Hard Photons in Heavy-Ion Collisions: Direct or Statistical?

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Photons with energies from 2 to 60 MeV have been measured in coincidence with binary fragments in the reaction ^{92}Mo+^{92}Mo at an incident energy of 19.5A MeV. The rapid change of the γ-ray spectrum and multiplicity with the fragment total kinetic energy in the exit channel indicates that the γ rays are emitted statistically by the highly excited fragments. Temperatures as high as 6 MeV are inferred.

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The emission of high-energy photons in heavy-ion reactions at intermediate incident energies have attracted much attention recently, both experimentally[1-5] and theoretically.[6-12] Among the many models proposed to explain the published data, the incoherent nucleon-nucleon bremsstrahlung picture,[8,12] which assigns the emission of hard photons to the earliest stages of the reaction, is most commonly accepted. Unfortunately, a definitive and unambiguous verification of the various theories is made difficult by the limitations in the experiments. The available data are either inclusive with no specification of the exit channel, or they are characterized by rather coarse gates meant to define some impact-parameter range. Under these circumstances it is difficult to establish whether the γ rays are produced in the initial stage of the reaction through nucleon-nucleon bremsstrahlung, or, rather, are emitted at a later time by some intermediate object, or even by highly excited fragments that may be present in the exit channel.

In order to improve on the above situation, we have performed a more exclusive experiment in which the exit channel is characterized not only by the γ rays, but also by the main outgoing fragments and by their associated kinetic energy. We have chosen to study the reaction ^{92}Mo+^{92}Mo at 19.5A MeV where exit-channel properties in terms of fragment masses and kinetic energies have been extensively investigated in prior experiments.[13-15] These experiments have indicated that the deep-inelastic process is the dominant mechanism in this reaction. We will show below that the observed yield of high-energy photons associated with this reaction can be fully accounted for by the statistical emission from the excited fragments in the exit channel.

An isotopically pure target of ^{92}Mo was irradiated with ^{92}Mo ions at an incident energy of 19.5A MeV at the UNILAC at Gesellschaft für Schwerionenforschung (GSI). Velocity vectors of heavy fragments were measured in a setup of twelve parallel-plate avalanche counters located in the forward hemisphere with an almost complete 2π coverage in the laboratory. A full kinematic reconstruction of the binary events, which yields primary quantities like fragment masses and kinetic energies, is possible.[15] The counters were sensitive to fragments with $Z \geq 10$ and allowed us to study the dominant part of the reaction cross section with an efficiency of 30%.

Photons were detected in six arrays consisting of seven BaF_2 modules each, located at angles from 90° to 170° in the laboratory at a distance of 30 cm from the target. These modules were of hexagonal shape, 5.25 cm in height, and 20 cm in length. They were calibrated at the Universität Mainz tagged-photon facility[16] with collimated monoenergetic photons ranging from 5 to 50 MeV. Their response is well described by a Monte Carlo shower simulation,[17] which also reproduces the energy resolution amounting to 13% for 50-MeV photons for the calibration run. The simulation was then used to describe the response in the experimental geometry, where the full front face of the crystals was illuminated. The relative calibration was performed with cosmic rays as a high-energy reference point and with standard radioactive sources in the low-energy range. Light charged particles and neutrons were discriminated by means of time flight with respect to the pulsed beam. The overall time resolution was 0.8 ns FWHM. Low-energy charged particles were additionally suppressed by a 1-cm-thick Plexiglas absorber in front of the photon detectors. The probability of chance coincidences between low-energy photons and the remaining charged particles is estimated to be of order 10^{-7} or less and therefore negligible. The cosmic-ray background amounted to less than 5% even in the high-energy tail of the spectrum and was eliminated by the subtraction of the appropriate beam-off spectra. Coincidences from uncorrelated events were monitored by our recording hits from different beam pulses. The amount of uncorrelated prompt events was measured not to exceed 10% and was subtracted.

The exclusive γ-ray spectra were transformed into the center-of-mass system, which is uniquely defined in symmetric systems, and were found to be isotropic within 20%. Therefore, they were integrated over all angles in order to improve statistics. Figure 1 shows three such spectra associated with binary fragments for different 100-MeV-wide bins in the total kinetic-energy loss (TKEL). All the spectra show three characteristic features: a low-energy component extending up to 10 MeV; an intermediate region from 10 to 20 MeV; and the high-energy tail. In this paper we shall concentrate on the enhancement ("bump") in the intermediate region combined with the high-energy tail. The low-energy part can be explained by the multiple γ decay of the fragments at the end of the evaporation chain and will not be discussed further.

