BREMSSTRAHLUNG γ-RAY EMISSION IN HEAVY-ION COLLISIONS AT 6–11 MeV/u* **

M. Kicińska-Habior and Z. Trznadel

Institute of Experimental Physics, Warsaw University
Hoża 69, 00–681 Warsaw, Poland

(Received December 1, 1998)

It is shown that in mass-asymmetric reactions, such as $^{12}C + ^{24,26}Mg$ and $^{12}C + ^{58,64}Ni$, the two types of γ-ray radiation, statistical GDR decay and bremsstrahlung emission, may be disentangled by angular distribution measurements. The data are well reproduced when bremsstrahlung spectra are calculated for velocity of the emitting source $\beta_s = 0.5 \cdot \beta_{\rm beam}$ and an inverse slope parameter E_0 depending on γ-ray energy.

PACS numbers: 24.30.Cz, 25.70.–z, 23.20.–g

1. Introduction

I would like to discuss in this short report the bremsstrahlung photon emission in heavy-ion collisions at projectile energies around 10 MeV/u. Studies of this high-energy component in a γ-ray spectrum measured at projectile energies in the intermediate range of 6–11 MeV/u are of great importance for extraction of the giant dipole resonance (GDR) parameters in hot nuclei as well as for an analysis of the bremsstrahlung process itself. We have analyzed data for four reactions in the projectile energy range of E_p/A = 6–11 MeV/u: $^{12}C+^{24,26}Mg$ [1] and $^{12}C+^{58,64}Ni$ [2] and have done some calculations for $^{18}O+^{100}Mo$ reaction measured in Seattle at projectile energy of 11 MeV/u [3]. For all these reactions high-energy γ-ray spectra at five (or three) angles have been measured and the angular coefficients $A_0(E_\gamma)$, $a_1(E_\gamma)$ and $a_2(E_\gamma)$ have been extracted in the nucleus–nucleus CM frame from the data by fitting Legendre polynomials:

$$\frac{d^2\sigma(E_\gamma,\theta_{\rm CM})}{d\Omega dE_\gamma} = A_0(E_\gamma)[1 + a_1(E_\gamma)P_1(\cos\theta_{\rm CM}) + a_2(E_\gamma)P_2(\cos\theta_{\rm CM})]\,.$$

* Presented at the XXXIII Zakopane School of Physics, Zakopane, Poland, September 1–9, 1998.

** This work was partly supported by the Polish State Committee for Scientific Research (KBN Grant No. 2 P302 071 07).

The shape of γ-ray spectrum measured at these projectile energies is well known. It has a strong low-energy component caused by γ-decay of nuclei formed in fusion reaction and already cooled down by particle evaporation, a pronounced bump above $E_\gamma = 10$ MeV, which originates from the GDR decay in the initial compound nucleus and first daughter nuclei, and a nearly exponential tail at high-energy, well visible above $E_\gamma = 20$ MeV, which can be explained by the incoherent superposition of bremsstrahlung radiation emitted during individual first chance proton–neutron (p–n) collisions within participants zone. In all these studied cases the measured $a_1(E_\gamma)$ coefficients in the nucleus–nucleus CM frame are positive and the asymmetry of the angular distributions grows with the increase in the projectile energy. Since the $a_1(E_\gamma)$ coefficient should be zero for statistical emission, the non-zero value of the measured a_1 must result from the non-statistical bremsstrahlung emission in mass-asymmetric heavy-ion collisions. In order to disentangle the statistical GDR decay and the bremsstrahlung emission, measured γ-ray spectra ($A_0(E_\gamma)$) and angular distributions ($a_1(E_\gamma)$) have been fitted simultaneously by the sum of CASCADE calculations and non-statistical contribution $\sigma_{\rm brem}(E_\gamma)$, using new version of the CASIBR-FIT code [4]. It was assumed that the bremsstrahlung radiation is emitted in the first chance p–n collisions, its high-energy γ-ray spectra being exponential: $\sigma_{\rm brem}(E_\gamma) = \sigma_0 \exp(-E_\gamma/E_0)$, where E_0 is an inverse slope parameter. An isotropic angular distribution in the nucleon–nucleon CM frame was assumed. An analytic expression for the differential cross-section of the non-statistical emission in the nucleus–nucleus CM frame was derived and characterized by $a_1^{\rm brem}(E_\gamma) \neq 0$, which depends on the velocity β_s of the emitting source and E_0 value. We have assumed that $\beta_s = 0.5 \cdot \beta_{\rm beam}$, according to the experiments at higher projectile energies [5], and that E_0 does not depend on E_γ, *i.e.* $E_0 = {\rm const}$. In the fitting procedure, including folding of the calculated spectra with the detector line-shape, GDR parameters: S, $E_{\rm GDR}$, Γ and bremsstrahlung parameters: σ_0, E_0 are extracted. In this way we have been able to fit well the spectrum shape for all reactions studied and obtained reasonable fit parameters. However, the a_1 coefficients, especially for the highest projectile energy studied, could not be satisfactorily fitted [4] (see also dashed curve in Figs 5(a) and 6(a)). This fact inclined us to more detailed estimates of the bremsstrahlung spectra. Our knowledge of the bremsstrahlung emission at projectile energies around 10 MeV/u can be based on some experimental results at higher projectile energies, where this process is dominating and the statistical GDR decay contribution can be neglected. It can also rely on theoretical calculations, *i.e.* the BUU (Boltzmann–Uehling–Uhlenbeck) nuclear transport equation [6]. In this report the inclusive experimental results for ^{12}C+^{26}Mg and ^{12}C+^{64}Ni reactions at 11 MeV/u are presented in the light of the BUU calculations and compared with exclusive experiments at 40–60 MeV/u [7,8].

