paid to studying of the possible effects which can distort the experimental distributions (neutron scattering in the fission source and other surrounding materials, “cross-talks” between neutron detectors, etc.). The series of control experiments together with their cross-check by Monte-Carlo simulations allowed us to estimate the final uncertainty of the resulting experimental n-n angular distribution on the level of 1%.

The coincidence count rates obtained in this experiment for different angles between neutron detectors were integrated over directions of fragment motion and over the neutron energies. The necessary input parameters for the Monte-Carlo calculations of such coincidences were obtained from the other experiments and fixed. There were: the data for energy spectra of neutrons in the fragment CM system; the average multiplicity and dispersion of emitted neutrons from each fragment together with the covariance parameter. The last parameter allowed us to maintain a proper ratio of evaporated neutrons from light or heavy fragment in each fission event. In addition to the above parameters the most probable final velocities of light and heavy fragments were introduced and fixed. We had also two fitting parameters, which determine the contribution of scission neutron component and their spectrum shape. It was supposed that the form of this component corresponds to Weisskopf distribution.

Using all of these parameters we have calculated the number of n-n coincidences for various angles between detectors, taking into account seven different neutron energy thresholds. The comparison of calculated results with the experimental data, obtained in PNPI, allowed us to determine the most probable contribution of the isotropic component associated with so-called "scission" neutrons. This share was estimated as (8±2)% with averaged neutron energy 2.4 MeV. The result was presented at ISINN-20 [14].

Unfortunately, the estimations of this contribution performed by different authors are not in agreement even for the same dividing nucleus. Although the result [14] is in an acceptable accordance with the conclusion [15] but they both are very different from the evaluation of this component in spontaneous fission of ^{252}Cf, which was made by Budtz-Jørgensen&Knitter [2] and their followers [16]. It seems that this result is strongly dependent on how the experiment was performed and on the method of its processing.

The data obtained in the experiment of Budtz-Jørgensen&Knitter were analyzed event by event. At first glance, these measurements have a great advantage in comparison with [1, 4, 14, 15] because in this case the simplifying of data processing associated with the introduction of two fragment groups was eliminated. In contrast to above mentioned investigations Budtz-Jørgensen&Knitter have taken into account actual masses and velocities of the fragments. The experimental set-up, which was used by these authors, allowed them to determine for each fission event 6 quantities: two fragment energies $E_{L,H}$, two fragment masses $A_{L,H}$, neutron energy E_n, and its emission angle θ_n.

The complete experimental determination of all kinematic parameters allows then to deduce the neutron spectrum in the center-of-mass system of fission fragment. However, as the authors note, this transformation is not straightforward, because at each angle only the sum of contributions from the two fragments is observed. Thus an initially unknown contribution from complementary fragment must be subtracted. Fortunately this correction is small.

