Analysis of hard two-photon correlations measured in heavy-ion reactions at intermediate energies

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Recently reported measurements of hard photon correlations in the reactions ^{36}Ar on ^{27}Al at 95*A* MeV, ^{86}Kr on ^{nat}Ni at 60*A* MeV, and ^{181}Ta on ^{197}Au at 39.5*A* MeV are analyzed. A Boltzmann-Ühling-Uhlenbeck transport model is used to describe the photon production by individual nucleon-nucleon collisions. In the lighter systems we find the best agreement with data when taking into account only photons from first-chance collisions of nucleons or photons produced during the passage of the nuclei, while the model predicts also a considerable late-time emission of photons, which leads to a depletion of the calculated correlation function. The accuracy of the present data does not allow firm conclusions on the reliability of this late-time evolution. Our investigations do not support a recently reported interference pattern in the heavy Ta + Au system.

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Recently, measurements of correlations of hard photons have been reported for the reactions ^{36}Ar + ^{27}Al at 95*A* MeV [1], ^{86}Kr + ^{nat}Ni at 60*A* MeV [2,3], and ^{181}Ta + ^{197}Au at 39.5*A* MeV [3]. On the basis of the Hanbury-Brown-Twiss effect such two-photon correlations are utilized to get information on the space-time extent of the emitting source. Photons are particular suitable probes of the whole space-time history of strongly interacting matter since they leave the system without suffering from final state interactions.

In the field of heavy-ion collisions the interferometry is a useful tool for measuring the spatial dimensions and the lifetime of the resulting fireball. More specifically one can address such questions as whether the compound system undergoes a significant expansion before disassembling, or whether the radiation of hard photons [4] lasts a long time interval. Intimately related to the latter temporal aspect of the hard photon emission is the interplay of direct photons coming from first-chance nucleon collisions and the thermal hard photons produced at later times in the fireball [5]. Of particular interest is the suggestion [3] that sufficiently heavy nuclei in central collisions at not too large a bombarding energy may merge to a fireball which undergoes pronounced monopole-like density oscillations [6], which in turn cause a temporal modulation of the photon emission rate since the hard photons are predominantly emitted in the compression stages during the oscillations. Beside this repeatedly flashing source one might also speculate whether in more peripheral collisions two radiating projectile-like and target-like sources recede and generate an interference pattern known from double slit experiments in optics. Indeed, Ref. [3] seems to substantiate this conjecture in the Ta + Au reaction.

Usually one defines the two-particle correlation function by $C_2(\vec{q}_1,\vec{q}_2)=Y_2(\vec{q}_1,\vec{q}_2)/(Y_1(\vec{q}_1)Y_1(\vec{q}_2))$ [7], where $Y_{1,2}$ are the single and two-particle yields of the photons with momenta $\vec{q}_{1,2}$. This correlation C_2 is a function in the six-dimensional space $\vec{q}_1\otimes\vec{q}_2$. Several models [7] have been employed to derive correlation functions C_2 which contain physically motivated parametrizations of the source function describing the photon emission. Experimentally, however, one mostly projects C_2 on certain hypersurfaces, e.g., one describes the correlation as function of the quantities $|\vec{q}|=|\vec{q}_1-\vec{q}_2|$, $q_0=E_1-E_2$ [1], or $Q_{\rm inv}=\sqrt{\vec{q}^{\,2}-q_0^2}$ [2,3]. In these projections one integrates over all other variables, and the acceptance of the detector equipment and the imposed gates generally change the region of integration and thus may have substantial effects. Therefore, the physical information cannot simply be read off from the measured correlation by comparing the observed correlation $C_2^{\rm exp}$ to an *ad hoc* given source parametrization [8].

It is the aim of the present Rapid Communication to employ a dynamical transport model to determine the photon source distribution, and, within this framework, to analyze the photon correlations reported in Refs. [1–3]. Here, the Boltzmann-Ühling-Uhlenbeck (BUU) approach is applied for generating the source function.

