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Abstract

The γ decay of the giant dipole resonance has been studied with mass-symmetric and mass-asymmetric fusion-evaporation reactions similar to those for which entrance-channel effects were previously reported in the population of superdeformed bands. No entrance-channel effects have been observed in the high-energy γ-ray spectra associated with the decay of the ^{146}Gd compound nucleus populated at an excitation energy of 82 MeV via the reactions ^{30}Si+^{116}Sn and ^{76}Ge+^{70}Ge. The absence of entrance-channel effects in the present data set is well explained by dissipative collision calculations.

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In the last few years, the high-energy γ rays associated with the decay of the giant dipole resonance (GDR) have been successfully used as a probe of the dynamics of heavy-ion fusion reactions. In particular, it has been shown that some mass-symmetric reactions take a relatively long time to reach equilibrium, and that pre-equilibrium effects can strongly affect the shape of the GDR spectrum [1]. The study of the feeding mechanism of superdeformed bands can also provide some information concerning reaction dynamics. In contrast with the results obtained for the superdeformed bands in the $A \sim 130$ [2,3] and $A \sim 190$ [4] mass regions, the superdeformed bands in the $A \sim 150$ mass region are more strongly populated in fusion reactions symmetric in mass in the entrance channel [5,6]. Smith *et al.* have suggested [5] that the observed differences in the population of the superdeformed bands could be due to a longer compound-nucleus formation time for symmetric reactions when compared with asymmetric target-projectile combinations. If this explanation is correct, a measurement of the high-energy γ-ray spectra associated with such reactions should reveal the difference in the fusion times.

An experiment was performed in order to search for the above-mentioned entrance-channel effects in the GDR decay. The compound nucleus ^{146}Gd was populated at an excitation energy of 82 MeV with a mass-symmetric (^{76}Ge+^{70}Ge) and a mass-asymmetric (^{30}Si+^{116}Sn) reaction at bombarding energies of 319 and 156 MeV, respectively. These reactions were selected to produce the compound nucleus at excitation energies and angular momenta similar to the entry conditions used in the investigations of the superdeformed band feeding in the $A \sim 150$ mass region [5,6]. Furthermore, the selected reactions have the same asymmetry in their ratios (N/Z) of the number of neutrons to protons. Therefore, the GDR spectra should not present major differences due to pre-equilibrium effects associated with the N/Z asymmetry in the entrance channel [7].

The silicon and germanium beams were provided by the accelerators at the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at the Chalk River Laboratories. The targets, consisting of stacks of two thin foils ($\sim$0.4 mg/cm^2 of ^{116}Sn and $\sim$0.3 mg/cm^2 of ^{70}Ge), were surrounded by a 44-element array of CsI crystals [8] to detect charged particles evaporated by the hot nuclei. The γ rays emitted by the de-exciting nuclei were detected with half of the 8π spectrometer [9]. (The second half of the spectrometer was moved away from the beam axis by 0.6 m relative to its usual position, in order to study our ability to discriminate between γ rays and neutron-induced events by a time-of-flight technique.) The bismuth germanate (BGO) core of the spectrometer was used as a calorimeter and multiplicity filter. Furthermore, the high-energy γ rays associated with the GDR decay were measured by the individual BGO scintillators of the half of the spectrometer close to the target. The γ-ray detectors were energy calibrated with ^{88}Y (0.898 MeV and 1.836 MeV) and Pu-Be (4.439 MeV) γ sources. The energy calibration of the BGO detectors was monitored in beam by measuring the 10.20 MeV γ ray following the capture of thermalized neutrons by ^{73}Ge [10]. The trigger to record an event on tape required that at least one Compton-suppressed HPGe detector and four BGO elements responded, with the detection of at least 2.5 MeV of energy by one of the BGO crystals. The HPGe detectors were collimated, so their inclusion in the trigger reduced the background by selecting reactions that occurred at the target position. A further reduction of the background and an increase in the selectivity of fusion-evaporation events were obtained in the off-line analysis by requiring the response of at least one charged-particle detector. Because the total cross section for the gadolinium isotopes (xn channels) represents less than 10% of the total yield of evaporation residues, the charged-particle coincidence restriction does not strongly bias our results and we have verified that it does not modify our main conclusion. Due to the kinematics of the reactions, the neutrons are preferentially emitted in the forward direction in the laboratory frame of reference. The neutron-induced background was reduced by imposing a narrow time window in the off-line replay and the analysis was restricted to events that fired BGO elements located at backward angles.