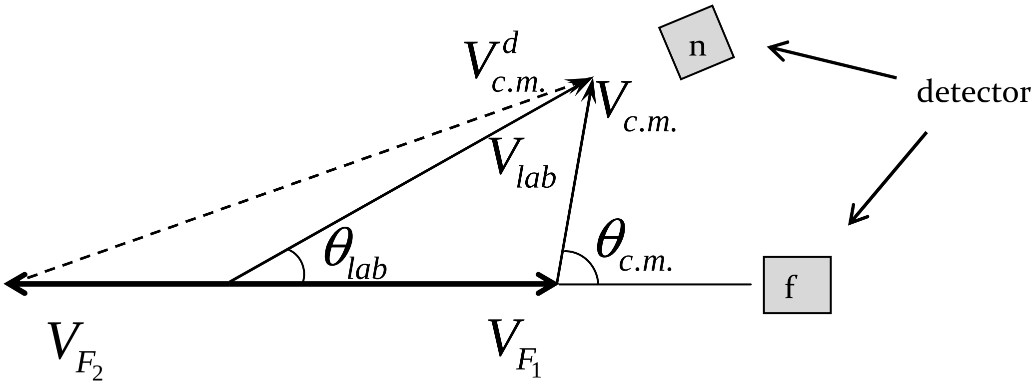

Fig.1 The reaction kinematics: V_{F_1}, V_{F_2} - the velocities of detected fission fragment and complementary fragment, respectively; V_{lab} - the neutron velocity measured in laboratory system; $V_{c.m.}$ -the neutron velocity in case of its evaporation from the first fission fragment; $V_{c.m.}^d$ - the neutron velocity in case of its evaporation from complementary fission fragment.

The figure 1 shows the kinematics of the neutron evaporation from the moving fragment. In the works [2, 16] it was assumed that only neutrons from the fragments flying into the hemisphere facing the neutron detector are detected. The neutron center-of-mass velocity $V_{c.m.}$ is then given by the observed laboratory-system quantities:

$$V_{c.m.}^2 = V_{F_1}^2 + V_{lab}^2 - 2V_{F_1}V_{lab}\cos\theta_{lab}\,. \tag{6}$$

Since neutron emission in the fragment center-of-mass system is symmetric about 90° the following analysis was restricted to the case:

$$0° \le \theta \le 90°\,. \tag{7}$$

This condition implies that only such events were included in the analysis:

$$V_{lab} \ge V_{F_1} / \cos\theta_{lab}\,. \tag{8}$$

Neutrons, for which this equation is realized, must be emitted with laboratory energies that are larger than the minimum fragment energy per nucleon. Furthermore, the larger in laboratory system the deviation of a neutron from the fragment's moving direction is the larger neutron energy must be.

Due to analysis of such a way selected events the authors of discussed article have got the angular distribution of neutrons in the reference frame of the fragment center-of-mass. The result of this analysis can be seen in the figure 2. Here is the copy from the above mentioned article. Evidently, the energy and angular distributions of neutrons in the CM system of the fragment, which are shown in this figure, belongs to the fragment not with a specific mass but with the average one. Thus, there is not even a separation into two groups of fragments: light and heavy. However, using namely these figures Budtz-Jørgensen and Knitter make the conclusion that the overwhelming part of neutrons is emitted isotropically from the fully accelerated fragments and the influence of scission component is negligibly small up to 10 MeV neutron energy in the fragment center-of-mass system.