From inspection of Fig. 1 one can observe two features: (a) The slope of the spectra and the multiplicity for $E_\gamma \gtrsim 20$ MeV depend dramatically on the dissipated energy (TKEL); (b) at all total kinetic energy losses a bump near 18-MeV photon energy is visible which is superimposed on the exponential tail.

The former feature can be quantified by our fitting the spectra for $E_\gamma \gtrsim 25$ MeV with a distribution of the form $f(E_\gamma) \propto E_\gamma^2 \exp(-E_\gamma/T)$ and by plotting the fit parameter T vs TKEL. This is done in Fig. 2(a): As already seen qualitatively from the spectra, the "temperature" T rises with increasing energy loss and reaches its highest value for the completely damped events, where the two fragments separate with only their Coulomb energies (TKEL $\approx$ 800 MeV). This striking dependence of T

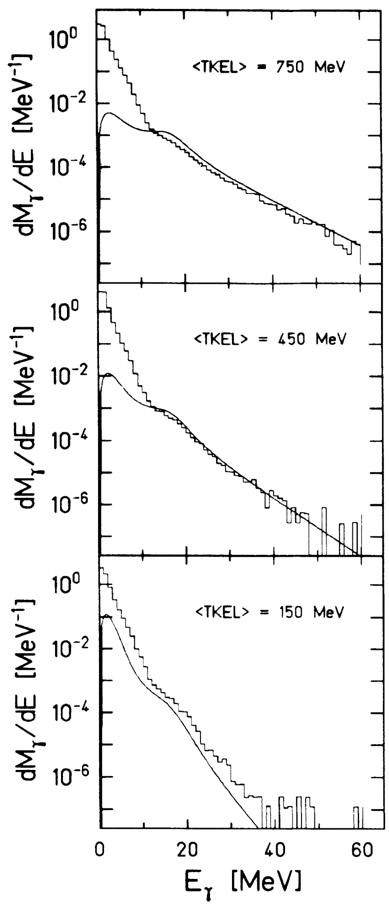

FIG. 1. Exclusive experimental photon energy spectra for different bins in total kinetic-energy loss (TKEL). The continuous curves are the results of statistical-model calculations discussed in the text with (solid curve) and without (dotted curve) the quasideuteron component in the γ cross section.

upon TKEL makes it very tempting to consider it as reflecting the actual temperature of the two excited fragments emitting γ rays in statistical competition with light particles. The observation of an enhancement [cf. feature (b)] just where the $E1$ giant resonance of the fragments should appear reinforces its interpretation as an exit-channel effect.

Figure 2(b) gives the integrated γ multiplicities for two different lower γ-energy cuts of 15 and 30 MeV, respectively. They show a distinctive rise with increasing TKEL. This rise is slower for the 15 MeV than for the 30-MeV cut. The error bars represent statistical errors only. The systematic error is estimated to be about 50%.

Summarizing the experimental findings we observe the following: (i) The slopes depend suggestively upon TKEL which we associate with the total excitation energy of the fragments in the exit channel; (ii) the bump appears superimposed on the exponential slope and its position at 18 MeV is in good agreement with the pre-

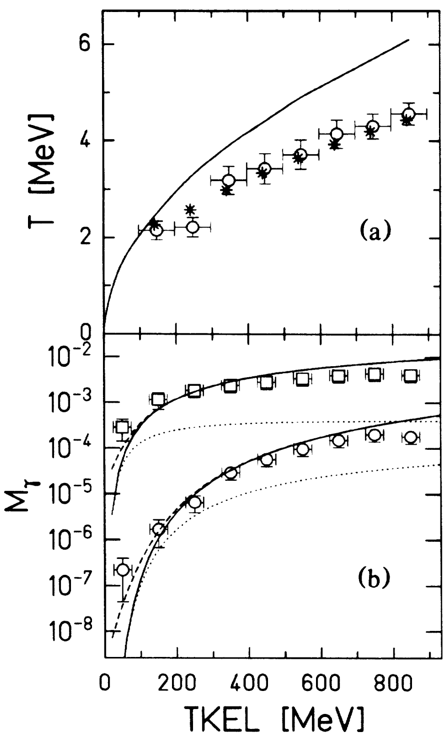

FIG. 2. (a) "Temperatures" derived from Boltzmann fits to measured and calculated γ-ray spectra (see Fig. 1) are represented by circles and stars, respectively. The solid line denotes the initial temperature of the fragments which has been calculated in the Fermi-gas approach. (b) Experimental and theoretical multiplicities of hard photons with energies ≥ 15 (squares) and 30 MeV (circles). Statistical-model calculations show the first-chance contribution (dotted line), the sum over all generations (solid line), and the effect of the experimental excitation energy smearing (dashed line).

dicted position of the giant dipole resonance of the fragments.[18]

This combined evidence strongly suggests that all the γ rays are emitted statistically from the fragments, whose compoundlike emission of neutrons, protons, and α particles have been observed.[15] In other words, the fragments in the exit channel are known to decay like compound nuclei, and so they must emit γ rays besides the other particles. It appears that it is indeed these γ rays that we are observing in our experiment.