2. Results of BUU calculations

We have done BUU calculations for ^{12}C+^{26}Mg, ^{12}C+^{64}Ni and ^{18}O+^{100}Mo for E_p/A= 11 MeV/u with the code of Wolf [6]. Calculations of the γ-ray emission probability $P(b, E_\gamma)$ have been performed for several values of the impact parameter b in the range from 0 fm to the values corresponding to R_p+R_t, sum of the projectile and target nuclei, and for the collision time from t =0 to 100 fm/c, which corresponds to the first compression phase of the system. The BUU cross-section has been then calculated as

$$\sigma_{\rm BUU}(E_\gamma) = 2\pi \int\limits_0^{b_{\max}} P(b, E_\gamma)\, b\, db\,.$$

For all reactions studied here the function $P(b, E_\gamma) \cdot b$ peaks around the impact parameter value corresponding to the maximum angular momentum for complete fusion. Average impact parameters calculated with BUU are shown in Fig. 1. The $\sigma_{\rm BUU}(E_\gamma)$ has been also fitted with an exponential formula $\sigma_{\rm BUU}(E_\gamma) = \sigma_0 \exp(-E_\gamma/E_0)$ in order to extract an inverse slope parameter E_0. In all three cases the $\sigma_{\rm BUU}(E_\gamma)$ cannot be fitted with a single E_0 value in the whole range of E_γ = 10–50 MeV.

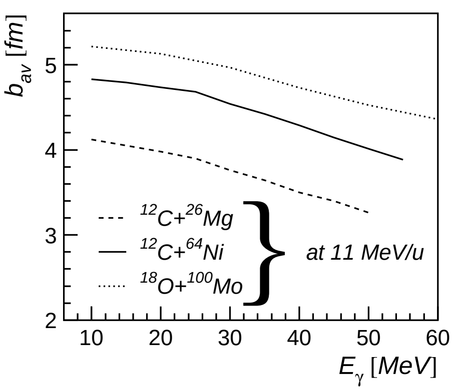

Fig. 1

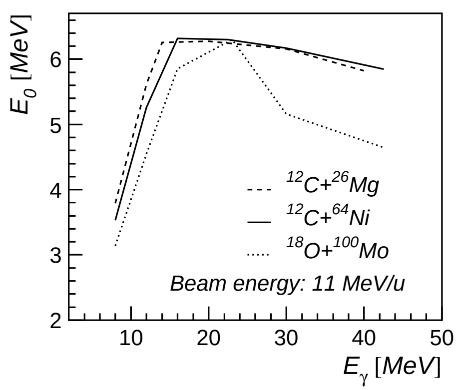

Fig. 2

Fig. 1. Average impact parameter calculated with BUU.