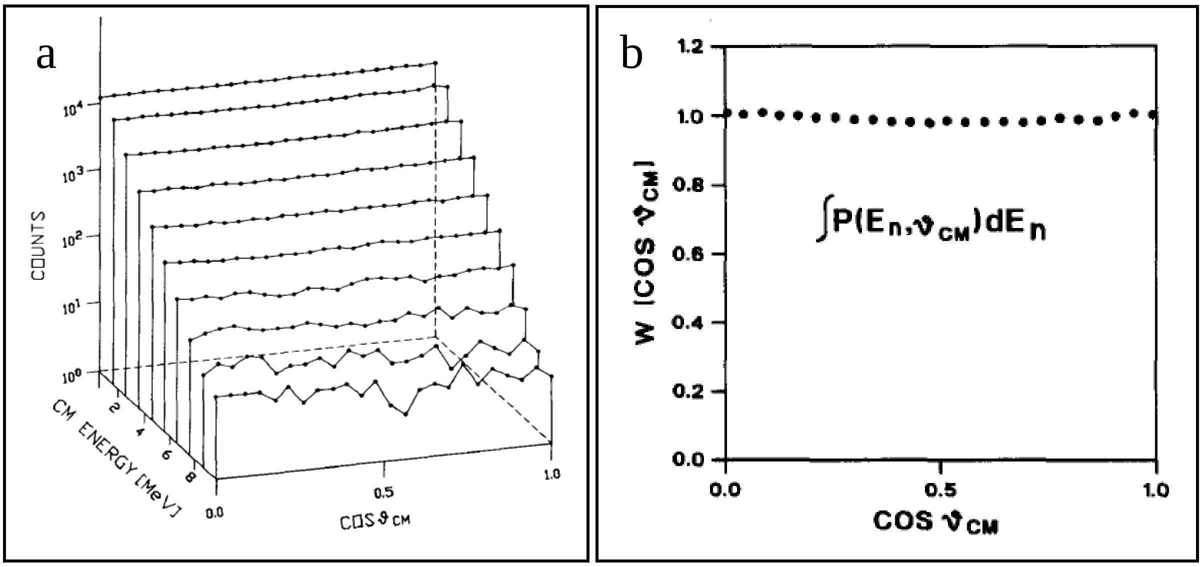

Fig.2. a) Fission neutron angular distribution as a function of fragment center-of-mass fission neutron energy; b) Fission neutron angular distribution in the fragment center-of-mass system integrated over all neutron energies.

Let us assume that the contribution of scission neutrons is about 8%, what corresponds to our estimation [14] of this component due to n-n correlation experiment. What figures would be getting by the authors of articles [2, 16] in this case? Could they distinguish with the help of their method scission neutrons from the neutrons emitted by the moving fragments, as well as observe the neutron emission anisotropy? The figure 3 demonstrates the angular dependences of neutron yields, which were calculated by Monte-Carlo method for both sides of fission fragment with the averaged mass and for scission neutron component.

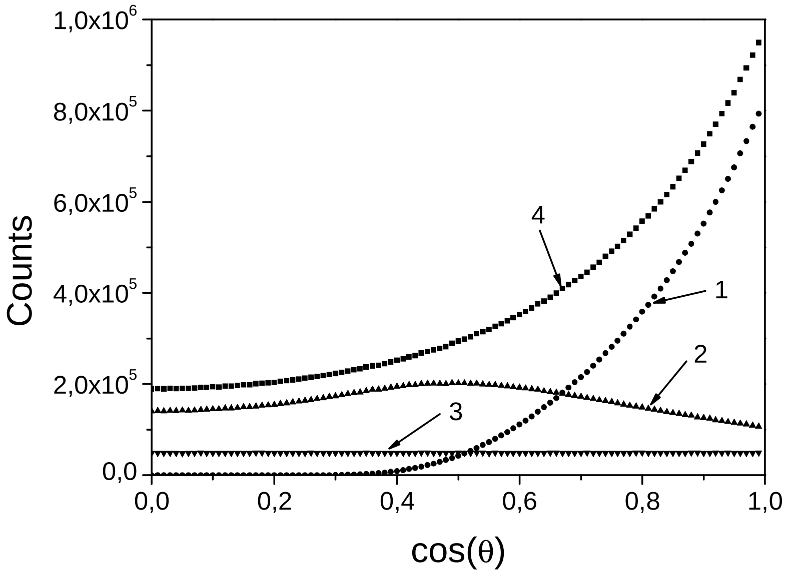

Fig.3. The angular dependences of neutron yields: 1 - the neutron emission from the forward side of fission fragment; 2 - corresponds to the neutron emission from the backside of fragment; 3 – describes the scission neutron component; 4 - the sum of all previous components.

The aim of Budtz-Jørgensen and Knitter analysis is to take into account only neutron emission from the forward side of fission fragment, it means the events belonging to the curve marked by 1 in the figure 3, and transform these events to the neutron spectrum in the fragment CM system. It is possible to agree with this fact, taking into account the symmetry of the neutron emission from the both sides of the fission fragment in his CM system. Together with these neutrons some part of events corresponding to scission neutron component will satisfy above mentioned condition (8) and should be included into consideration (see the figure 4).

