भारी-आयन प्रेरित नाभिकीय विखंडन

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आवेशित कण का उपयोग करके भारी-आयन प्रेरित विखंडन में उत्कृष्ट विशेषताएं

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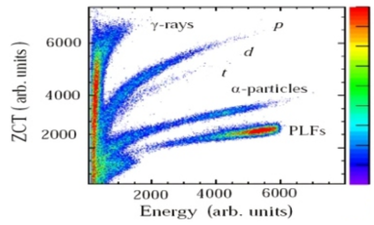

सीएसआई(टीएल) संसूचक में कण पहचान

सारांश

त्वरक और यंत्रीकरण प्रौद्योगिकियों में प्रगति के साथ, नाभिकीय भौतिकी अनुसंधान मानव जिज्ञासा को शांत करने के लिए भौतिक विज्ञान क्षेत्र के हॉटस्पॉट क्षेत्रों में से एक बना हुआ है। नाभिकीय चार्ट के विभिन्न क्षेत्रों की खोज समकालीन नाभिकीय भौतिकी अनुसंधान के प्राथमिक केंद्रों में से एक है। अतिभारी तत्वों संश्लेषण और बाहरी नाभिक के ज़मीनी अवस्था गुणधर्मों का अध्ययन समकालीन दौर में प्रमुख रूप से अग्रणी हैं। हम मुंबई में भापअ केंद्र-टीआईएफआर त्वरक सुविधा से स्थिर किरणपुंजों का उपयोग करके प्रयोगात्मक नाभिकीय भौतिकी कार्यक्रमों को आगे बढ़ाते हैं। विखंडन और विखंडन जैसी प्रक्रियाओं की अनुसंधान के साथ सीधी प्रासंगिकता है। अनुसंधान के अलावा, विखंडन प्रक्रिया सीमित नाभिकीय पदार्थ; नाभिकीय श्यानता के मौलिक गुण के बारे में अध्ययन की सुविधा भी प्रदान करती है। नाभिकीय श्यानता के बारे में कई सवाल अभी भी अनुत्तरित हैं। विखंडन प्रक्रिया के दौरान कण उत्सर्जन एक संभावित जांच प्रस्तुत करता है जो नाभिकीय श्यानता और पूरी विखंडन प्रक्रिया के प्रति भी संवेदनशील है। भापअ केंद्र-टीआईएफआर पेलेट्रॉन सुविधा में चल रहे हमारे कार्यक्रम से नाभिकीय विखंडन के बारे में कुछ नए पहलुओं पर हाल के प्रेक्षण यहां प्रस्तुत किए गए हैं।

Heavy-Ion Induced Nuclear Fission

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Novel Features in Heavy-ion Induced Fission using Charged Particle Emissions

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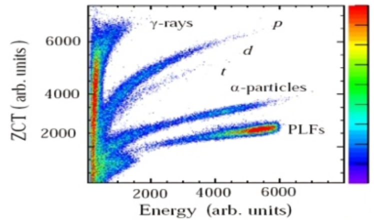

Particle identification in CsI(Tl) detectors.

ABSTRACT

With advancements in instrumentation & computation technologies, nuclear physics research continues to be one of the hotspot fields in physical science domain to quench the human curiosity. Exploring different regions of nuclear chart is one of the primary foci of contemporary nuclear physics research. We pursue experimental nuclear physics research using BARC-TIFR Pelletron Linac Facility (PLF) at Mumbai. Fission and fission like processes have direct relevance to research pertaining to super heavy elements synthesis. Fission process also facilitates study about a fundamental property of finite nuclear matter; nuclear viscosity. Several questions about the nuclear viscosity are still unanswered. Particle emission during the fission process presents a potential probe to study entire fission process and nuclear viscosity. Recent observations on some novel aspects about nuclear scission from our ongoing program at PLF are presented here.

KEYWORDS: *Nuclear physics research, Super Heavy Elements, Fission, Viscosity, Scission.*

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Introduction

Despite the substantial advances in the field of nuclear physics, certain subtle aspects still remain unresolved. The neck rupture process during the nuclear fission is one of them. It is a fascinating example of a delicate interplay of nuclear and Coulomb forces. Particle emission near the scission stage can provide valuable insights about the neck rupture process. Fission Physics Section (FPS) of NPD is pursuing research activities at PLF to understand the finer details of the heavy-ion induced fission process using charged particle emissions during the fission.