For a chaotic source the correlation function for two hard photons is given by the expression [9,10] (we employ units with $\hbar=c=1$)

$$C_2(\vec{q},\vec{K})=1+\Lambda\,\frac{|\int d^4x\;g(x,K)e^{iqx}|^2}{\int d^4x\;g(x,K-\frac{1}{2}q)\int d^4x\;g(x,K+\frac{1}{2}q)}. \tag{1}$$

For the sake of convenience we introduce four-vectors for the photon momenta $q_{1,2}=(E_{1,2},\vec{q}_{1,2})$ and the space-time coordinates $x=(t,\vec{x})$. The averaged four-momentum of the pair is denoted by $K=\frac{1}{2}(q_1+q_2)$ and its relative momentum by $q=q_1-q_2$. The photon momenta are taken on-shell, i.e., $E_{1,2}=|\vec{q}_{1,2}|$ and, therefore, the correlation function C_2 is solely a function of the two three-vectors $\vec{q}_{1,2}$ of the photons. The properties of the source are described by the source function $g(x,k)$, which gives the probability that a photon with four-momentum k is emitted from the space-time point x. Here we neglect contributions from off-shell momenta in the numerator of Eq. (1). At least in the case that the relative angle between the photons is small, the off-shell effect is not very important. In this case, inclusion of only the on-shell four-vector, i.e., $K_0 = \frac{1}{2}\sqrt{(\vec{q}_1+\vec{q}_2)^2}$, is sufficient.

If unpolarized photons are emitted the factor Λ in Eq. (1) reads $\Lambda = \frac{1}{4}(1+\cos^2\Theta_{12})$ [10], where Θ_{12} is the angle between the photon momenta. Therefore Λ is roughly 0.5 for small angles. However, if the photons are emitted from an anisotropic medium there might be a preferential polarization which could cause larger values of Λ, as it has been discussed in Ref. [11]. We shall not consider this possibility in the present work and put $\Lambda = \frac{1}{2}$ in our calculations.

To describe the dynamics of heavy-ion collisions at beam energies around 100*A* MeV we employ a transport model based on the BUU approach [12]. This model provides us the phase-space distribution $f(x,\vec{p})$ of the nucleons. In addition it models the collision term as a sequence of collisions of test particles. It is widely accepted [13] that these two-body collisions form the source of the hard photons. Since the typical wavelengths, which we consider, are much larger than the interaction region of two scattering nucleons the dipole radiation term dominates and, therefore, only proton-neutron collisions are important. Thus, for each impact parameter b we obtain a source distribution

$$g_b(x,\vec{K}) = \sum_i \delta^4(x-x_i)\frac{1}{\sigma_i^{pn}}\frac{d\sigma_i}{d\vec{K}} \times [1-f(x,\vec{p}_1')][1-f(x,\vec{p}_2')], \tag{2}$$

where the sum runs over the scattering centers i, and σ^{pn} denotes the total proton-neutron cross section. Since $(d\sigma_i/d\vec{K})/\sigma_i^{pn}$ is the probability for producing a photon in the ith collision, the function g_b represents a probability density. The photon production cross section $d\sigma/d\vec{K}$ depends on the initial momenta of the proton $\vec{p}_1$ and neutron $\vec{p}_2$, on the photon momentum, and on the direction of the difference of the final nucleon momenta $\vec{p}_1' - \vec{p}_2'$. For the sake of simplicity we assume that the photon angular distribution in the proton-neutron center-of-mass system is isotropic. For this purpose we adopt the formula (3.2) in Ref. [14] for the photon production cross section. Further, we take into account the fact that the nucleonic final states with momenta $\vec{p}_{1,2}'$ may be partially occupied, and this effect is dealt with by the Pauli blocking factors in Eq. (2).

In our BUU calculations we use a nuclear equation of state without momentum-dependent forces which gives an incompressibility of 240 MeV. We take 200 parallel ensembles, and the Pauli blocking is sensitive to phase space cells with a size of $|\Delta\vec{x}\times\Delta\vec{p}| = 2.7$ fm $\times$ 180 MeV.

