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A Comparative Study of Multiplicity Distribution of Secondary Particles of Hadronic Interactions at Cosmic Ray Energy with Machine Range of Energy

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Abstract:

In thepresent work, some results are reported and the finding results are compared with the machine range of energy. The most fundamental observable in the multiple production processes in high energy is the multiplicity of secondary particles produced in hadronic interactions. When a projectile hadron interacts with emulsion nuclei, broadly two types of charged particles, known as heavy particles and shower particles are produced. The heavy particles are mostly protons, deuterons, tritons, and alpha particles. They form heavily ionized tracks inside the emulsion medium. Their multiplicity is denoted by "n_h". On the other hand, the shower particles are fast particles consisting mostly of pions and they form lightly ionized tracks inside the emulsion medium. Their multiplicity is denoted by "n_s". The multiplicity distributions of secondary particles have been analyzedin terms ofpseudorapidity variables for nucleon-emulsion interactions at different primary energy.Thefinding resultscan be used to test the prediction of different models.

Keywords:*Charged particle, Nuclear Emulsion, Pseudo-rapidity, Angular distributions.*

Introduction:

Nuclear emulsion is composed of gelatinwithalarge number of microcrystals of silver halide (generally AgBr with ~5% AgI) dispersed in it. A small amount of glycerol and a variable quantity of water is also present. Gelatin in the emulsion keeps the silver halide crystals well dispersed and prevents their clumping. The elements present in the emulsion are C, N, O, H and AgBr. A charged particle while passing through an emulsion medium interacts with the atoms in its path and its result becomes slow down. The range of the particle in the medium is defined as the total distance traversed by it before coming to rest. The energy of the particle can be determined from its range. The charged particle loses energy by transferring it to the atomic electrons encountered in its path. If sufficient energy is transferred, the electron is liberated and the atom is said to be ionized. It is this process that makes the silver halide grains respond to the developer which turns the grains black thus making them recognizable. Therefore, a chain of black grains represents the path of the ionizing particle through the medium. It is found that the charged particles which have energy in the relativistic region have low ionization and they give rise to shower tracks. Whereas the low-energy particles cause high ionization in the emulsion and hence they are known as heavy tracks. The secondary charged particles produced in nuclear emulsions due to nuclear interactions can be classified into the shower, grey, black, and projectile fragments based on their specific ionization. The shower particles are the singly charged relativistic particles having the grain density $\leq 1.4I_{o,}$ where I_o is the number of developed grains per 100μmof a minimum ionizing track. The grey particles are mostly recoiling protons arising from the intranuclear cascade process having the grain density $1.4I_o \leq b \leq 10I_o$ and a range ≥3mm in the emulsion. The black particles are the charged particles with grain density, $b \geq 10I_o$. The sum of the black and grey particles are called heavily ionizing particles. They are mainly target fragments and their multiplicity is denoted by n_h.

Thus, the nuclear emulsion is one of the earliestand suitable detectors for achieving good spatial resolution and high efficiency for the detection of secondary particles over the full solid angle range in high energy hadronicinteractions.When the projectile hadron interacts in the nuclear emulsion, with multiple nucleons inside the target nuclei, the development of the interaction process starts. And the multiple interactions suffered by the projectile hadron inside the target nucleus enable to use of the proton-nucleus interaction for comprehending the space-time development of hadronic interaction [1]. Further, the multiple interactions inside the target nucleus may lead toextremelyhigh energy densities. This is the result of creatinga quark-gluon plasma (QGP), especially in heavy-ion interactions [2-3]. The studies of high-energy nucleon-nucleus and nucleus-nucleus interactions are acting in the same way with the superposition of the individual interaction [4-5]. Thus, with the understanding of this concept nucleon-nucleus interaction process over the wide range of primary energies has been relied on. Investigation of nucleon-nucleus interaction during the past few decades has allowed establishing a series of model-independent features of nucleon-nucleus interactions useful for understanding, the multi-particle production phenomenon [6-8]. In the beam fragmentation region of hadronicinteractions,the internal quark structure of hadron with a nucleus forms a composite and inclusive spectrum of produced particles. This result makesaneffect related to the collective nature of the nucleus itself and with its quark-gluon structure.