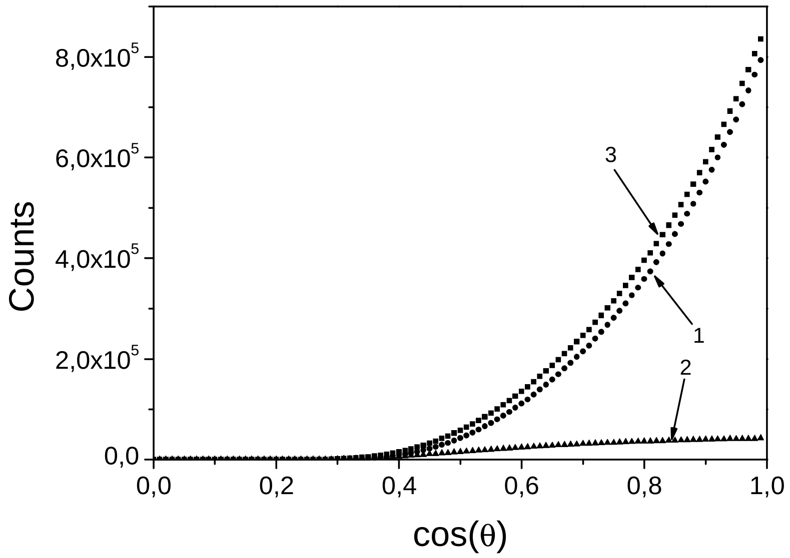

Fig.4. The result of Monte-Carlo calculations for angular dependences of neutron yields in the laboratory system: 1 - the neutron emission from the forward side of fission fragment; 2 - the part of scission neutron events which satisfy the mentioned condition (8) for neutron velocities; 3 - the sum of two previous curves.

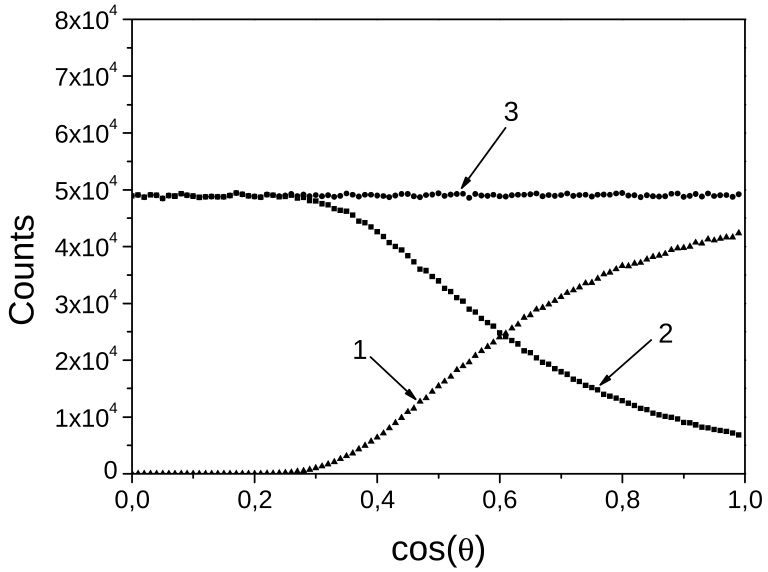

Fig.5. The result of Monte-Carlo calculation for angular dependence of neutron yields in the laboratory system of reference: 1 - the scission neutron events which satisfy condition (8); 2 - the scission neutrons which do not correspond to condition (8); 3 - all scission neutrons.

Nevertheless a sizeable part of this component close to 90° will have insufficient speed to match the condition (8) and will be ignored (the figure 5). It should be paid special attention to this fact because the use of such condition leads to a significant reduction of the share for scission neutrons, while the neutrons emitted by the front part of the fragment will be taken into consideration in full. Also, let me remind you that the analysis of n-f [1, 4, 8, 15] and n-n angular correlations [13, 14] was not finished at getting of the neutron spectrum for the moving fragment center-of-mass. On the base of such spectra for light and heavy fragments the neutron yields were calculated for different angles in the laboratory frame of reference and then they were compared with experimental values, without excluding any event of neutron emission. Note that particularly sensitive to the presence or absence of «scission» component is the range of angles close to 90 degrees, which in the works in question was excluded from the consideration at all.