The two factors in the denominator in Eq. (1) account for the one-particle emission. In the experiment it is not possible to observe the entire range of momenta for the produced photons. Due to limitations in the detector acceptance and for reasons of statistics it is convenient to compactify the data by performing projections on special variables $q_{\rm obs} = \bar{Q}(\vec{q}_1,\vec{q}_2)$ as mentioned above. This can be cast in an expression for the observable correlation function

$$C_2(q_{\rm obs}) = \frac{\mathcal{N}\int d\vec{b}\, d\vec{q}_1\, d\vec{q}_2\, \Pi(\vec{q}_1,\vec{q}_2)\,\delta[q_{\rm obs}-\bar{Q}(\vec{q}_1,\vec{q}_2)]|\bar{g}_b(q,K)|^2}{\int d\vec{b}_2\, d\vec{b}_2\, d\vec{q}_1\, d\vec{q}_2\, \Pi(\vec{q}_1,\vec{q}_2)\,\delta[q_{\rm obs}-\bar{Q}(\vec{q}_1,\vec{q}_2)]\bar{g}_{b_1}(0,K-\frac{1}{2}q)\bar{g}_{b_2}(0,K+\frac{1}{2}q)}, \tag{3}$$

where we have introduced the Fourier-transformed source function $\bar{g}_b(k,K) = \int d^4x\, g_b(x,K)\exp(ikx)$. The detector acceptance $\Pi(\vec{q}_1,\vec{q}_2)$ depends usually on the relative angle and a low energy cutoff, and it may strongly distort the shape of the correlation function C_2.

In our calculations we sample the photon production probabilities for a set of impact parameters. The numerator in Eq. (3) contains a sum over these probabilities, multiplied by weight factors which are determined by the impact parameter and detector acceptance. The denominator simulates the event mixing technique applied in the experiments [1]. This implies a mixing of different impact parameters suitably weighted. The normalization parameter $\mathcal{N}$ is chosen such that the same number of photon pairs contributes to the expressions in the numerator and the denominator.

Now we apply the above formulated model to the available experimental data for ^{36}Ar + ^{27}Al, ^{86}Kr + $^{\rm nat}$Ni, and ^{181}Ta + ^{197}Au. To disentangle the contributions of direct and thermal photons we carry out calculations assuming that the photons stem from different sources: photons which are created (i) only in primary-primary nucleon-nucleon collisions, (ii) in primary-primary + primary-secondary collisions, (iii) in collisions which happen during a time which corresponds to the geometrical passage-through of the colliding nuclei, and (iv) during a long BUU evolution time. The notion "primary" stands for nucleons which have not had previous hard nucleon-nucleon collisions, while the "secondary nucleons" have at least had one such collision.

^{36}Ar on ^{27}Al at 95 A MeV. We begin with the reaction Ar + Al, where two correlation functions $C_2(|\vec{q}|)$ and $C_2(q_0)$ for $|\vec{q}|<45$ MeV were measured. Photons with energies $E_{1,2}>30$ MeV and a minimum laboratory angle between the two photons of 15° [1] were observed in the MEDEA 4π detector.

In Fig. 1(a) the experimental data [1] and our calculations of the correlation function $C_2(q_0)$ for $|\vec{q}|<45$ MeV are displayed. We find the best agreement with the data when taking into account only those photons which are emitted in primary-primary collisions or within a sufficiently short time interval of about 35 fm/c counted from the moment of touching of the nuclei. Truncating the BUU evolution at this time of 35 fm/c, a smaller width of the correlation function is obtained with respect to that one would get in using first-chance collisions only. This proves that photons from first-chance collisions originate from a shorter time interval. A fit

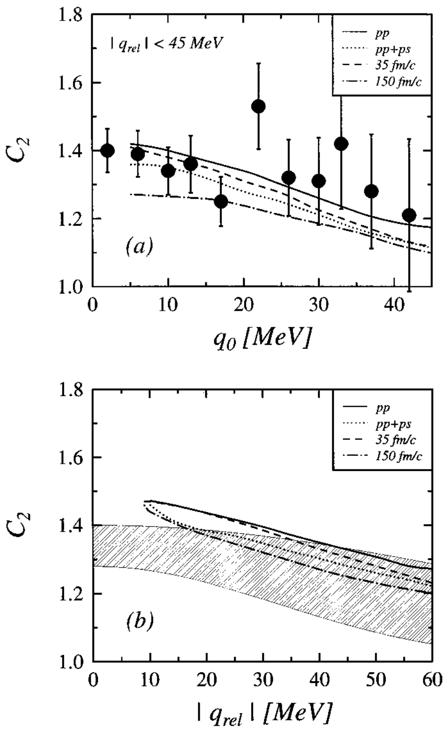

FIG. 1. The correlation functions $C_2(q_0,$ for $|\vec{q}|<45$ MeV) [(a), upper panel] and $C_2(q_{\rm rel}\equiv|\vec{q}|)$[(b), lower panel] in the reaction ^{36}Ar + ^{27}Al at 95*A* MeV. The curves are calculated using photons from primary-primary (pp), primary-primary + primary-secondary (pp+ps) nucleon-nucleon collisions and for two different freeze-out times. Experimental data [symbols in (a) and hatched area in (b)] from [1].