As can been seen in Fig. 1, the distributions in the number of BGO elements that fired, K, are virtually identical for both reactions. Angular momentum ranges in the compound system have been selected by imposing conditions on K. Figure 2 presents the high-energy γ-ray spectra associated with the conditions $4 \leq K \leq 8$, $9 \leq K \leq 12$, and $13 \leq K \leq 20$ corresponding approximately to average angular momenta of 22 $\hbar$, 36 $\hbar$, and 58 $\hbar$, respectively. These spectra have been corrected for the Doppler effect and normalized in intensity between 3 and 18 MeV. For the three selected angular-momentum windows, the spectra associated with the mass-symmetric reaction are identical, within statistical accuracy, to the spectra corresponding to the mass-asymmetric reaction. This can also be seen in Fig. 3 where the experimental spectra have been linearized by dividing them by theoretical spectra calculated with the computer program CASCADE [11] with a constant E1 strength function taking into account the response of the BGO detectors with the GEANT [12] subroutine package. This demonstrates that there is no evidence of entrance-channel effects from the high-energy γ-ray spectra for all three angular-momentum windows. Furthermore, the spectra for the mass-symmetric and mass-asymmetric reactions are well reproduced by statistical calculations without the inclusion of any time delay in the fusion process. Contrary to what could be inferred from a visual inspection of the linearized spectra (F_{GDR}) in Fig. 3, the centroid of the GDR strength function remains constant with increasing angular momentum. The *apparent* decrease of the centroid energy was recently explained in detail by Noorman *et al.* [13].

The absence of entrance-channel effects in the selected reactions can be readily explained by a dissipative collision model. In Fig. 4, the calculations performed with the code HICOL [14] show that the times required to reach equilibrium are very similar for both reactions. At low angular momenta, the compound-nucleus formation time is slightly longer for the symmetric reaction, but the difference is not large enough to produce any observable effects in fusion-evaporation events. Furthermore, this small time difference tends to disappear at higher angular momenta. Since the superdeformed bands in the $A \sim 150$ mass region are populated at very high spins, we can conclude that the intensity enhancement observed with mass-symmetric reactions [5,6] is not an entrance-channel effect associated with an increase in fusion time. We should point out that the calculations recently performed by Viesti *et al.* [3] corroborate this conclusion. The observed enhancement could simply be due to a difference in the angular momentum distribution of the compound system, the highest partial waves having a non-vanishing probability to survive fission and, consequently, to populate the evaporation residues and the superdeformed structures.

In summary, we have studied the high-energy γ-ray spectra associated with mass-symmetric and mass-asymmetric fusion-evaporation reactions. Enhancements of the population intensity of superdeformed bands have previously been reported for similar symmetric reactions in the $A \sim 150$ mass region. However, no entrance-channel effects have been observed in the γ-ray decay of the giant dipole resonance. This absence of measurable entrance-channel effects is consistent with dissipative collision calculations. Therefore, it can be concluded that the feeding enhancement for superdeformed bands is not an entrance-channel effect associated with an increase of the fusion time for mass-symmetric reactions.

