γ Rays from Peripheral and Central Collisions in the Reaction $^{40}Ar + ^{158}Gd$ at 44 MeV/Nucleon

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(Received 21 November 1986)

Inclusive and exclusive γ-ray spectra have been measured in the reaction $^{40}Ar + ^{158}Gd$ at 44 MeV/nucleon. Impact-parameter selection has been provided by various coincidence conditions with a forward-angle particle detector. The γ yield for $E_\gamma > 25$ MeV is consistent with emission from the nucleon-nucleon system and decreases strongly for larger impact parameters. Below 25 MeV, the photons originate from statistical decay of the excited fragments with a strength function dominated by giant resonances. The observed γ yields provide information on the excitation energies of the reaction products.

PACS numbers: 25.70.$-$z, 24.30.Cz

Recently, several studies of high-energy–photon emission in heavy-ion collisions at bombarding energies above 20 MeV/nucleon have been carried out.[1–4] The origin of hard photons with energies above 30 MeV has been described in terms of electromagnetic bremsstrahlung[5,6] emitted in an early stage of the collision. Another source of radiation above 10 MeV arises from statistical decay of highly excited fragments known to be dominated by a giant-dipole-resonance strength function.[7–10] This component bears information about the limits of formation of equilibrated fragments in this energy regime.[11] So far, hard-photon spectra have been studied only in inclusive experiments. Since the process of photon production depends strongly on the overlap of the colliding nuclei, experiments selective on the impact parameter are required. In this Letter, we report on a first experiment allowing for impact-parameter selection by the study of particle-γ correlations.

An isotopically enriched (95%) target of 5-mg/cm^2 ^{158}Gd has been irradiated with a 0.2-particle-nA ^{40}Ar beam of 44 MeV/nucleon provided by the Grand Accélérateur National d'Ions Lourds (GANIL). Heavy fragments and light charged particles were registered in a detector array consisting of annular parallel-plate avalanche counters (PPAC) as well as plastic scintillators subtending the angular range between 5° and 20° in the laboratory system. Fragments scattered within the grazing angle of 5° were not registered. The gas detector comprised two consecutive sections separated by an energy degrader (0.5 mm Al) to provide a larger dynamic range for heavy fragments. Light charged particles were detected in eight plastic scintillators shielded against low-energy γ rays by a 2-mm Pb layer, covering the rear of the parallel-plate counters. The first section of the PPAC was sensitive to heavy fragments ($A > 10$) in the energy range from 10 MeV/nucleon down to 10 MeV, while the second section registered heavy ions with $A > 20$ and energies larger than 25 MeV/nucleon. The effective detection threshold for light charged particles in the scintillators was approximately 30 MeV/nucleon. High-energy γ rays were detected in seven large BaF_2 detectors (hexagonal, diameter$=$10 cm, length$=$14 cm corresponding to 7 radiation lengths) positioned 60 cm from the target at 90° and between 135° and 155°, respectively. Their photon response has been measured in the energy range from 8 to 85 MeV with use of the tagged photon beam at the Universität Mainz microtron MAMI A[12] as well as quasimonochromatic photons from positron annihilation in flight at the Universität Giessen linac.[13] The energy resolution varies between 15% and 30% and the trigger efficiency amounts to $\geq 95\%$ in agreement with GEANT simulations.[14] Cosmic rays have been used as a reference point for the energy calibration. Photons, light charged particles, and neu-

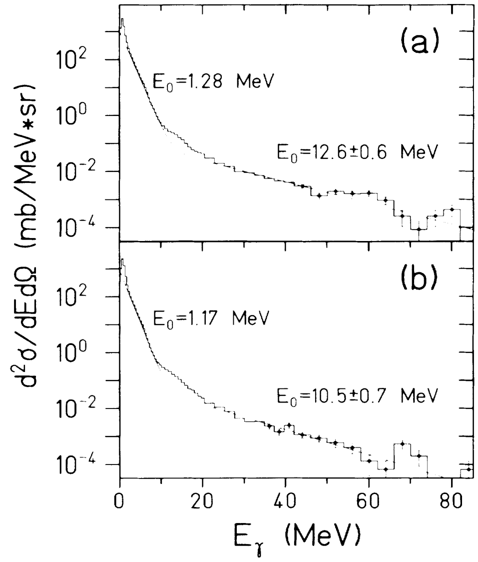

FIG. 1. Inclusive γ-ray spectra (a) at $\theta_{lab}=90°$, and (b) at an average angle of $\theta_{lab}=145°$. The solid curves represent fits with two exponential functions folded by the detector response.