of the source distribution, obtained in the BUU model, to a Gaussian distribution $\exp(-t^2/2\tau^2-\vec{r}^2/2R^2)$ delivers the source parameters $\tau=6$ fm/c and $R=1.4$ fm. Thus, the timelike correlation in Fig. 1(a) is comparable with a distribution $\exp(-q_0^2\tau^2)$ and measures roughly the duration of the radiation.

In Fig. 1(b) we compare our results to the spatial correlation data $C_2(|\vec{q}|)$. The hatched area in Fig. 1(b) indicates the range of the measured correlation, parametrized according to $C_2=1+\lambda\exp\{-\vec{q}^2R^2\}$ with the parameters $\lambda=0.34\pm0.06$ and $R=3.1\pm1.2$ fm from [1]. These data would favor a longer duration or a larger reaction volume of the heavy-ion collision. However, because of the large uncertainties in the data (due to π^0 decays) a final conclusion would be premature.

Simulating the detector acceptance by a Monte Carlo technique with a given correlation function $C_2=1+\lambda\ \exp\{-\vec{q}^2R^2-q_0^2\tau^2\}$ with $R=3$ fm and $\tau=3$ fm/c, we have found that the resulting projected correlation $C_2(|\vec{q}|)$ is nearly unaffected by the $q_0\tau$ term, while the projected correlation $C_2(q_0)$ is diminished by 20 (50)% for $|\vec{q}|<45$ MeV (all $|\vec{q}|$). This effect is in agreement with our BUU simulation, as seen in Figs. 1(a) and 1(b), while the measurements [1] show smaller values of the correlation function $C_2(|\vec{q}|)$ compared to $C_2(q_0)$.

Analyzing the formation of the photon source in our BUU calculation, we find that the majority of the photons are produced during the time interval $<$ 35 fm/c. The maximum compression is reached at 20 fm/c. In the following expansion phase the photon emission relaxes. At a time of 50 fm/c the maximum density does not exceed 1/3 of the normal nuclear matter density. However, some hard photons are produced also at later times. When we include these late photons from secondary collisions by extending the evolution up to 150 fm/c, the calculated correlation curves are significantly shifted down. However, then the data [1] are not reproduced well [see dotted and dot-dashed lines in Fig. 1(a)]. It seems that the late-time evolution is not adequately described by the BUU model, which describes the evolution of the single-particle distribution by classical means. Due to the comparatively low density the late nucleon-nucleon collisions are weakly Pauli blocked and, therefore, unphysically many photons are continuously emitted. However, it is well known that the excited nuclear matter starts fragmenting and forms compoundlike systems which evaporate nucleons. The fragments, which might be formed by quantum mechanical transitions to bound states, are probably much less excited than the homogeneously diluted matter in the BUU approach. Hard photons coming from the late evolution therefore appear as an artifact of the BUU approach. So, it seems that first-chance collisions are sufficient to describe the correlation data.

At a time corresponding to the passage of the two nuclei through one another we obtain a total photon cross section of $\sigma_\gamma=3.3$ mb that exceeds the measured value of 1.2 mb considerably, while the first-chance collisions alone give a cross section of 1.5 mb. However, the influence of many-particle effects of the surrounding matter on the elementary photoproduction cross section is currently not well known and may lead to a noticeable decrease of the photon production (see, e.g., [15]). Therefore, the present overestimation of σ_γ should not be taken too seriously, in particular since we are interested in the calculation of the correlation function.

The different scenarios discussed above give also different slopes T of the single-photon spectra: $T=$ 35 (i), 27 (ii), 30 (iii), and 24 (iv) MeV, which must be compared with the experimental value of $T=29$ MeV [1]. These values show the degree of thermalization of the source as the apparent temperature becomes lower with increasing reaction time. The values given above depend slightly on the details of the parametrization of the nucleon-nucleon cross sections and would favor our scenarios (ii) and (iii), where photons stem from the first-chance and primary-secondary collisions or where photons are created during the passage-through time. Again, the long term BUU evolution seems to be ruled out.