Fig. 2. Energy dependence of the inverse slope parameter calculated with BUU.

The E_0 value extracted for different energy intervals and scaled by a constant factor is shown in Fig. 2. For the ^{12}C+^{26}Mg and ^{12}C+^{64}Ni the behavior of E_0 versus E_γ is much the same. An increase for ^{18}O+^{100}Mo reaction at low energies is similar but a decrease at higher energies is faster. Such variations of E_0 versus E_γ may be connected with the dependence of the E_0 on the impact parameter b. An inverse slope parameter E_0^b extracted from the fitting of the exponential function to the $P(b, E_\gamma)$ for every b value in the range of $E_\gamma = 30$–55 MeV plotted versus $R_p + R_t - b$, an overlap distance between projectile and target, is decreasing when going from central collisions to the peripheral ones (Fig. 3). It means that the γ-ray spectrum for more central collision is harder. Similar effect was observed experimentally for Kr+Ni at 60 MeV/u [8], where various impact parameters have been selected from the charged particle multiplicity and PLF mass (Fig. 30 in [8]). It was explained by Martinez *et al.* [8] as a result of the dynamical effects in the collision. In the first compression phase in the heavy-ion reaction the bremsstrahlung photons are mostly emitted during a short time (few fm/c) after maximum density has been reached. During that time the

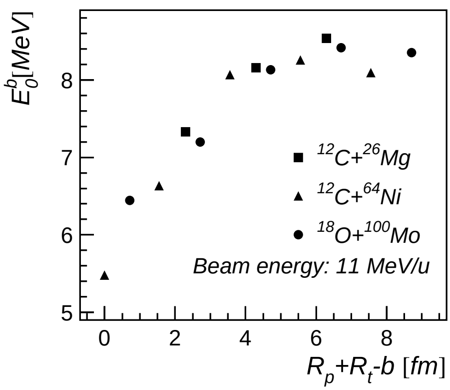

Fig. 3

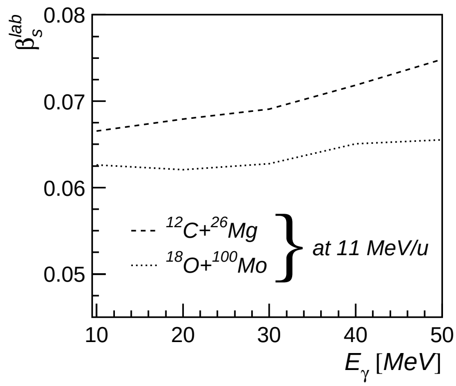

Fig. 4

Fig. 3. Inverse slope parameter E_0^b calculated with BUU

Fig. 4. Mean source velocity of the emitting source calculated with BUU

nucleons can be accelerated by the potential gradient which depends on the density and as a result they obtain an extra intrinsic momentum. Since the compression is less important in peripheral collisions, the acceleration and an extra intrinsic momentum are smaller. Consequently, the average energy available in an individual p–n collision is larger in central than in peripheral collisions. This is reflected in the photon energy and thus in the slope of the photon spectrum. The $E_0(E_\gamma)$ for Kr+Ni at 60 MeV/u and Ta+Au at 40 MeV/u extracted from the experimental data (Fig. 20 in Ref. [7]) shows similar behavior as found in our BUU calculations presented in Fig. 2. The absolute value of E_0 calculated within BUU for ^{12}C+^{26}Mg, ^{12}C+^{64}Ni and ^{18}O+^{100}Mo for $E_p/A=$ 11 MeV/u is larger than extracted from the CASIBRFIT and larger than estimated on the basis of the Cassing systematics [6,7]. Thus, $E_0(E_\gamma)$ shown in Fig. 2 was scaled by a constant factor to agree with the Cassing systematics at E_γ= 25 MeV. We have parameterized the $E_0(E_\gamma)$ dependence with a function: $E_0(E_\gamma) = E_0^0(1+aE_\gamma+bE_\gamma^2)$, where E_0^0 was treated as a variable parameter in CASIBRFIT calculations. Another quantity characteristic for bremsstrahlung emission, which can be estimated with the BUU, is the velocity β_s of the emitting source. Its value affects the asymmetry of the angular distribution in the laboratory frame due to the Doppler shift. Thus, the a_1 coefficient calculated in the nucleus–nucleus CM frame depends also on the source velocity used. In the simple picture of the individual first-chance p–n collisions β_s should be equal to the nucleon–nucleon CM velocity, $\beta_{\rm NN}$, which is close to the half of the beam velocity $\beta_{\rm beam}$. Due to the Fermi motion of nucleons in colliding nuclei the intrinsic momenta of the proton and the neutron in a p–n collision add to the relative momentum of the projectile and the target nucleons, and the resulting source velocity can differ from $\beta_{\rm NN}$. The mean source velocity β_s of the emitting source can be estimated from the source velocity distribution calculated with the BUU for each E_γ energy and impact parameter value. With increasing E_γ, the value of $\langle\beta_s\rangle$, averaged over impact parameter, approaches the value of the nucleon–nucleon CM velocity, $\beta_{\rm NN}$ (Fig. 4).