Fission of an atomic nucleus provides an opportunity to learn about the properties of nuclear viscosity. Understanding about the precise nature of the nuclear viscosity (one-versus two-body) and its dependence on temperature and coordinate space (deformation) is still quite unclear [1, 2]. During fission, the finite nuclear matter undergoes through a steep potential gradient. As debated earlier in the literature, the energy dissipation at the scission stage might be quite different than just before it [3, 4]. The rapidly moving potential walls might justify suitability of one-over two-body viscosity near to the scission point [1, 2]. A clear understanding about the nuclear viscosity at such a nascent stage is of fundamental importance, in particular with varying temperature.

The overall study of fission dynamics can be divided in the two energy regimes; (a) Low energy fission (spontaneous-, thermal-neutron induced, photo-fission) and (b) heavy-ion induced fission which populate compound nucleus at an elevated temperature.

In the low energy fission, it is widely accepted that the neck rupture is quite sudden [5, 6]. Yield of various Light Charged Particles (LCPs) has been measured in the low energy fission [5,6]. It is seen that among various LCPs, α-particle emission near the scission stage is the dominant one. Historically, in the low-energy fission these α-particles are also known as Long Range α particles (LRAs) [7].

The LRAs are preferentially emitted perpendicular to the fission axis, also known as "Equatorial Emission (EE)" [8]. In the low energy fission, a very small fraction is also emitted along the fission axis, referred as the "Polar Emission (PE)" [8-11]. For Z=1 particles, total yield for each is much lesser than α particles, however, their relative intensities are greater in PE than EE [8, 9]. The difference is striking for the case of protons, where PE component is observed to be around twenty times of that of EE component [9]. On the other hand, in heavy-ion induced fission, except for α particles, none of the other near-scission emissions has been observed so far.

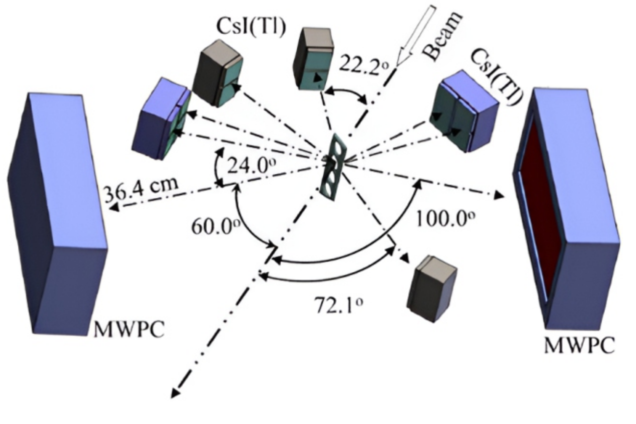

Fig.1: A schematic diagram of the experimental setup, consisting of a target ladder, two MWPCs, and a large number of CsI(Tl) detectors.

Disentangling of Near Scission Emission (NSE) particles in heavy-ion induced fission is quite challenging task due to presence of emissions from different stages. In heavy-ion induced fusion-fission, particle emission takes place continuously; from the onset of the fusion process to the stage where produced fission fragments have attained their asymptotic velocities. Other than the near scission emission, the rest could be categorized into two major groups, namely emissions from the fully equilibrated compound system (pre-scission) and from the fully accelerated fission fragments (post-scission) [12-16]. A systematic study of different particle emissions from different stages can provide valuable insight about the fission dynamics.

Heavy-ion induced fusion-fission plays a crucial role in reaching to the island of stability in the super-heavy mass region [17, 18]. Unravelling the very presence of non-equilibrium with respect to several degrees of freedom pertaining to heavy-ion induced fission is utmost important. Mass distributions, angular distribution, mass-angle correlation, and kinetic energy distributions of fission fragments (FFs), often deviate from the expected decay of an equilibrated compound nucleus in heavy-ion fusion reactions [19]. These deviations indicate about the presence of Non-Equilibrium (NEQ) fission. Over the years, "quasi fission" [20-22], pre equilibrium fission [23-26]", and slow quasi fission [27,28]" have been associated with NEQ fission. But, it is not well established whether the underlying mechanisms are different or they originate from a common dynamic source. Charged particle multiplicities in heavy-ion induced fission could be instrumental in inferring the subtle presence of a NEQ. In this newsletter, we present results on various aspects of fission dynamics obtained from measurements of charged particle energy spectra in coincidence with fission fragments at different relative angles.