The finding parameters of nucleon-nucleus interaction in recent years has been observed as weak dependence on the mass number of the particle of the incident projectile. Similarly, the multiplicity distributions of average shower particles have a weak energy dependencein nucleon-nucleon (N-N) interaction [9-12]. The investigation of the multiplicity distributions ofsecondaryparticlesand their dependence on the space-time development of nucleon-nucleon interaction enables us to test the different theoretical models [13-15]. The multiplicity distribution of charged particles and angular distribution of shower particles in nucleon-Emulsion interactions can well be described by the hydrodynamical model [9]. The parameterization of the angular distributions of shower particles produced in nucleon-emulsion interactions has been shown [18-19]. It is necessary to improve considerably the accuracy of the observational data and the variety of measured and characteristicsat higher incident energy for achieving further progress in the understanding of the multi-particle production.

The main objectives of the present studyare the analysis of the multiplicity distributions of secondary particles produced in hadronic interactions of cosmic ray nucleonemulsion nuclei and the finding results are compared with machine range of primary energy. The cosmic ray data provide a rare platform for studying hadronic interaction at ultra-high primary energies which is so far unattainable in man-made accelerators [20-21]. The predictions of the relevant theoretical models in the analysis and interpretation of cosmic ray data have been taken into considerations. Further, the distribution of shower particles of the cosmic ray data can be parameterized for the angular distributions, for the formation of intermediate states of hadronic matter preceding particle production [22-23].

Observational Data:

The data used for carrying out the present work are from the ICEF (International Co-operative of Emulsion Flight) raw data sheets [13] and the Chicago stack [14] which contain the data of cosmic ray interactions in the nuclear emulsion. We have analyzed a total of 580 events of nucleon-Emulsion (N-Em) nuclei interactions. We have followed the criteria propounded by Friedlander [10] for the selection of different types of events. Thus, we have classified the nucleon-Emulsion interaction events into the following categories depending on the number of heavy tracks (n_h) for each event:

1) the events with no heavy prong (n_h=0) are considered to be nucleon-nucleon (N-N) interactions and

2) the events with $n_h \geq 1$ may be considered as nucleon-nucleus (N-A) interactions.

The latter category of events is nucleon-nucleus interactions may be further classified into two distinct types:

i. The events with $2 \leq n_h \leq 5$ may be considered to be nucleon-nucleus N-A(light) interaction events. The N-A(light) interaction events are those events where the cosmic ray nucleon interacts with light nuclei (such as C,N,O group) of the nuclear emulsion nuclei.
ii. The events with $n_h \geq 9$ to be nucleon-nucleus N-A(heavy) interaction events [14]. The NA (heavy) interaction events are the events where the cosmic ray nucleon interacts with heavy nuclei (such as Ag, Br group) of the emulsion medium.
iii. The region $6 \leq nh \leq 8$ has been left out as the "kink region" or the "overlapping region" where the nature of the target nuclei is ambiguous.

The primary energy of the incident cosmic ray nucleon has been estimated by the E_{ch}-method [16] for the nucleon-nucleon (N-N) interaction events and the Bhowmik et al. method [17] for the nucleon-nucleus (N-A) interaction events.

The definition of true rapidity (Y) which has been used in the analysis of the multiplicity distribution of secondary particles is given by:

$$Y = \frac{1}{2}\ln\frac{(E+\mathrm{Pl})}{(E+Pt)} \quad \ldots\ldots\ldots (1)$$

in the laboratory frame. Here E and Pl are respectively the total energy and the longitudinal component of linear momentum of the secondary particle under study. Since the secondary particles are mostly pions with the almost constant transverse component of momentum (Pt~0.4 GeV/c), the true rapidity (Y) defined by (1) may be approximated, at very high primary energy, by the pseudorapidity, (η) given by:

$$\eta = -\ln\frac{tan\Theta}{2} \ldots\ldots\ldots (2)$$

where Θ is the degree of deflection or deviation from is straight trajectories of the incident projectile particle.