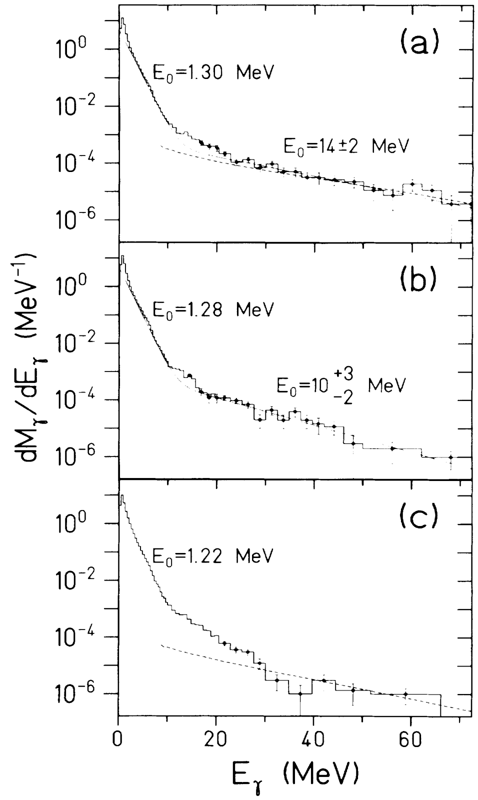

FIG. 2. γ-ray spectra taken at 90°, (a) in coincidence with a slow (E/A =0.2–10 MeV) fragment, (b) in coincidence with a fast ($E/A > 25$ MeV) fragment, and (c) in anticoincidence to the particle detector system. The solid curves represent fits with two exponential functions folded by the detector response. The dashed curves are the result of bremsstrahlung calculations (Ref. 6) scaled to the present projectile-target combination for (a) central collisions (complete geometrical overlap) and (c) grazing collisions (impact parameter 12.5 fm).

trons were identified by pulse-shape analysis[15,16] and by time of flight with respect to the pulsed GANIL beam. A time resolution of 0.7 ns was obtained. The cosmic-ray background was eliminated by subtraction of appropriate spectra taken at beam-off periods.

Inclusive γ spectra have been accumulated as well as spectra under the following conditions: (i) in coincidence with a slow heavy fragment in the first section of the PPAC, emphasizing central collisions; (ii) in coincidence with a fast projectilelike fragment in the second section of the PPAC, thereby enhancing peripheral interactions with the projectilelike fragment scattered to angles larger than the grazing angle of 5°; (iii) with the entire charged-particle detection system as a veto detector, selecting grazing collisions with low momentum and energy transfer. It should be noted that the impact-parameter ranges selected by the above trigger conditions may have some overlap.

Figures 1(a) and 1(b) show the inclusive angle- and energy-differential cross section for γ rays at 90° and 135°–155°, with respect to the beam direction. The spectra exhibit three distinct features: an exponentially falling soft-phonon component, a hard-photon component up to 70 MeV, and an excess yield in the region between 10 and 25 MeV. For energies $E_\gamma > 25$ MeV the spectra can be fitted by an exponential function $\exp(-E_\gamma/E_0)$. The deduced slope parameter $E_0 = 12.6 \pm 0.6$ MeV at 90° lies between the results of Ref. 3 and those reported in Refs. 1, 2, and 4. With the assumption of a source which emits γ rays with an angle-independent energy distribution, the ratio of spectral slopes observed in the laboratory at 90° and 145° [Figs. 1(a) and 1(b)] yields a source velocity of $\beta_s = 0.24 \pm 0.10$. This is compatible with the velocity of the nucleon-nucleon system ($\beta=0.15$), but excludes the nucleus-nucleus center-of-mass system ($\beta=0.06$) as a possible source. For $\beta_s=0.15$ the γ-ray yields observed at both angles correspond to an anisotropy of $W(90°)/W(145°)=1.3\pm0.25$ in the source frame. With the assumption of isotropic emission an angle-integrated cross section of 2.0 ± 0.8 mb is deduced for $E_\gamma > 30$ MeV.

The spectra taken at 90° with conditions (i)–(iii) [Figs. 2(a)–2(c), respectively] exhibit qualitatively similar features. However, a decrease in the hard-photon multiplicity as well as a small variation of the spectral slope is observed with increasing impact parameter (Table I). The hard-photon yield can be understood in terms of bremsstrahlung from individual nucleon-nucleon collisions.[5,6] Calculations with the quantal phase-space model[6] for high-energy γ emission agree al-

TABLE I. Slope parameters, cross sections, and multiplicities of hard photons at $\theta_{lab}=90°$ for various impact-parameter ranges.