The statistical-decay hypothesis can be tested quantitatively. The partial γ-decay width can be reliably calculated from the inverse γ-absorption cross section by the application of the detailed-balance principle,

$$d\Gamma_\gamma(\epsilon)=\frac{1}{(\pi\hbar c)^2}\sigma_\gamma(\epsilon,A)\epsilon^2\exp\left(-\frac{\epsilon}{T}\right)d\epsilon, \quad (1)$$

where σ_γ is the photon-absorption cross section, ϵ is the photon energy, and A the fragment mass. In the same way the neutron decay width can be written as

$$d\Gamma_n(\epsilon)=\frac{2}{(\pi\hbar c)^2}\sigma_n(\epsilon,A)m_nc^2\epsilon\exp\left(-\frac{\epsilon+B}{T}\right)d\epsilon, \quad (2)$$

where B is the neutron binding energy, σ_n is the neutron-absorption cross section, and ϵ is the neutron kinetic energy.

The proton and α-decay width can be calculated in a similar manner, so that the γ branching ratio or first-chance emission probability $\Gamma_\gamma/\Gamma_{\rm tot}$ can be evaluated. The total γ multiplicity is obtained by our adding to the first-chance emission probability the higher-order probabilities of emitting a γ ray after one, two, three, etc., particle emissions.

In order to implement this calculation we took a nominal cross section of 1 b for the neutron-absorption cross section. For the inverse γ cross section we took a broadened Lorentzian satisfying 100% of the sum rule (with a peak cross section of 56 mb, a peak position of 16 MeV, and a width of 10 MeV [19]) and a quasideuteron term calculated with the Levinger expression[20] with a reduced Pauli damping because of the large temperatures. This latter contribution can be estimated to be ≈ 15 mb and is approximately constant over the γ-ray energies of interest, consistent with available data.[21] We further assumed that the quasideuteron cross section leads completely to compound-nucleus formation as a result of the very short nucleon mean free path (approximately one-half of its value at $T=0$) prevailing at these high temperatures.

The results of this calculation are shown in Figs. 1 and 2 as solid lines. The dotted line for the highest excitation energy in Fig. 1 represents the γ-ray spectrum with use of the giant-dipole-resonance strength function only. The calculated spectra in Fig. 1 show an impressive agreement with the data. It is to be noted that we performed an absolute calculation without the use of any normalization. The agreement between the experimental and the calculated temperatures is shown in Fig. 2(a), where the same fitting procedure has been applied to the experimental and calculated spectra. The primary temperature was calculated from TKEL with the Fermi-gas formula with use of a level-density parameter of $a=A/8$ and is shown as a solid line. It is interesting to observe that the γ spectrum at the highest TKEL verifies the temperature of $T_{\rm max}\approx 6$ MeV that can be inferred from the missing kinetic energy. The same temperature has been observed in the proton and α channels associated with the same reaction. Furthermore, the position and the strength of the bump are quite well reproduced by the statistical-model calculations, lending support to the hypothesis that it is due to the giant dipole excitation of the fragments.

Similar comments can be made for Fig. 2(b): The calculation reproduces very well the integrated multiplicities both for $E_\gamma \gtrsim 15$ MeV and $E_\gamma \gtrsim 30$ MeV. This calculation has been verified by a detailed statistical-model calculation (CASCADE[22]) for the lower excitation energies.

As is the case for light-particle emission, the statistical decay of the exit-channel fragments can account consistently and quantitatively for all the observed experimental features, thus leaving little room for alternative mechanisms. This agreement is obtained in a remarkably model-independent way by our relying upon the γ-ray absorption cross section. It is interesting to notice that in this way we have documented directly the formation of perhaps the hottest thermalized nuclear systems yet known, with a temperature of 6 MeV. This demonstrates the effectiveness of deep-inelastic reactions in transferring kinetic energy into internal excitation energy.

While in this specific reaction at 19.5A MeV the observed hard-photon yield can be quantitatively accommodated for by statistical γ emission, we are, of course, in no position to make a corresponding statement about other reactions, partially because of the limited characterization of their exit channels. However, it is quite clear that statistical γ emission from excited nuclei in the exit channel may introduce an important component that deserves full experimental attention in order to demonstrate and characterize other possible mechanisms.

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