3. Results of the CASIBRFIT calculations

Calculations performed with the BUU for the three reactions studied gave consistent results and it has encouraged us to include the $E_0 = E_0(E_\gamma)$ and $\beta_s = \beta_s(E_\gamma)$ dependence in the CASIBRFIT code. The fits were done with 5 variable parameters: S, $E_{\rm GDR}$, Γ, σ_0, E_0, for different options with E_0= const, β_s= const, $E_0 = E_0(E_\gamma)$ and $\beta_s = \beta_s(E_\gamma)$, where the shape of the dependence on E_γ were done by BUU calculations. If the experimentally confirmed value of $\beta_s = 0.5 \cdot \beta_{\rm beam}$ is used, then in order to reproduce the $a_1(E_\gamma)$ coefficient data for ^{12}C+^{24,26}Mg reactions, a dependence $E_0(E_\gamma) = E_0^0(1 + 0.0078E_\gamma - 0.00019E_\gamma^2)$ was initially included [9], where E_0^0 was assumed to be a variable parameter. An even better fits were presently obtained for both ^{12}C+^{24,26}Mg and ^{12}C+^{64}Ni reactions with $E_0(E_\gamma) = E_0^0(1 + 0.0166E_\gamma - 0.00039E_\gamma^2)$, (1). Our data are not sensitive to the low-energy $E_0(E_\gamma)$ increase. However, in order to fit well $a_1(E_\gamma)$ at E_γ=30–50 MeV the $E_0(E_\gamma)$ has to have appropriate curvature. The fits performed with E_0= const and $\beta_s = 0.5 \cdot \beta_{\rm beam}$ (see dashed curve in Figs 5(a) and 6(a)) or β_s depending on energy to describe the BUU trend, failed to reproduce $a_1(E_\gamma)$. The $a_1(E_\gamma)$ can be fitted with E_0= const, for larger β_s value only, *i.e.* $\beta_s = 0.65 \cdot \beta_{\rm beam}$ (dotted line in Figs 5(a) and 6(a)), or β_s increasing from 0.47 $\cdot\beta_{\rm beam}$ up to $0.75 \cdot \beta_{\rm beam}$ in the range of E_γ = 20–50 MeV [4]. The best fits obtained at E_p/A = 11 MeV/u with $E_0 = E_0(E_\gamma)$ according to (1) and $\beta_s = 0.5 \cdot \beta_{\rm beam}$, high-energy γ-ray spec-

