Vol. 33 (2002) ACTA PHYSICA POLONICA B No 3

ENERGETIC PHOTONS FROM HEAVY-ION REACTIONS AT 4–12 MeV/u*

M. Kicińska-Habior, Z. Trznadel, O. Kijewska, and E. Wójcik

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

(Received February 15, 2002)

Statistical emission is the main source of high-energy photons measured in heavy-ion reactions at projectile energies up to 5 MeV/u, as it is shown for ^{12}C + ^{58,64}Ni reactions. At higher projectile energies another important process occurs — the bremsstrahlung emission. Besides that, the Giant Dipole Resonance can be excited in hot nuclei produced not only via complete fusion reactions but also by incomplete fusion and/or after - preequilibrium emission of light particles. The importance of those processes is demonstrated for ^{12}C + ^{58,64}Ni and other reactions.

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

1. Introduction

The intention of this report is to present sources of energetic photons from heavy-ion reactions at projectile energy $E_{\rm p}/A = 4$–12 MeV/u and to show how they influence the Giant Dipole Resonance (GDR) parameters extracted from the measured photon spectra. Generally, there are two main sources of high-energy γ-rays in the energy range of interest: statistical emission due to the decay of the GDR built in the highly excited compound nucleus and non-statistical emission originating from individual nucleon-nucleon collisions of the projectile and the target nuclei, *i.e.* bremsstrahlung emission.

At projectile energies below 5 MeV/u the bremsstrahlung radiation is negligible. Thus, the high-energy photons arise from the decay of the GDR built in the initial compound nucleus with initial excitation energy $E_{\rm in}$ formed in complete fusion reaction and in the daughter nuclei with lower mass and lower excitation energy populated during subsequent steps of the decay. The average excitation energy $\bar{E}_i$ of the average nucleus undergoing

* Presented at the VI TAPS Workshop, Krzyże, Poland, September 9–13, 2001.

the GDR decay corresponds to the excitation energy averaged over the decay steps. The GDR parameters extracted from the measured photon spectra are usually presented as a function of the nuclear temperature and/or spin. The average final-state temperature is defined as $T = [d\ \ln(\rho)/dE]^{-1}$ where ρ is the level density, and E is related to the average thermal energy of the final state $\bar{E}_{\rm f} = \bar{E}_i - \bar{E}_{\rm rot} - E_{\rm GDR}$ where $\bar{E}_{\rm rot}$ — averaged rotational energy of the average nucleus after the GDR decay, $E_{\rm GDR}$ — GDR resonance energy. The temperature T is then $T = \sqrt{\bar{E}_{\rm f}/a}$, where a — nuclear level density parameter. It has been found that the GDR strength S, and the centroid energy $E_{\rm GDR}$ are not affected by the nuclear temperature and spin. The width Γ increases rapidly with spin and temperature due to increasing spin induced deformation and increasing thermal shape fluctuations.

At higher bombarding energies, where the angular momentum saturates, it has been proposed that the GDR width should saturate [1]. However, at these energies the nonstatistical bremsstrahlung emission occurs and it has to be taken into account. Moreover, the compound nucleus in which the GDR is built can be formed in complete fusion, incomplete fusion, or after preequilibrium emission of light particles. Thus, the initial excitation energy of the decaying compound nuclei is difficult to estimate. We have shown [2] that the disentanglement of the bremsstrahlung and statistical γ-ray yields can be done when analyzing the angular distribution of high-energy γ-rays in terms of the Legendre polynomials. However, in order to estimate the preequilibrium and/or incomplete fusion losses of mass, charge, and excitation energy of the average produced compound nucleus, the experimental information from light charged particle and neutron spectra measured in coincidence with high-energy photons should also be available. It has been partially achieved for ^{18}O + ^{100}Mo reactions [3], where angular distributions of protons and α particles have been measured in coincidence with high-energy γ-rays in order to estimate preequilibrium losses. The neutron contribution has been determined by model calculations. It has been found that the effects of preequilibrium emission are significant in the studied energy range.

Here we refer mostly to the results obtained for ^{12}C + ^{58,64}Ni reactions at $E_{\rm p}/A$ = 4–11 MeV/u presented by Trznadel in his PhD thesis [4,5]. Preliminary results for ^{20}Ne + ^{12}C reaction are also shown.

2. Experimental results

Measurements of the ^{12}C+^{58,64}Ni reactions at 4 MeV/u and the ^{20}Ne+^{12}C reaction at 5.2 MeV/u have been undertaken using the cyclotron beams at the Heavy-Ion Laboratory of Warsaw University. High-energy γ-rays have been detected in a large NaI spectrometer in the JANOSIK set-up [6]. For all the studied reactions the γ-ray emission cross-sections and angular distributions have been measured. Angular distribution coefficients $A_0(E_\gamma)$, $a_1(E_\gamma)$ and $a_2(E_\gamma)$ for ^{12}C + ^{58,64}Ni reactions have been extracted from the data measured at three angles: 60°, 90° and 120°. The $a_1(E_\gamma)$ coefficient has been found to be close to zero proving statistical character of the measured γ-ray spectra. The $a_2(E_\gamma)$ for ^{76}Se is showing the dispersion shape which suggests the deformation of that nucleus [4]. For the ^{20}Ne + ^{12}C reaction the angular distribution data are presently under analysis.