Observational Results and Analysis:

For carrying out the analysis of the cosmic ray data on nucleon-Emulsion interaction, the entire sample of 580 events has been classified into three categories according to the average primary energy estimates viz. $\langle E_p \rangle$=32.6 TeV, 15.44TeV and 9.50TeV respectively (1TeV=10^3GeV = 10^{12}eV). The average value of heavy particle and shower particles has been shown in Table 1. By examining Table 1, it is evident that while parameter $\langle n_s \rangle$ shows a weak increasing trend with primary energy, the parameter

$\langle n_h \rangle$for hadron emulsion and nucleon nucleus (light) and nucleon nucleus (heavy) interaction remains almost constant but independent of primary energy.A parameter, $<n_s>/D$ shows a slow dependence on the energy for the cosmic ray data. This feature is in excellent agreement with the corresponding feature in hadron-Emulsion interaction at the machine range of primary energies [19] and is in total agreement with the prediction of the theoretical models [9].

Table 1.Characteristics of the multiplicity distribution.

Energy TeV	<ns>em	D	$<n_s>/D$	<nh>em	<nh>AgBr	<nh>CNO	Ref.
32.6	22.94 ±1.51	14.24 ±0.20	1.61 ±0.11	7.97 ±0.40	15.15 ±0.50	2.05 ±0.20	Present work
15.44	21.69 ±1.00	14.20 ±0.19	1.59 ±0.09	7.49 ±0.49	15.08 ±0.20	2.02 ±0.10	Present work
9.50	19.48 ±0.59	12.62 ±0.28	1.57 ±0.40	7.38 ±0.20	15.01 ±0.28	2.01 ±0.20	Present Work
0.30	15.10 ±0.20	9.00 ±0.20	1.69 ±0.10	7.10 ±0.18	-----	-----	[12]
0.20	13.20 ±0.19	7.80 ±0.20	1.68 ±0.10	7.40 ±0.20	-----	-----	[4]

The ratio of the average secondary particles, <ns>created in nucleon-nucleus (N-A) interactions to the average secondary particle,$<n_{ch}>$ created in nucleon-nucleon (N-N) interactions is defined as anew parameter R_{em}. Taking into consideration the leading particle multiplicities α_A fornucleon-nucleus (N-A) interactions and the leading particle multiplicity $\alpha_H$fornucleon-nucleon (N-N) interactions, the parameter R_{em} is given mathematically by:

$$\text{Rem} = \frac{<ns> - \alpha A}{<nch> - \alpha H} \qquad \text{………. (3)}$$

It has been reported that the value of α_A for nucleon-nucleus interaction is 0.67 and the value of α_H fornucleon-nucleon interactions is 0.9. The parameter R_{em} defined above has been observed and getting a similar value nearly equal to 1.5 which is independent of energy.

Table 2.The values of the parameters $<N_s>$, R_{em}, α, D, and Δ for different types of hadronic interactions at different average primary energies.

Energy TeV	$<n_s>$	Rem	α	D	Δ	Ref.
32.6	22.89 ±1.50	1.59 ±0.50	0.18 ±0.07	14.24 ±0.02	197±2	Present Work
15.44	21.70 ±0.98	1.48 ±0.01	0.18 ±0.01	13.82 ±0.03	196±2	Present Work
9.50	19.39 ±0.58	1.45 ±0.07	0.17 ±0.01	12.61 ±0.01	185±3	Present Work
0.40	17.00 ±0.21	1.49 ±0.04	0.18 ±0.01	10.15 ±0.19	146±3	[22]
0.20	13.59 ±0.10	1.57 ±0.02	0.19 ±0.03	8.24 ±0.09	123±2	[4]

This ratio R_{em}, have been calculated separately for the three groups of energy categorized in nucleon Emulsion events of the cosmic ray data and we have found that the values of R_{em} maintain almost a constant value independent of primary energy. A similar result was also found in proton-Emulsion interactions at the 30-400GeV energy range [12,22].

If we write the relationship between R_{em}, and A as a power law of the form R_{em}, = A^{α}, where the value of the exponent on is such that:

$$(Rem)average = \Sigma_i P_i R_{em} = \Sigma_i P_i A^{\alpha} \qquad \ldots\ldots\ldots (4)$$