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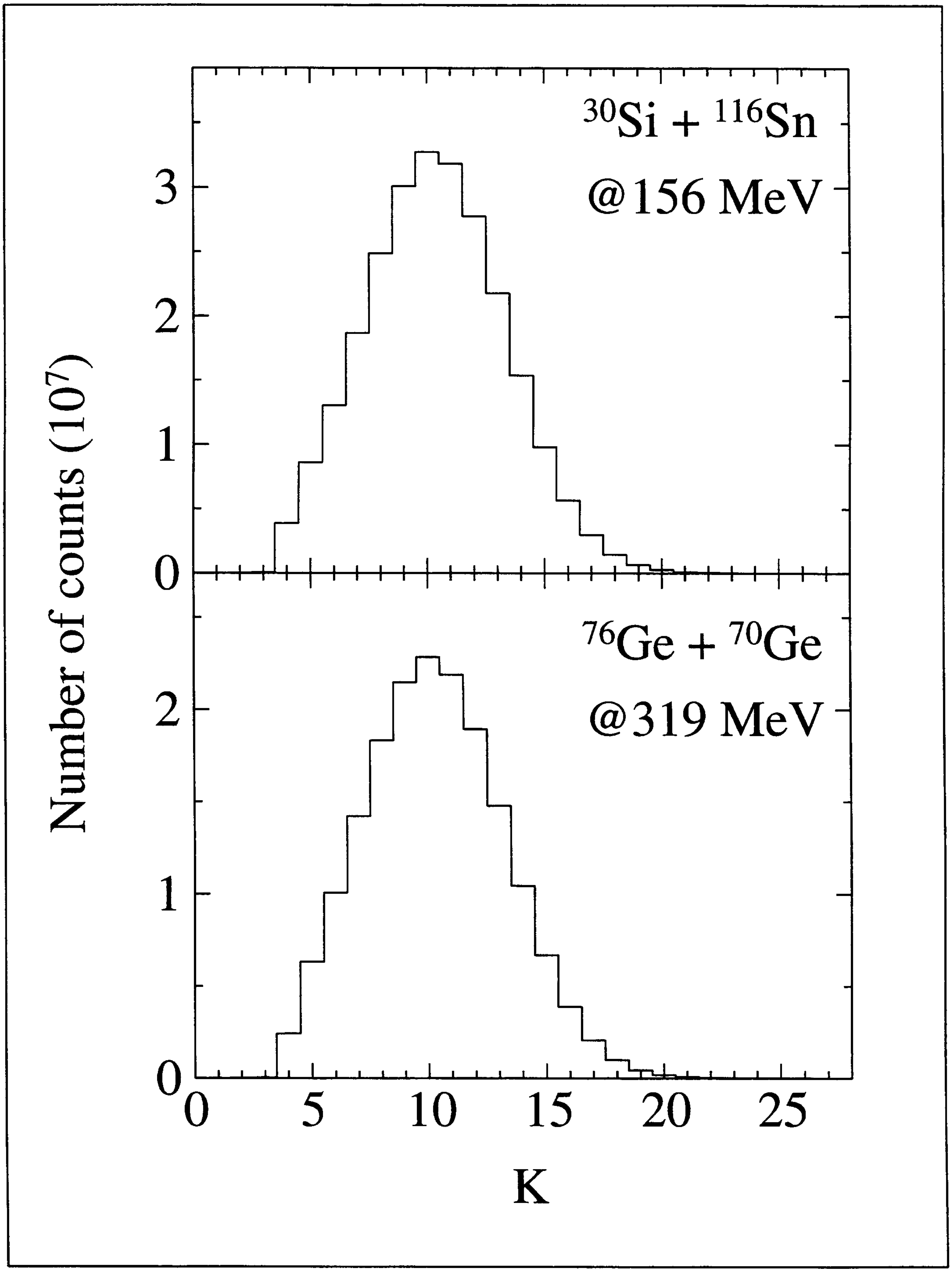
FIGURES

FIG. 1. Number of responding BGO detectors, K, measured for the reactions $^{30}Si+^{116}Sn$ and $^{76}Ge+^{70}Ge$ at bombarding energies of 156 and 319 MeV, respectively.