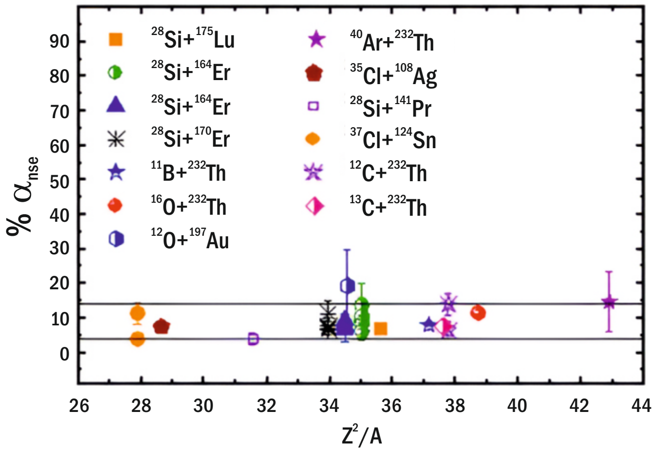

Fig.2: Fraction of near scission multiplicity of alpha particles as a function of fissility parameter.

Experimental Techniques

Experiments have been performed using the heavy-ion beams from Pelletron-Linac Facility (PLF). A schematic diagram of the typical experimental setup is shown in the Fig.1. Gas based detectors such as the Multi-Wire Proportional Counters, or ionization chambers have been used for detecting the fission fragments. CsI(Tl) detectors placed at different angles with respect to beam direction have been used for measuring the energy spectra of charged particles. In order to ensure a coincidence, time correlations are recorded between charged particles and fission fragments. CsI(Tl) detectors are energy calibrated periodically throughout the experiments using ^{229}Th source. The energy calibration in the full energy regime for protons as well as α particles is achieved using the techniques as outlined in the Refs. [29,30].

Particle identification is achieved using a pulse shape discrimination (zero crossover) technique. The gamma rays, light charged particles (p, d, t, and α), and PLFs are well separated in the two-dimensional plot of zero crossover versus pulse height [13, 29-31]. The time correlation between light particles and FFs is recorded through a time-to-amplitude converter (TAC). The event trigger for data collection is generated with the fission events from the gas detector.

Data Analysis & Results

Charged particle multiplicity spectra are obtained at different relative angles with respect to beam direction and the scission axis by dividing the energy spectra with fission-singles events. Typically, one billion fission singles events are collected for each measurement. Depending on relative angles, each spectrum includes different contribution for different particle emission stages. A Moving Source Disentangling Analysis (MSDA) is employed to determine contributions from different emission stages. Measurements have been performed for several reactions, major highlights of the results are as follows;

Changeover in neck-rupture process with energy

In low energy fission, a large fraction of particle emission take place near the scission stage (NSE) [6]. From different observations of NSE, it is widely accepted that the neck rupture is quite sudden in low energy fission [5, 6]. On the other hand, at elevated temperatures from heavy-ion induced fission the absolute near scission multiplicity does not show any systematic trend. However, fraction of near-scission multiplicity is observed to be nearly the same at around 10% of the total pre-scission multiplicity for various systems over a wide range of Z^2/A and excitation energy [13, 15, 29, 32-36] as shown in the Fig.2. It is well established that pre-scission emission is statistical in nature. The constant fraction of near scission multiplicity irrespective of fissioning system and excitation energy clearly suggest that at higher excitation energies, the near scission emission is a statistical process [13]. Whereas it is a dynamical process in low energy fission. It is conjectured from here the neck rupture becomes slower in going from low energy fission to heavy-ion induced fission (high excitation energy); nuclear viscosity at the scission stage undergoes a changeover from very low to a high value in going from low to high temperatures. This conjecture appeared true for near-scission proton emission too [30]. Specific investigations to look for the point around which the transition from dynamical to statistical occurs, are of fundamental importance to pursue in future.