where P_i is the probability of an inelastic encounter in a target nucleus of mass number A, we have found that α =0.17±0.01, 0.18±0.01, and 0.18±0.01 for the three groups of events having primary energy $<E_p>$= 9.5 TeV, 15.4 TeV, and 32.6 TeV respectively. The nuclear mass numbers were calculated [22], by noting the fact that 71% of the nuclear interactions in emulsion are due to AgBr nuclei (39% in Ag, 32% in Br), 25% due to C,N,O nuclei. Thus, we obtain A≅73 for average emulsion nuclei A≅95 for AgBr nuclei, and A≅14 for C,N,O nuclei. The proton-Emulsion data [12] at 300 GeV primary energy provided the result α =0.19±0.10. Our result concerning the value of α for the cosmic ray nucleon-Emulsion interaction data is in total agreement with the aforesaid result of proton-Emulsion interactions at 300 GeV primary energy. Thus, we have found that the exponent α is independent of the primary energy. This energy-independent nature of α and the calculated value of α is shown in the prediction of the hydrodynamical model [9].

Statistical quantities of interest which characterize the deviation from a true Poissonian distribution are the dispersion D defined as $D =(<n_s^2>-<n_s>^2)^{1/2}$ and the deviation parameter Δ defined as $\Delta= (100 (D(<n_s>^{1/2})/-<n_s>^{1/2})$ [22]. The parameter Δ is a measure of percentage deviation from the Poissonian distribution. To examine quantitatively the deviation of the shower particle distribution of the cosmic ray data from a true Poissonian distribution we have calculated these parameters for the two groups of categorized events and the result is presented in Table 2. may be inferred that both the parameters D and Δ have slow dependence on the primary energy. The energy dependence of these parameters has already been investigated by several workers [4,12,22], of course in the accelerator domain of primary energy. Our results are consistent with those results in the accelerator region and thus, they bring out the fact that the shower particle distributions of the cosmic ray data are presently under the study of deviation from pure Poissonian distribution.

Multiplicity Distribution of Shower Particles:

The multiplicity distributions of the charged secondary particles (i.e., shower particles) have been analyzed in terms of the pseudorapidity variable η = -ln(tanθ/2), where θ is the space angle of a shower particle to the direction of the incident cosmic ray nucleon (proton). The angular distributions may be studied to the primary energy and the target size which have been shown respectively in Fig.1.

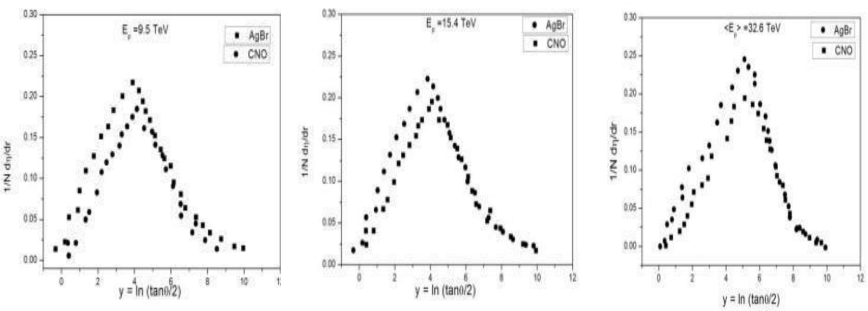

Figure 1.Pseudorapidity distributions of shower particles for nucleon-nucleus N-A(light) and nucleon-nucleus N-A(heavy) interactionsat the energies shown.The events are normalized to one.

Following the usual convention [7], the entire pseudorapidity space for the cosmic ray data may be divided into three regions:

(i) The pseudorapidityrange,wherey (≈η)>5 i.eProjectile fragmentation region (PFR).

(ii) The pseudorapidityrange,where $2 \leq y$ (≈η) 5, i.e, Pionization region (PR).

(iii)The pseudorapidityrange,where y (≈η) < 2, i.e. Target fragmentation region (TFR).