Data for the ^{12}C + ^{58,64}Ni reactions at higher projectile energies of 5.5, 8 and 11 MeV/u have been measured at the University of Washington Nuclear Physics Laboratory using the tandem-liniac accelerator beams. High-energy γ-rays have been measured with three large NaI spectrometers. Gamma-ray spectra at five angles: 40°, 55°, 90°, 125° and 140° and at each projectile energy have been fitted by the Legendre polynomials and the $A_0(E_\gamma)$, $a_1(E_\gamma)$ and $a_2(E_\gamma)$ coefficients have been extracted. A large bremsstrahlung tail in the $A_0(E_\gamma)$ spectrum and large positive $a_1(E_\gamma)$ coefficient value, increasing with projectile energy have been found at γ-ray energies above 20 MeV [4,5].

3. Data analysis and results

Gamma-ray energy spectra for the ^{12}C + ^{58,64}Ni and ^{20}Ne + ^{12}C reactions measured at $E_\mathrm{p}/A = 4$ and 5.2 MeV/u, respectively, have been analyzed assuming statistical decay of the compound nucleus formed in complete fusion reaction, only. The spectra have been fitted by using CASCADE code with Reisdorf level density approach in statistical model calculations. The GDR contributions for ^{76}Se and ^{32}S (Fig. 1) are described better when double Lorentz functions are used for the GDR strength function. It suggests the deformation of nuclei studied in agreement with the observed character of $a_2(E_\gamma)$ dependence for ^{12}C + ^{64}Ni reaction.

For higher projectile energies the measured energy spectra and angular distributions of emitted γ-rays have been analyzed taking into account statistical decay of the compound nuclei formed in complete and incomplete fusion and nonstatistical bremsstrahlung emission. The $A_0(E_\gamma)$ spectra and $a_1(E_\gamma)$ coefficients have been fitted with CASIBRFIT code [2] calculations, including complete fusion, incomplete fusion, and bremsstrahlung emission. An isotropic angular distribution and an exponential spectrum shape: $\sigma = \sigma_0 \exp(-E_\gamma/E_0)$ have been assumed for the bremsstrahlung emission in the nucleon–nucleon CM frame. An inverse slope parameter E_0 was found to depend on the γ-ray energy in agreement with the dependence estimated on the basis of BUU transport equation calculations [4,5]. In order to see the effect of neglecting of an incomplete fusion process in statistical component of the γ-ray yield, the γ-ray spectrum has been calculated in

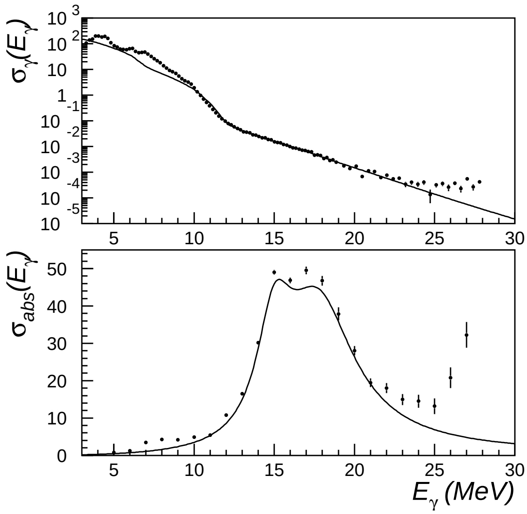

Fig. 1. Measured and fitted high-energy γ-ray spectrum (top) and absorption cross-section (bottom) for ^{20}Ne + ^{12}C reaction at 5.2 MeV/u. Preliminary results.

two ways. Firstly, statistical decay of the compound nucleus with initial mass, charge, spin and excitation energy as created in complete fusion was calculated. Secondly, an incomplete fusion has been included by assuming statistical decay of the compound nucleus which had mass, charge, spin and excitation energy reduced and estimated by averaging over those created in complete and incomplete fusion processes. In the ^{12}C+^{58,64}Ni experiment only γ-rays had been measured, thus the properties of the average compound nuclei created have been estimated using available experimental data for ^{12}C + ^{51}V reaction [7] and model calculations. It was assumed that an incomplete fusion process consisted in emission of ^{4}He and ^{8}Be clusters before equilibration of the composite system. The reduced initial excitation energies $E_{\rm init}$ calculated in this way for the reactions studied are shown in Fig. 2.