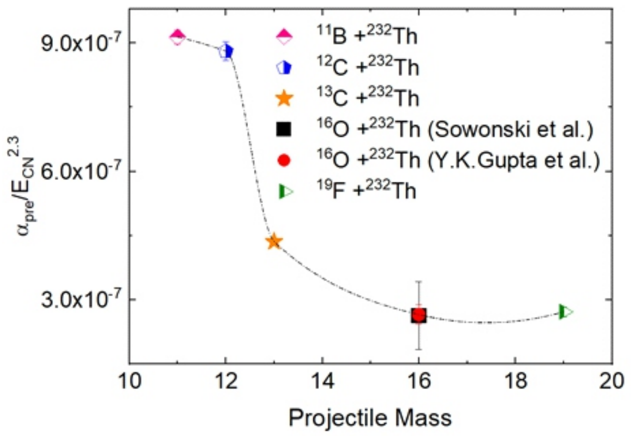

Fig.3: Normalized pre-scission alpha particle multiplicity as a function of projectile mass.

Signature of non-equilibrium fission

Using α_{pre} data of ^{11}B, ^{12,13}C, ^{16}O, and ^{19}F induced fission of ^{232}Th, a systematic study is carried out [13, 29, 31]. It is seen (Fig.3) that the α_{pre} makes a changeover from high to a very low value in going from asymmetric (^{11}B) to more symmetric (^{19}F) entrance channel [29]. The discontinuous behaviour in α_{pre} is similar to what has been observed earlier in angular anisotropy data [23], which was attributed to "pre-equilibrium fission". Using particle emission as a probe to understand the fission dynamics, a clear signature of non-equilibrium fission has been observed for the first time from α_{pre} [29]. However, such a discontinuous behaviour has not been observed for the pre-scission neutron multiplicity (ν_{pre}) data [37]. It is shown earlier that the vpre after normalizing with E_{CN} remains almost the same over a wide fissility range. Insensitivity of the ν_{pre} with respect to non-equilibrium fission has been observed in another work also. A transition to quasifission is clearly

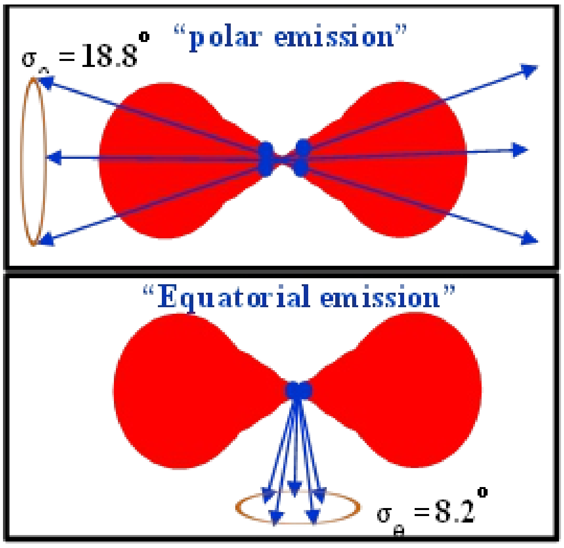

Fig.4: A schematic diagram of "polar" and "equatorial" emissions.

observed in ^{16}O + ^{238}U fission at beam energies just below the Coulomb barrier from fission fragment mass and angular distributions, however, the ν_{pre} does not show any discontinuity with decreasing beam energy. Present results demonstrate that α_{pre} could be a potential probe to gain further insight about the non-equilibrium fission. It would be of further interest to carry out measurements on α_{pre} using projectiles heavier than the ^{19}F bombarding on ^{232}Th in the similar excitation energy bracket as of the present work. Also, investigations are being made for ^{209}Bi target and varying projectiles.