By examining Fig.1, it is evident thatthemultiplicity distributions of the shower particles for nucleon-nucleus light (CNO) interactions and nucleon-nucleus heavy (AgBr) interactions emerge asymptotically in the region of large rapidity values i.e., the PFR for all the three categorized groups of energy. This indicates that, at a given primary energy, the multiplicity distributions of the shower particles in the PFR are independent of the size of the target nucleus. Further, on close examination of the two plots in Fig.1 at different energies, we have found that the angle where the distribution peak appears is energy-dependent,thepeak is higher as energy increases and the angle is decreased with the increase of primary energy. Again, by comparing the angular distributions for the light and heavy group of nuclei i.e. Fig.1, we have observed the nature of the distributions are very similar forms in the three groups of energy. In the lower value of pseudorapidity, the peak value is higher for a heavygroup of nuclei. It has been shown physically that the particle production process is influenced only by the number of interactions of the incident particle with the target nucleus. Fig.2 shows the plots of the multiplicity distribution of the shower particles produced in cosmic-ray nucleon (proton) interaction events with light target nuclei (CNO group) and heavy target nuclei (i.e. AgBr group) for the categorized events of three energy groups. The figure shows that the distributions for both nucleon-nucleus (light) and nucleon-nucleus (heavy) are independent of energy in the small value of pseudorapidity that means in the targetfragmentationregion(TFR). Whereas beyond the pionization region the distributions for both types of interactions reveal the dependence of energy. As the energy increases the pseudorapidity value increases which shows the decreases of space angle and at some higher value both remain the same. Figure 3 shows the plots of the angular distributions of shower particles for hadron interactions at different star sizes (i.e., different n_h groups) for different primary energies.

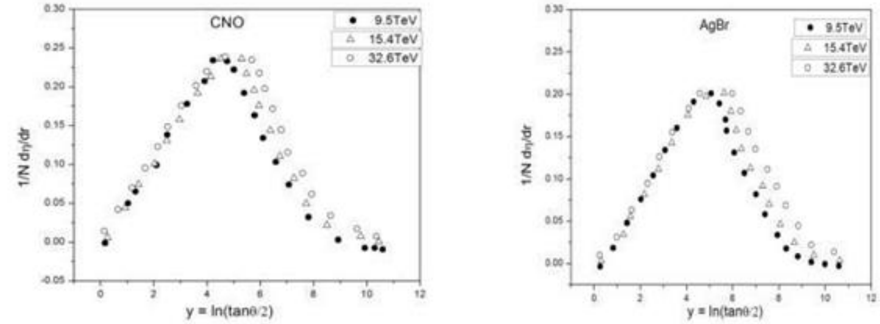

Figure 2.Pseudorapidity distributions of shower particlesat the three groups of energyfor nucleon-nucleus N-A(light) and nucleon-nucleus N-A(heavy) interactionsareshown.The events are normalized to one.

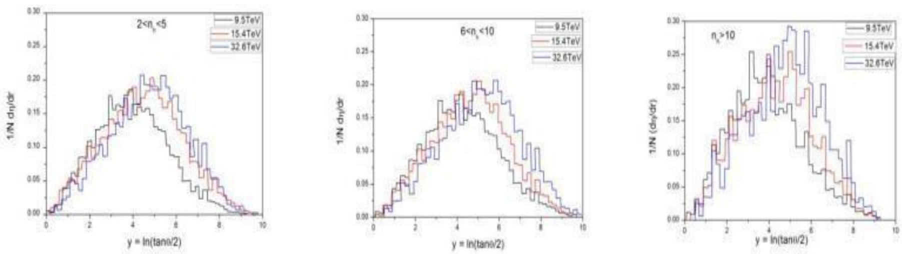

Figure 3.Pseudorapidity distributions of shower particles for hadron interactions at different n_h groups and different groups of primaryenergy.The events are normalized to one.The black, red, and blue lines are the ones indicated at primary energies 9.5 TeV, 15.4 TeV, and 32.6 TeV respectively.

The multiplicity distributions of the shower particles at a different group of $n_h$viz. 2≤nh≤5, 6≤nh≤10 and n_h>10, show that the similar behavior form has been seen in the lower value ofpseudorapidity,η<2i.e target fragmentation region (TFR). At the large value of pseudorapidity, i.e. the projectile fragmentation region (PFR), the dependence behavior of energy has shown. It can be observed that the excess of particles appears at higher energy and larger rapidity values i.e. at smaller space angles. The mean multiplicities of shower particles at the present considered energies having $\eta<\eta_o$and $\eta>\eta_o$, where η_o is taken to be 3 corresponding to the center of momentum rapidity of hadron emulsion interactionshave been given in Table 3. This shows that the mean multiplicities of the shower particles having η<3.0 remain independent of the incident energy, whereas the average multiplicity of shower particles having η>3.0 increases with increases of projectile energy. From table 4, it has been seen that the results obtained at 400GeV [Ref.22],300GeV [Ref.12], and 200GeV [Ref.4] for the sake of comparisons of the present work with those done at the accelerator data.