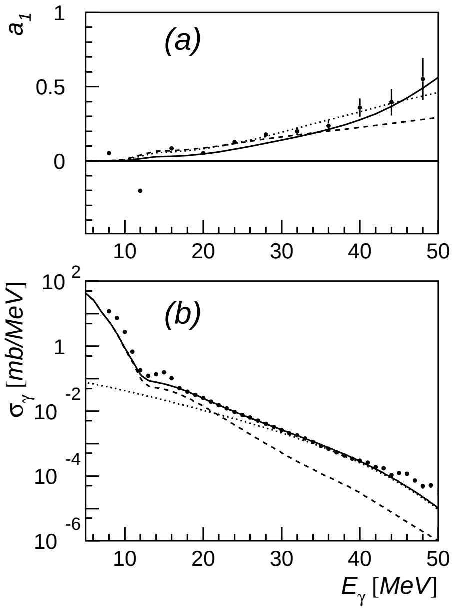

Fig. 5

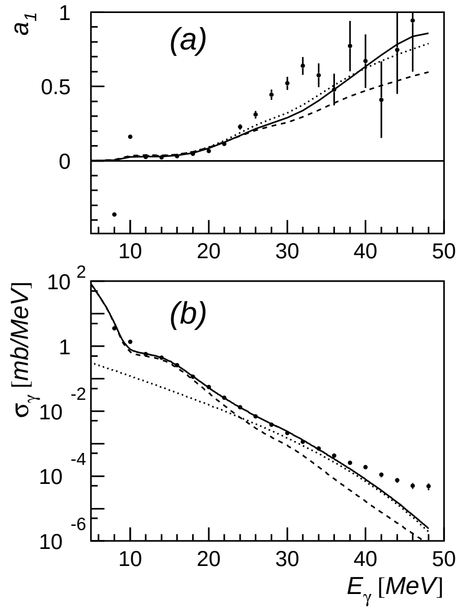

Fig. 6

Fig. 5. Gamma-ray spectra and a_1 coefficients for ^{12}C + ^{26}Mg reaction at 11 MeV/u (see text).

Fig. 6. Gamma-ray spectra and a_1 coefficients for ^{12}C + ^{64}Ni reaction at 11 MeV/u (see text).

tra and $a_1(E_\gamma)$ coefficients, are shown by solid curves together with the data in Figs 5 and 6. Bremsstrahlung and statistical spectra are shown in Figs 5(b) and 6(b) by dotted and dashed curves, respectively. It can be seen that the used energy dependence of $E_0(E_\gamma)$ gives lower bremsstrahlung cross-section at both low and high E_γ energies. The bremsstrahlung parameter $\langle E_0 \rangle = E_0(E_\gamma = 30$ MeV) extracted from the fits agrees with the values extrapolated from the Cassing systematics [6,7].

4. Conclusions

It was shown that by reproducing simultaneously the γ-ray spectra and the $a_1(E_\gamma)$ coefficients measured in heavy-ion collisions at 6–11 MeV/u it is possible to disentangle the statistical and non-statistical contributions and obtain also information about the bremsstrahlung process. Analyzed data for ^{12}C+^{24,26}Mg reaction as well as preliminary data for ^{12}C+^{58,64}Ni reaction suggest that the inverse slope parameter E_0 depends on γ-ray energy in agreement with BUU calculations, which may correspond to its dependence on impact parameter. However, the absolute values of E_0, obtained from BUU at E_p/A= 6–11 MeV, are larger than expected from systematics and obtained from CASIBRFIT fits to the data.

REFERENCES

[1] M. Kicińska-Habior, K.A. Snover, A. Maj, Z. Drebi, D. Ye, M. Kelly, *Acta Phys. Pol.* **B26**, 439 (1995).

[2] Z. Trznadel, M. Kicińska-Habior, M.P. Kelly, J.P.S. van Schagen, K.A. Snover, to be published.

[3] M.P. Kelly, J.P.S. van Schagen, K.A. Snover, M.Kicińska-Habior, Z. Trznadel Proceedings of the Topical Conference on Giant Resonances, Varenna, May 11–16, 1998, to be published in *Nucl. Phys.*

[4] M. Kicińska-Habior, Z. Trznadel, K.A. Snover, A. Maj, M. Kelly, *Acta Phys. Pol.* **B28**, 189 (1997).

[5] H. Nifenecker, J. Pinston, *Ann. Rev. Nucl. Part. Sci.* **40**, 113 (1990).

[6] W. Cassing, V. Metag, U. Mosel, K. Niita, *Phys. Rep.* **188**, 363 (1990); also G. Wolf, BUU code, private communication.

[7] Y. Shutz *et al.*, *Nucl. Phys.* **A622**, 404 (1997).

[8] G. Martinez *et al.*, *Phys. Lett.* **B334**, 23 (1994).

[9] M. Kicińska-Habior, Z. Trznadel, A. Maj, M.P. Kelly, J.P.S. van Schagen, K.A. Snover, Proceedings of the Topical Conference on Giant Resonances, Varenna, May 11–16, 1998, to be published in *Nucl. Phys.*