Observation of near-scission "polar" and "equatorial" proton emission in heavy-ion induced fission

The proton multiplicity spectra were measured in coincidence with fission fragments at different relative angles in ^{16}O (96 MeV) + ^{232}Th reaction [30]. The multiplicity spectra were analysed within the framework of a Moving Source Disentangling Analysis (MSDA) to determine contributions from different emission stages. The MSDA conclusively shows "near-scission proton emission" as an essential ingredient in the proton multiplicity spectra. These near-scission proton emissions are observed to be focused parallel ("polar") and perpendicular ("equatorial") to the fission axis with similar intensities as depicted in the Fig.4. It is the first time that "near-scission proton emission" has been disentangled from other emission stages in a heavy-ion induced fusion-fission inevitable presence of "polar emission" in a heavy-ion reaction has been observed for the first time [30]. It is also observed that the pre-scission multiplicity for protons is one order of magnitude lesser than those of α particles. However, the near scission fraction of the proton yield is almost four times larger than the same fraction for α particles which is attributed to deformation effects of the fissioning nucleus. These results open up a new avenue for simultaneous investigation of different particle emissions in heavy-ion induced fission reactions with varying degrees of freedom.

Presence of direct reaction as a source of α-particle emission during fusion-fission process

We have measured the α-particle energy spectra in coincidence with FFs in the ^{12}C(69 MeV)+^{232}Th reaction at different relative angles with respect to FF direction [31]. The α-particle multiplicity spectra are fitted with the moving-source model to determine prefission and postfission components of α-particle emission. In this analysis, the near scission multiplicity is observed to be anomalously enhanced in comparison to the established heavy-ion systematics, indicating the presence of another source of α-particle emission in the ^{12}C+^{232}Th reaction in addition to pre-scission, post-scission and near-scission emission stages. In the two-dimensional particle identification plot, a high-energy component corresponding to the summed energy of two α particles is observed [31]. The observation of these 2α events suggests that, due to the α-cluster structure of ^{12}C, there is a significant component of ^{8}Be breakup followed by α-transfer-induced fission events. Since the α-transfer grazing angle for the ^{12}C(69 MeV) +^{232}Th system is at ~120°, the intensity of these 2α events dominates at the backward angles with respect to the beam direction. The analysis of 8Be breakup explains very well the 2α-particle multiplicity spectra at different laboratory angles. For the first time, a new component corresponding to the transfer-breakup process has been considered in the moving-source model to disentangle the different contributions to the inclusive α-particle multiplicity. Reanalysis of the α-particle multiplicity spectra including five sources in the moving-source model- the compound nucleus, both fission fragments, the NSE, and 8Be breakup, has been carried out.

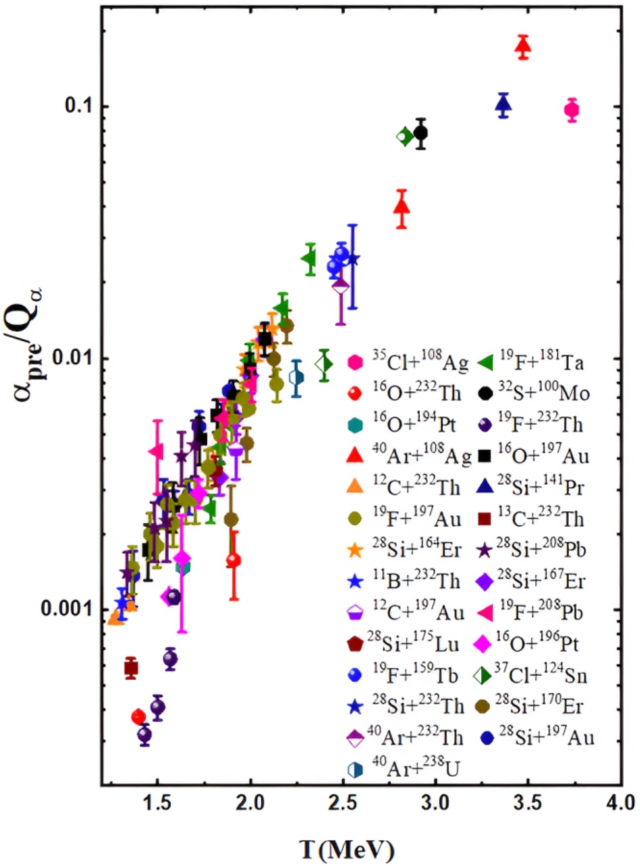

Fig.5: Normalized pre-scission alpha particle multiplicity as a function of compound nucleus temperature.