^{86}Kr on ^{nat}Ni at 60A MeV. In this reaction the experimental correlation data are measured as a function of $Q_{\rm inv}$ [2,3]. In addition, the experimental acceptance substantially influences the folding procedure $\{q_0,\vec{q}\}\rightarrow Q_{\rm inv}$. We employ here the following filter which is very similar to the experiment: $E_{1,2}>25$ MeV, detector positions between polar angles of 35° and 165° (orienting downstream), azimuthal opening angles of $0°\pm28°$ and $180°\pm28°$, and 18° for the minimum opening angle.

The different contributions to the correlation function are compared to experiment in Fig. 2. Apparently, the best agreement with the data is again achieved for photons which come from primary-primary collisions or equivalently for those ones produced in the beginning of the reaction during the passage-through time of 50 fm/c. This is also consistent with

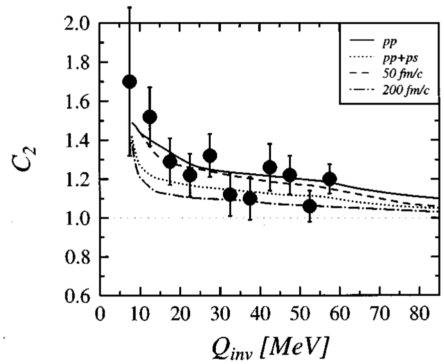

FIG. 2. The correlation function $C_2(Q_{\mathrm{inv}})$ for the reaction ^{86}Kr + $^{\mathrm{nat}}$Ni at 60 MeV. The meaning of the curves is as in Fig. 1(a). Data are from [2,3].

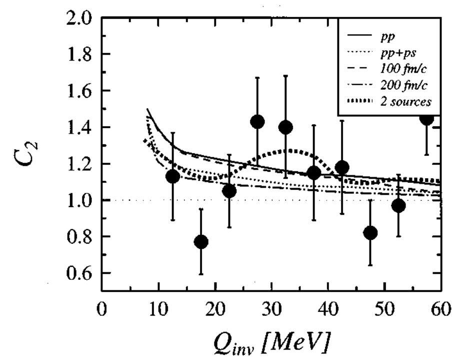

FIG. 3. The same as in Fig. 2 but for the reaction ^{181}Ta + ^{197}Au at 39.5A MeV. Data are from [3]. The oscillatory heavy dotted curve (2 sources) depicts the result of Eq. (4) for parameters described in the text.

our finding for the total photon cross section, which points to an even smaller production time than 50 fm/c.

The slope parameters of the single-photon spectra are $T=$ 25 (i), 18 (ii), 20 (iii), and 15 (iv) MeV. The experiment reports $T=$ 21.5 MeV [2]. In Ref. [6] the energy spectrum is decomposed into a direct and a thermal part giving two distinct slope parameters of $T_{\mathrm{dir}}=$ 20.2 MeV and $T_{\mathrm{th}}=$ 8.5 MeV. Therefore, the scenarios (ii) and (iii) are supported. Our BUU calculation for the considered reaction shows, in agreement with Ref. [6], density oscillations with a time period of 100 fm/c between the first and second maximum compression. The photon emission rate shows correspondingly the same temporal modulation which is absent in the lighter system Ar + Al. However, it is questionable whether this second maximum contributes in the experiment. This is supported by the experimental finding [6] that the direct part of the photon spectra is six times stronger than the thermal part. Our analysis favors an evolution scenario wherein the late photons should not occur. With the freeze-out time of 50 fm/c the second emission stage is cut off. It seems that these oscillations are an artifact of the transport model.

^{181}Ta on ^{197}Au at 39.5A MeV. Here, the same filter is employed as in the previous reaction, since the correlation function is measured with essentially the same equipment. In Fig. 3 the correlation function is displayed together with the experiment. As in the previous reaction the correlation function declines sharply in the long term evolution scenario. However, in contrast to the Kr + Ni reaction the data do not allow us to draw conclusions on a preferred model. Since the Ta + Au system is larger in time and space extension the correlation functions are narrower. As a consequence of the acceptance filter the correlation functions do not much differ from one another.