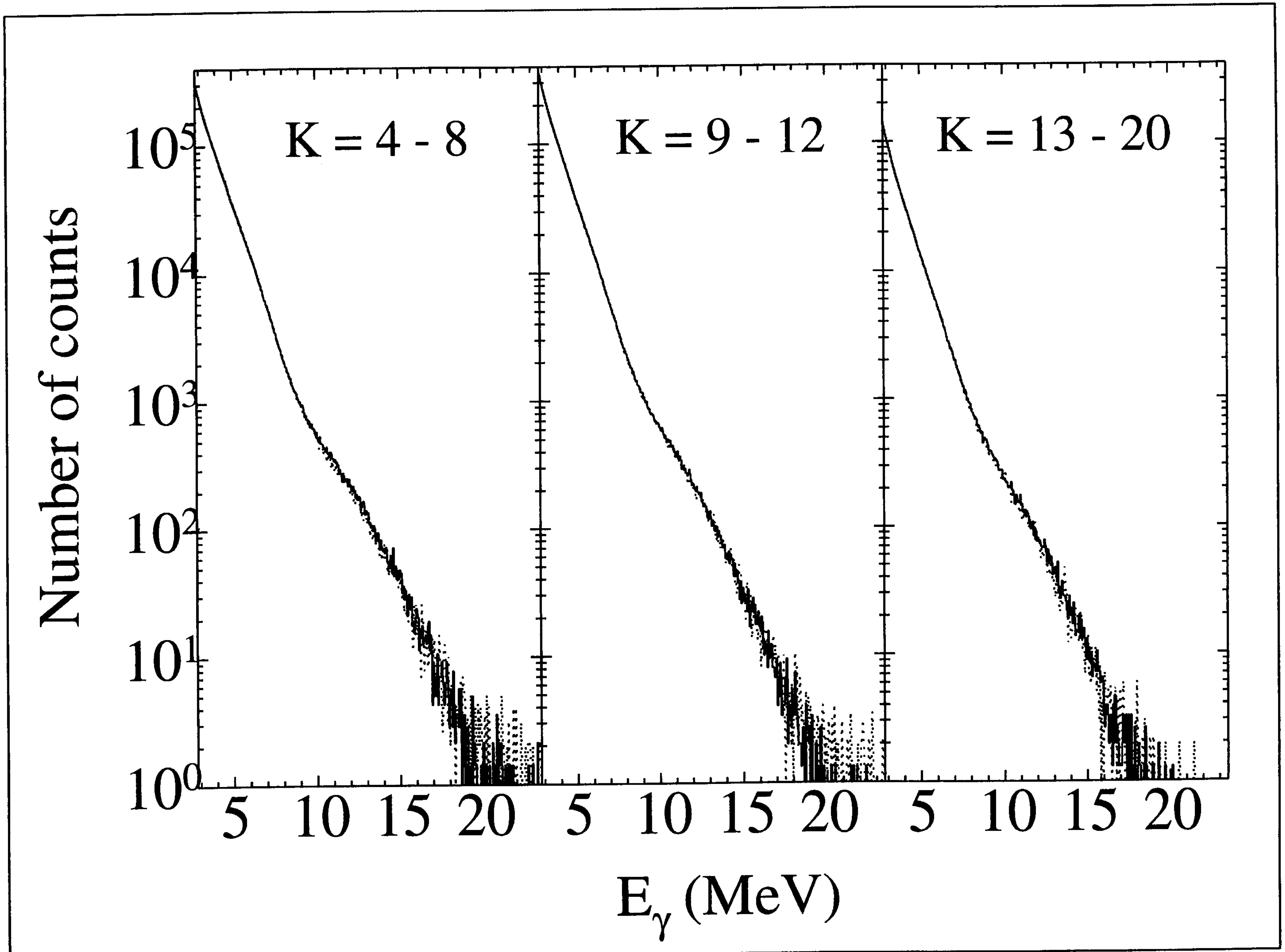
FIG. 2. Gamma-ray spectra measured with the reactions $^{30}Si+^{116}Sn$ (solid lines) and $^{76}Ge+^{70}Ge$ (dotted lines) for three different K windows. The spectra for the mass-symmetric and mass-asymmetric reactions have been normalized in intensity between 3 and 18 MeV. Where not seen, the dotted lines lie strictly on top of the solid lines.