Using the condition (8) in the experimental data processing, the authors [2, 16] have reduced the sensitivity of the experiment for the presence of scission neutrons, because they have eliminated a significant part of these neutrons. Budtz-Jørgensen&Knitter and their followers have concluded the absence of appreciable amount of scission neutrons on the basis of an isotropic distribution of neutrons in the fragment CM system (flat curves). Generally speaking, the isotropic emission of neutrons in the fragment reference frame is not essential condition of neutron evaporation. There is a reasonable opinion about the anisotropic distribution of prompt neutrons in the fragment center-of-mass system, caused by the large spin of fission fragment [5]. This phenomenon leads to the preferential emission of neutrons along the fission axis (the curves 1, 2, 3 in the figure 6), while the presence of a certain contribution of scission neutrons (the curve 4) could somewhat offset the first effect. The aggregate result, which is represented by the curve 5 of this figure, looks like the curve of Budtz-Jørgensen&Knitter in the figure 2b and insignificantly differs from the horizontal one. Very likely, the authors [2, 16] have described their curves through the underestimation of both factors: the anisotropy of neutron emission in the fragment CM system and the contribution of the scission component.

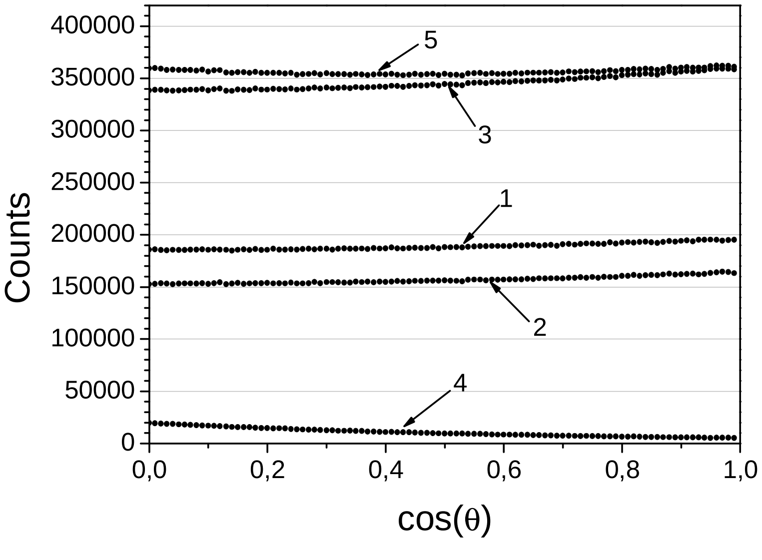

Fig.6 The results of calculations for the angular dependence of the neutron emission in the fragment CM: 1, 2 – describes the neutron emission from the forward side of light or heavy fragment, respectively, and 3 is their sum; 4 – scission neutrons, which were taken into consideration after the application of condition (8); 5 – the total amount of neutrons.

Recognizing the existence of all other advantages of Budtz-Jørgensen's work it is necessary to mention that in such a way organized data analysis is not sensitive enough to the magnitude of the scission component contribution as well as to the possible anisotropy of the neutron emission in the CM system of fission fragment. A similar opinion has been expressed already by the authors of the article [10], who have re-analyzed the experimental data obtained in [2] and have found a nonzero contribution of scission neutrons component.

It is important to note that the correct understanding of fission neutrons emission is possible only with the consideration of the anisotropy of their evaporation in the CM system for each fragment. New experiments started in PNPI, as well as experiments performed by our colleagues from ITEP, may contribute to achieve this goal. They are devoted to the studying of the ROT-effect for neutrons and gamma-rays accompanying fission [17]. The one of the necessary condition for this phenomenon is the presence of the already mentioned anisotropy.

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