	Experiment		Theory[c]	
	E_0 (MeV)[a]	Angle-integrated yield ($E_\gamma > 30$ MeV)[b]	E_0 (MeV)	Angle-integrated yield ($E_\gamma > 30$ MeV)
Inclusive spectra	12.6 ± 0.6	2.0 ± 0.8 mb	17.5	1.5 mb
Exclusive spectra				
Central [condition (i)]	14 ± 2	$M_\gamma = (1.3 \pm 0.3) \times 10^{-3}$	17.5	$M_\gamma = 1.1 \times 10^{-3}$
Peripheral [condition (ii)]	10^{+3}_{-2}	$M_\gamma = (5.3 \pm 1.6) \times 10^{-4}$		
Grazing [condition (iii)]	...	$M_\gamma = (7.7 \pm 2.4) \times 10^{-5}$	14.1	$M_\gamma = 1.2 \times 10^{-4}$

[a]Fit interval $E_\gamma > 25$ MeV.
[b]Integrated cross section 0.4 ± 0.2 mb for $E_\gamma > 50$ MeV.
[c]See Ref. 6.

most quantitatively with the observed hard-photon yields and slope parameters. The calculated anisotropy in the nucleon-nucleon system of $W(90°)/W(145°) = 1.29$ is also consistent with the experimental observation. The results of calculations for complete geometrical overlap of the colliding nuclei [corresponding to condition (i)] and for grazing collisions [corresponding to condition (iii)] are incorporated in Figs. 2(a) and 2(c) and in Table I.

For energies $E_\gamma < 25$ MeV the inclusive spectra (Fig. 1) exhibit an exponentially shaped soft-photon component with $E_0 \cong 1.2$ MeV. By comparison of the data to the solid curve representing the sum of the two exponential components, an excess yield of 9 ± 4 mb in the region between 10 and 25 MeV is observed. Similar observations are made for the spectra [Figs. 2(a) and 2(b)] taken for central collisions [condition (i)] and peripheral collisions [condition (ii)], respectively. Because of insufficient statistics in the high-energy photon tail for the spectrum in Fig. 2(c), we have not applied this procedure here. Corresponding structures have been observed in heavy-ion-fusion reactions[7-10] and have been explained in terms of giant-resonance decay of highly excited nuclei. The structures observed in the present experiment are most likely of the same origin, since estimated cross sections for direct excitation and subsequent γ decay of giant resonances in inelastic scattering are roughly two orders of magnitude smaller than observed.

An attempt has been made to describe the measured multiplicity in the resonance region within the statistical model, with use of the code CASCADE.[17] For peripheral collisions [condition (ii)] the giant-resonance part is found to be dominated by the targetlike fragment while photons below 10 MeV are predominantly emitted from projectilelike fragments. This allows us to obtain independent information on the excitation energies of both fragments. The data can be accounted for [Fig. 3(b)] by the assumption of a projectilelike fragment ($A=40$) with an excitation energy of 50 MeV ($T=3.3$ MeV) and a targetlike fragment ($A=158$) excited to 90 MeV ($T=2.2$ MeV). In this calculation, a Lorentzian-shaped γ-strength distribution (FWHM=6.0 MeV) exhausting 100% of the giant-dipole energy-weighted sum rule has been used. The inferred temperatures imply a division of the energy loss which does not scale with the fragment mass ratio. For central collisions [condition (i)] a broader mass distribution is expected with a smaller