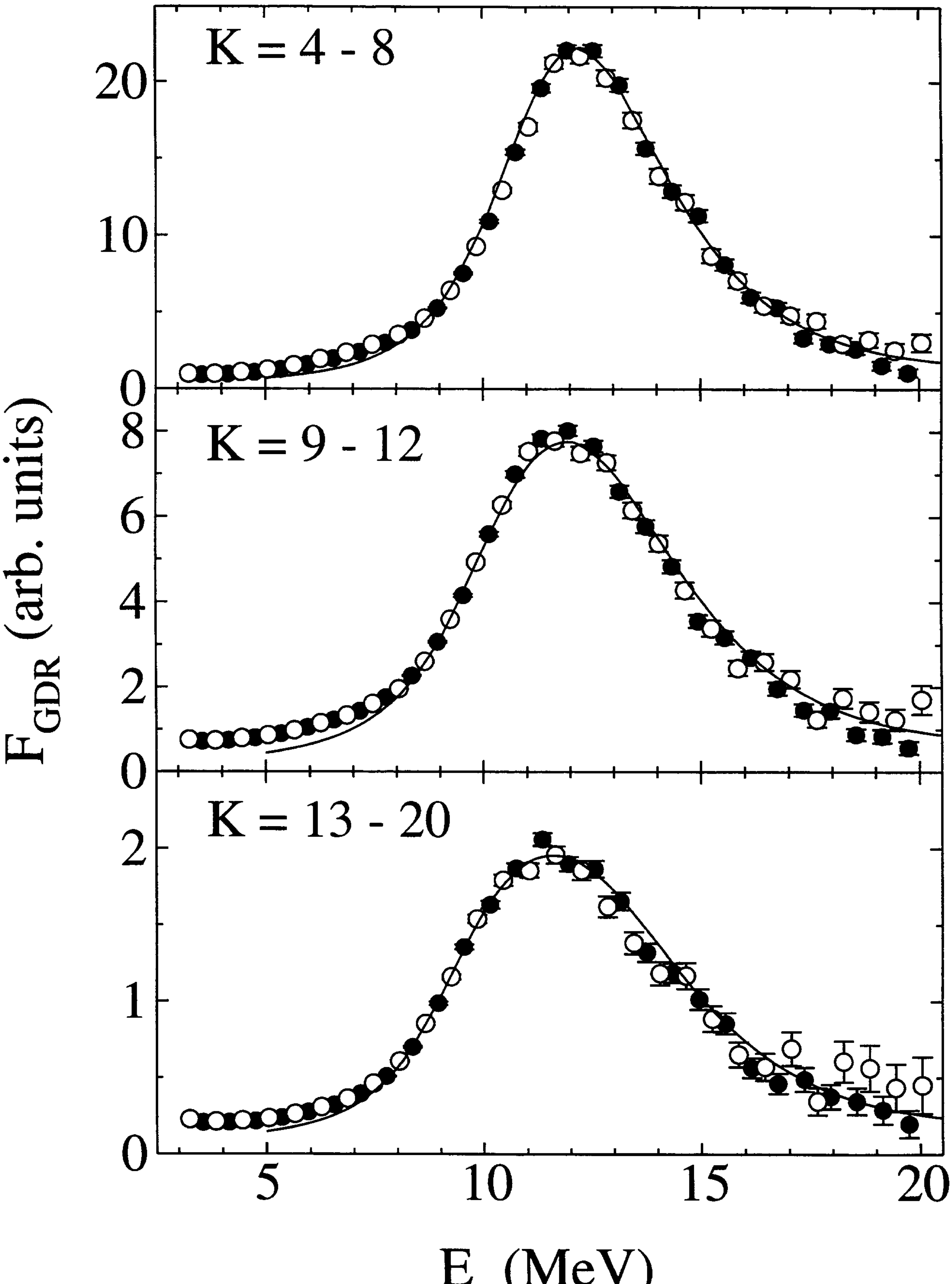
FIG. 3. Linearized plots (see text) of the experimental γ-ray spectra for the three selected K windows. The filled (empty) circles correspond to the reaction $^{30}Si+^{116}Sn$ ($^{76}Ge+^{70}Ge$). The linearized plots for the mass-symmetric and mass-asymmetric reactions have been normalized in intensity between 3 and 18 MeV. The solid lines correspond to calculations performed with the statistical code CASCADE with a single Lorentzian strength function with a centroid E_{GDR} = 13.8 MeV and a width Γ_{GDR} = 8.4 MeV.

FIG. 4. Evolution of the excitation energy relative to the equilibrium value as a function of time for the angular momenta I = 15, 40, and 65 $\hbar$. The solid (dashed) lines correspond to the reaction $^{30}Si+^{116}Sn$ ($^{76}Ge+^{70}Ge$) at a bombarding energy of 156 (319) MeV.