We notice the slope parameters of the photon spectra $T=$ 17 (i), 13 (ii), 15 (iii), and 12 (iv) MeV, which are to be compared with the observed value of 13.4 MeV [6]. This favors again the scenarios (ii) and (iii) and seems also to exclude the photons which stem from the long term evolution.

We stress that in all our BUU model simulations we do not find an indication of the oscillating structure, which is believed to be seen in Ref. [3]. To clarify this challenging point we also tried to reproduce the oscillatory structure with a schematic two-source model

$$C_2-1=\frac{1}{2(s_1+s_2)^2}(s_1^2\exp\{-\vec{q}^{\,2}R_1^2\}\exp\{-(q_0-\vec{q}\vec{v}_1)^2\tau_1^2\}+s_2^2\exp\{-\vec{q}^{\,2}R_2^2\}\exp\{-(q_0-\vec{q}\vec{v}_2)^2\tau_2^2\}$$
$$+2s_1s_2\exp\{-\tfrac{1}{2}\vec{q}^{\,2}(R_1^2+R_2^2)\}\exp\{-\tfrac{1}{2}[(q_0-\vec{q}\vec{v}_1)^2\tau_1^2+(q_0-\vec{q}\vec{v}_2)^2\tau_2^2]\}\cos[\vec{q}\vec{\Delta}-q_0\Delta_0]), \tag{4}$$

where $R_{1,2}$, $\tau_{1,2}$, and $s_{1,2}$ are the radii, durations, and strength parameters of the two Gaussian sources, which are separated in time and space by $(\Delta_0,\vec{\Delta})$, and move with velocities $\vec{v}_{1,2}$. The case of $\vec{v}_1=\vec{v}_2=\vec{v}$ and $\vec{\Delta}=\vec{v}\Delta_0$ would describe one source which moves with velocity $\vec{v}$ and flashes at $t=0$ and $t=\Delta_0$. For realistic values of the parameters ($R_{1,2}>$ 1 fm, $\tau_{1,2}>$ 1 fm/c, $\Delta_0\sim$ 100 fm/c, and v given by the center-of-mass velocity) neither our schematic model (4) nor our BUU analysis give hints for such structures as advocated in Ref. [3]. Only the use of very exceptional parameters can produce local minima and maxima in the experimentally accessible window of $Q_{\mathrm{inv}}=$ 10–60 MeV. For instance, the heavy dotted curve in Fig. 3 displays our results for $R_1=R_2=3$ fm, $\tau_1=1$ fm/c, $\tau_2=$ 3 fm/c, $|\vec{\Delta}|=40$ fm, $\Delta_0\ll|\vec{\Delta}|$, $v_{1,2}=0$, $s_1=s_2$, and $T=15$ MeV. Contrary to the conclusion in Ref. [3] one gets the impression that a spatial separation (not a temporal one) of two sources could be responsible for the oscillatory structure. The inclusion of the above-mentioned Neuhauser factor Λ into Eq. (4) causes a slight depletion of C_2 for $Q_{\mathrm{inv}}>20$ MeV and weakens the oscillatory structure.

In conclusion, the analysis of the observed two-photon correlations for three different systems supports the idea that the photons originate from an early stage of the reaction — as already conjectured previously [5]. In contrast, the BUU approach predicts a considerable yield of hard photons at a rather late stage of the evolution. These photons would lead to a depletion of the measured correlation function. At least for the lighter systems Ar + Al and Kr + Ni this depletion seems not to agree with the data.

On the other hand it is well known that in heavy-ion reactions the multifragmentation process sets in during the expansion phase. This multifragmentation stage is not correctly described by the BUU model. Therefore, there is a physical reason to stop the calculations at a time comparable with the passage time of the two nuclei. Using such a breakup time the agreement with the data is improved. The correlation data are also well described by photons from first-chance nucleon-nucleon collisions.

It is worth noting that an increased accuracy of the correlation data would be necessary to make firm conclusions, in particular about the reported oscillatory structure of the correlation function for the Ta + Au reaction. If the latter will be confirmed experimentally, this would imply that some important mechanism in the BUU model or in the implemented two-photon propagation is missing.

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