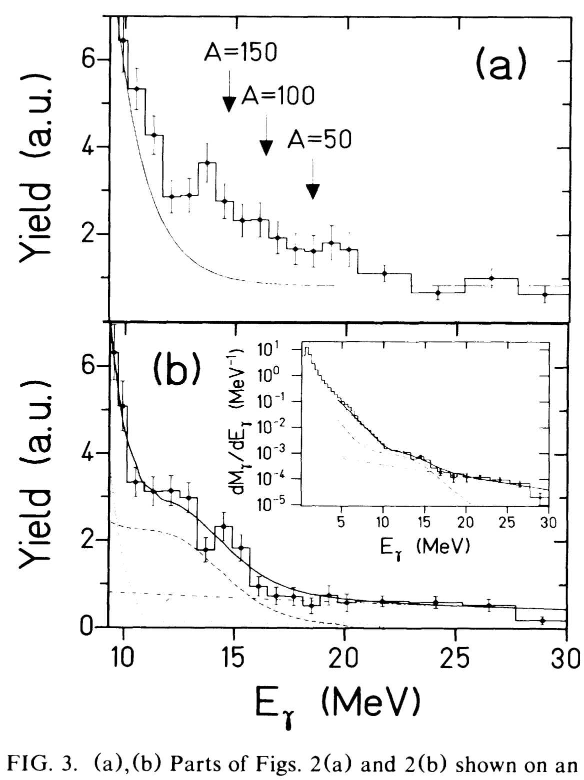

FIG. 3. (a),(b) Parts of Figs. 2(a) and 2(b) shown on an expanded energy scale. The spectra and fitted curves have been multiplied by $\exp(\alpha E_\gamma)$ with $\alpha^{-1} = 12.5$ MeV to allow for a comparison on a linear plot. In (a) the giant-dipole resonance energies (Ref. 8) for various nuclei of mass A are indicated. The dash-dotted curve in (b) represents the bremsstrahlung contribution determined from a fit for $E_\gamma > 25$ MeV. The dashed and dotted curves correspond to statistical-model (CASCADE) calculations for γ emission from targetlike and projectilelike fragments, respectively. Inset: The energy spectrum without multiplication by $\exp(\alpha E_\gamma)$.

average fragment mass than in peripheral collisions. As observed in Fig. 3(a) this leads to higher-energy photons as a result of the $A^{-1/3}$ dependence of the giant-dipole resonance energies. A quantitative interpretation is more difficult because of the complexity of the mass and excitation energy distributions.

In summary, γ-ray–particle correlations have been studied for various impact-parameter ranges in heavy-ion collisions at intermediate energy. Hard photons emitted in the nucleon-nucleon center-of-mass system have been observed. Their yield is found to decrease for larger impact parameters combined with a small change in spectral slope. Calculations of high-energy γ-ray emission on the basis of individual nucleon-nucleon bremsstrahlung can account for the experimental observations. For γ-ray energies below 25 MeV the spectra can be ascribed to statistical γ decay of excited fragments governed by the giant-dipole-resonance strength function. Exclusive measurements of γ-ray emission in heavy-ion collisions near the Fermi energy seem to be a rather promising tool to obtain information about the first instant of the nuclear interaction.

We would like to thank the accelerator staff of GANIL for delivering the stable ^{40}Ar beam. We are grateful to H. Folger and the Gesellschaft für Schwerionenforschung Darmstadt target laboratory staff for preparing the excellent targets. The collaboration of S. Riess, H. Ströher, B. Schoch, U. Kneissel, and W. Wilke in measuring the energy response of the BaF_2 detectors is gratefully acknowledged. This work was supported in part by the Gesellschaft für Schwerionenforschung and the Deutsches Bundesministerium für Forschung und Technologie.

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[1]E. Grosse *et al.*, Europhys. Lett. **2**, 9 (1986).

[2]N. Alamanos *et al.*, Phys. Lett. **173B**, 392 (1986).

[3]M. Kwato Njock *et al.*, Phys. Lett. **175B**, 125 (1986). R. Bertholet *et al.*, J. Phys. (Paris), Colloq. **47**, C4-201 (1986).

[4]J. Stevenson *et al.*, Phys. Rev. Lett. **57**, 555 (1986).

[5]H. Nifenecker and J. P. Bondorf, Nucl. Phys. **A442**, 478 (1985).

[6]W. Cassing *et al.*, Phys. Lett. **181B**, 217 (1986).

[7]O. Newton *et al.*, Phys. Rev. Lett. **46**, 1383 (1981).

[8]K. A. Snover, Annu. Rev. Nucl. Part. Sci. **36**, xx (1986).

[9]J. J. Gaardhøje *et al.*, Phys. Rev. Lett. **53**, 148 (1984), and **56**, 1783 (1986).

[10]B. Haas *et al.*, Phys. Lett. **120B**, 79 (1983).

[11]R. A. Broglia, in *Proceedings of the Twenty-fifth International Winter Meeting on Nuclear Physics, Bormio, Italy, 1986*, edited by I. Iori (Univ. of Milan Press, Milan, Italy, 1986), p. 23.

[12]J. D. Kellie *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **241**, 153 (1985).

[13]U. Kneissl *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **127**, 1 (1975).

[14]R. Brun *et al.*, GEANT3, CERN Report No. CERN/DD/EE/84-1, 1986 (unpublished); S. Riess, thesis, Universität Giessen, 1987 (unpublished).

[15]R. Hingmann *et al.*, Nouvelles de GANIL **17**, 8 (1986).

[16]T. Murakami *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **253**, 163 (1986).

[17]F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).