$^{30}Si + ^{116}Sn$
@156 MeV
$^{76}Ge + ^{70}Ge$
@319 MeV
Number of counts (10^7)
0
1
2
3
0
1
2
0
5
10
15
20
25
K


K = 4 - 8
K = 9 - 12
K = 13 - 20
Number of counts
10^5
10^4
10^3
10^2
10^1
10^0
5 10 15 20
5 10 15 20
5 10 15 20
E_γ (MeV)



K = 4 - 8
K = 9 - 12
K = 13 - 20
F_GDR (arb. units)
E_γ (MeV)
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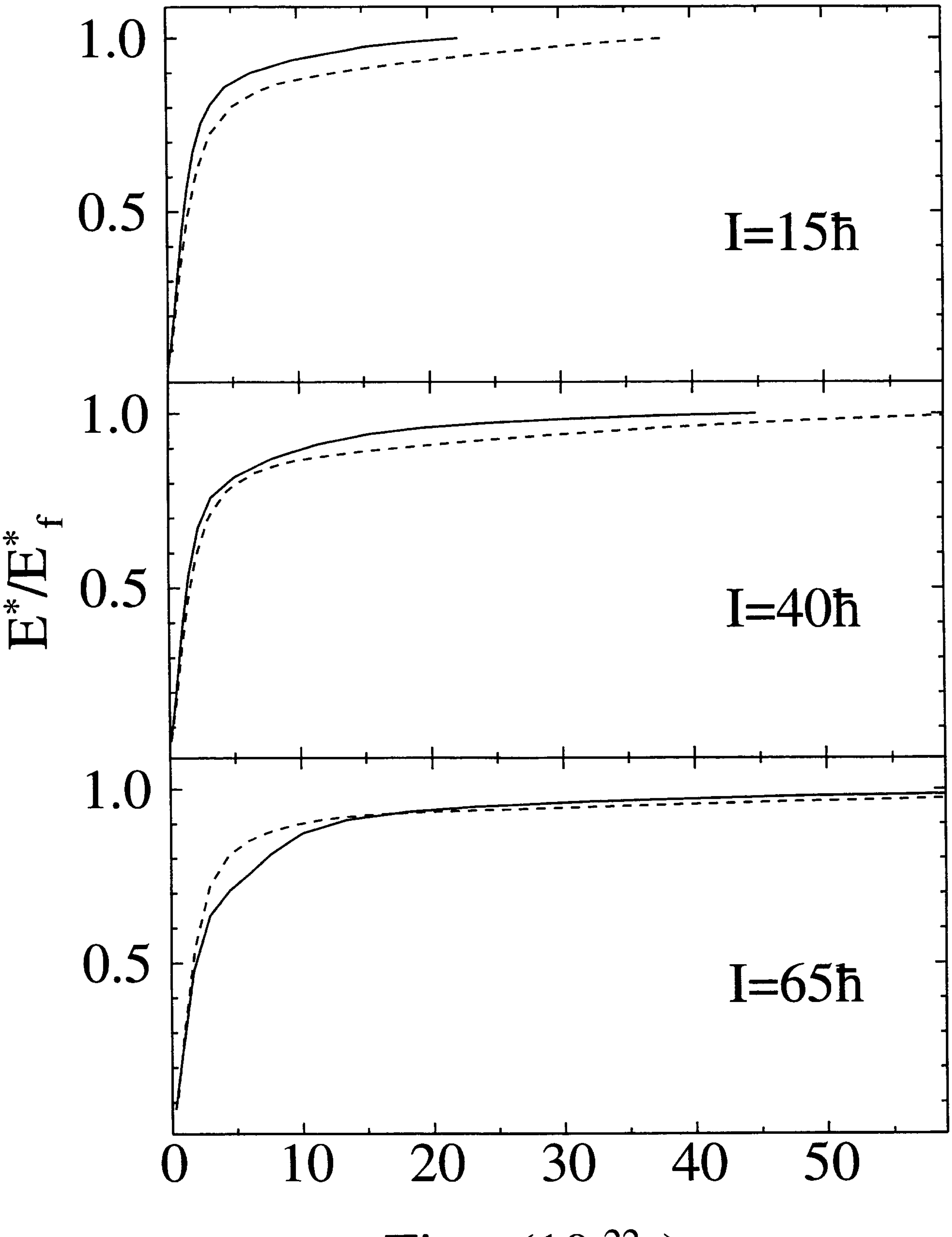
10
20
0
2
4
6
8
0
1
2
5
10
15
20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0.5
I=15ħ
1.0
0.5
I=40ħ
1.0
0.5
I=65ħ
E*/E*f
0
10
20
30
40
50
Time (10-22s)