Table 3: Shower particle multiplicities at high cosmic ray energies

nh - Range	$\langle n_s \rangle$ at 32.6 TeV	$\langle n_s \rangle$ at 15.4TeV	$\langle n_s \rangle$ at 9.5TeV
Range of pseudorapidity (η) space or space angle Θ			
(i) η<3.0 (i.e. Θ >5.7^0)			
2≤nh≤5	17.6± 0.8	17.28±0.2	17.6±0.3
6≤nh≤10	19.1±0.8	18.9±0.7	18.7±1.0
nh>10	24.0±0.6	23.9±0.5	23.7±0.5
(ii) η>3.0 (i.e. Θ <5.7^0)			
2≤nh≤5	17.9±0.1	17.6±0.5	16.6±0.5
6≤nh≤10	27.4±0.2	21.0±0.3	18.8±0.7
n_h>10	32.0±0.8	31.5±0.5	30.5±0.8

The observed results are almost similarto the results obtained at machine energies (shown in Table 4). The values of the average angle of emission of the central particles have been found as 2.18°, 0.62°, and 0.43° for the group of events having energies $\langle E_p \rangle$=9.5 TeV, 15.4 TeV, and 32.6 TeV respectively. Thus, there is a tendency of decreasing the angle of emission with the increase in primary energy. These observed features with the cosmic ray data are in agreement with the ones observed with accelerator data [4,12,22].

Table 4: Shower particle multiplicities at machine energies using refs

nh - Range	$\langle n_s \rangle$ at 400GeV [Ref.22]	$\langle n_s \rangle$ at 300 GeV [Ref.12]	$\langle n_s \rangle$ at 200GeV [Ref.4]
Range of pseudorapidity (η) space or space angle Θ			
(i) η<3.0 (i.e., Θ >5.7^0)			
2≤nh≤5	5.8± 0.2	5.9±0.3	5.8±0.4
6≤nh≤10	8.6±0.3	8.0±0.6	8.0±0.7
n_h>10	13.73±0.3	13.7±0.8	13.6±1.0
(ii) η>3.0 (i.e. Θ <5.7^0)			

2≤nh≤5	7.7±0.3	7.1±0.4	4.7±0.3
6≤nh≤10	8.2±0.3	7.7±0.6	5.6±0.5
n_h>10	10.1±0.3	9.3±0.5	6.4±0.4

Conclusion:

The main results for the work presented in this chapter, using the cosmic ray data, may be summarized as follows:

(i) The multiplicity of the average value of shower particles i.e., $<n_s>$ depends on the primary energy. But the multiplicity of the average value of heavy particles, $<n_h>$ maintains a constant valueand independent primary energy.

(ii) The parameter $<n_s>/D$ maintains a constant value ($\cong 1.6$) independent of incident energy.

(iii) The mean normalized multiplicity, R_{em} maintains almost a constant value ($\cong$1.5) independent of primary energy.

(iv) The parameters D and Δ have slow dependence on the primary energy.

(v) At a given primary energy, the multiplicity distribution of the angular shower particles for nucleon-nucleus light (CNO) interactions and nucleon-nucleus heavy (AgBr) interactions in the region of large rapidity values i.e., the projectile fragmentation region (PFR) is asymptotically merged that shows energyindependent. Further,themultiplicity of the angular distributions in the target fragmentation region (TFR)dependson the types of interactions and their maxima peak shifts towards the nucleon-nucleus(heavy) interaction.

(vi) In the different multiplicity of heavy particle, n_h intervals, the maximum peak for multiplicity distribution of the angular shower particles shifts towards the higher energyandthe mean multiplicities of the shower particles havingpseudorapidity, ($\eta<3.0$) remains independent of the incident energy, whereas themean multiplicity of shower particles having pseudorapidity, $\eta>3.0$ increases with increases of projectile energy.

It has been observed that the angular distribution of charged secondary particles supports the class of theoretical models for multiparticle production which requires the formation of an intermediate state of hadronic matter preceding particle production. From the comparative study of the multiplicity distributions of secondary particles of hadronic interactions, it can be concluded that similar behaviors have been found in both thecosmic ray energy and the machine range of energy.

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