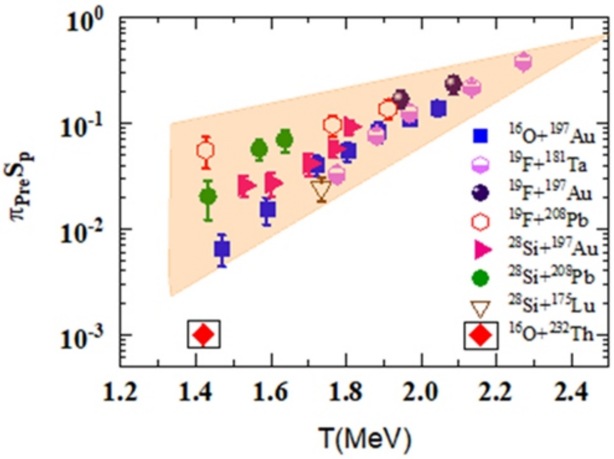

Fig.6: Normalized pre-scission proton multiplicity as a function of compound nucleus temperature.

The results obtained for pre-scission and near-scission multiplicities follow the recently developed heavy-ion systematics very well. The present results clearly indicate a possible extra source of α-particle emission in the α-cluster-projectile-induced fusion-fission reactions. The very presence of this transfer breakup source has been further verified by performing measurements at different beam energies and also using the ^{13}C projectile where α transfer results in ^{9}Be having a high threshold for breakup.

Global Systematics for pre-scission particle emissions

Pre-scission proton and α-particle multiplicity data have been compiled for a wide range of reactions. At first, the α_{pre} data were plotted as a function of compound nucleus temperature, T. The data show an overall increasing trend with increasing T. The α_{pre} at a given temperature deviate from single value and shows large spread. This spread reduces significantly if α_{pre} is normalized by α-particle emission Q-value (Q_α) as shown in the Fig.5. After normalizing α_{pre} with Q_α , one can note from the Fig.5 that cluttering of the data reduces quite significantly and increasing trend with increasing T becomes more robust. It shows that while looking at α_{pre} data globally encompassing a wide range of compound nuclear systems, the Q_α becomes important. In addition to increasing excitation energy and hence the nuclear level density of the residual nucleus, the larger Q_α also indicates about more pre-formation probability of the α-particle. One can note from the Fig.5 that even after correcting for the effects of Q_α, a certain spread in the normalized α_{pre} values at lower temperatures around 1.5 MeV remains. This spread is related to non-equilibrium fission as discussed earlier. Unlike to neutron and α--particle emission, the studies for other particles have been quite limited, primarily owing to their lower multiplicities. Proton-emission is the next candidate (charged particle) after α-particle emission which has been studied to some extent in heavy-ion induced fusion-fission. However, in the case of proton emission the background contribution to the energy spectra is significantly larger than the α-particle and neutron. The primary source of the background protons stems from direct reactions with hydrocarbon impurities deposited on the target during the experiments. Also enhanced random coincidences due to lower multiplicities contribute to the background. Amidst these difficulties, pre-scission proton multiplicity (π_{pre}) data have been reported only for a few number of heavy-ion induced fission reactions as shown in the Fig. 6.

Similar to pre-scission α -particle multiplicity data, the proton multiplicity (π_{pre}) data also exhibit a descent systematic behaviour after normalizing with proton separation energy (Sp) as shown in the Fig. 6. One can note from Fig. 6 that for a given temperature around 1.4 MeV, the π_{pre} value is noticeably smaller than the systematic trend in the case of ^{16}O + ^{232}Th reaction. It again reinforces the presence of pre-equilibrium fission as inferred from α_{pre} data [29].

Summary & Future Outlook

A program to study the fission dynamics using particle emission as a probe is being pursued at BARC-TIFR Pelletron Linac Facility (PLF). Experimental and data analysis techniques are briefly discussed. Recent observations on novel features of fission dynamics and nuclear viscosity are outlined. Further measurements to understand the fission dynamics from different perspectives will be performed at PLF. Specifically, measurements will be performed for different systems to establish the “polar” proton emission in heavy-ion induced fission. Experiments where event rates are quite small such as the measurement of mass gated particle and gamma multiplicities are envisaged. A Versatile Detector Array (VDA) is being developed at PLF to carry out above mentioned experiments.

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