The extracted GDR parameters for ^{12}C + ^{58,64}Ni reactions in both cases, assuming complete fusion and bremsstrahlung only, and with an incomplete fusion included are shown in Fig. 3. It is clearly seen that the saturation of the GDR width above the $T = 2.4$ MeV found for ^{12}C + ^{64}Ni reaction analysis with incomplete fusion process neglected, does not occur when the incomplete fusion process is included. Thus, we claim that the GDR width is still increasing over temperature range up to 2.4 MeV. Similar effect has been found for ^{18}O + ^{100}Mo reaction mentioned earlier in the temperature range up to $T = 3.2$ MeV [3].

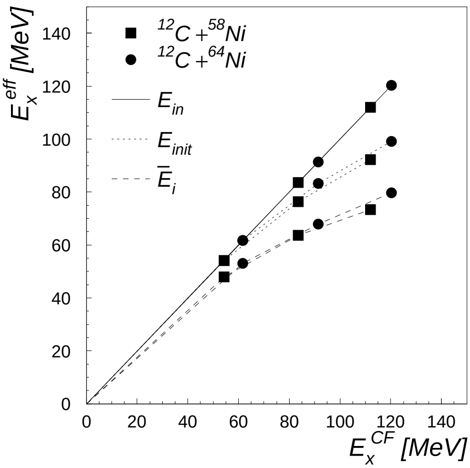

Fig. 2. Reduced average excitation energy of the compound nuclei produced in ^{12}C + ^{58,64}Ni reactions. Solid line: complete fusion initial excitation energy $E_{\rm in}$. Dotted lines: initial excitation energy $E_{\rm init}$ of the average compound nucleus formed in complete and incomplete fusion reactions. Dashed lines: Average excitation energy $\bar{E}_i$ preceding the GDR decay, *i.e.* $E_{\rm init}$ averaged over the decay steps.

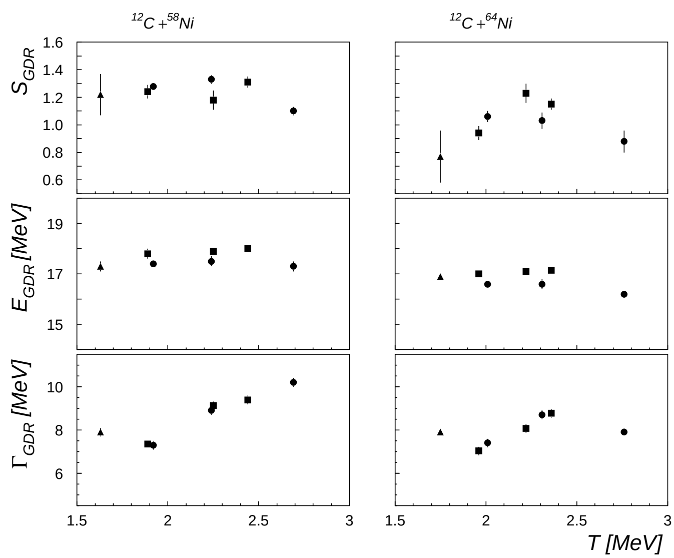

Fig. 3. Extracted GDR parameters for ^{12}C + ^{58}Ni (left) and ^{12}C + ^{64}Ni (right) as a function of nuclear effective temperature: squares — with incomplete fusion included, circles — without incomplete fusion.

The CASIBRFIT fitting analysis allowed also to extract the bremsstrahlung parameters and thus, the theoretical function reproducing the bremsstrahlung component of the γ-ray spectra for both measured reactions of ^{12}C + ^{58,64}Ni. The accuracy of the bremsstrahlung cross-section estimates depends mostly on the statistical accuracy of the measured $a_1(E_\gamma)$ coefficient value, which is the main constrain in the disentanglement of the bremsstrahlung and the statistical γ-ray yields, and only little on the characteristics of the processes responsible for the statistical component. The bremsstrahlung inverse slope parameters E_0 obtained from our analysis: 3.0 ± 0.1, 4.8 ± 0.1 and 5.7 ± 0.1 MeV for ^{12}C + ^{58}Ni at 5.5, 8 and 11 MeV/u, and 2.7 ± 0.1, 3.7 ± 0.1, 5.2 ± 0.1 MeV for ^{12}C + ^{64}Ni at 5.5, 8 and 11 MeV/u are in good agreement with the systematics for higher projectile energies [8]. It was also found that the ratio of the extracted bremsstrahlung cross-sections for ^{12}C + ^{64}Ni and ^{12}C + ^{58}Ni reactions (Fig. 4) is substantially larger than 1.19, the value expected for the ratio of high-energy photon production cross-sections calculated for our reactions according to the semiempirical formula [9, Eq. 5.1]. In that formula the cross-section at $E_\gamma >$

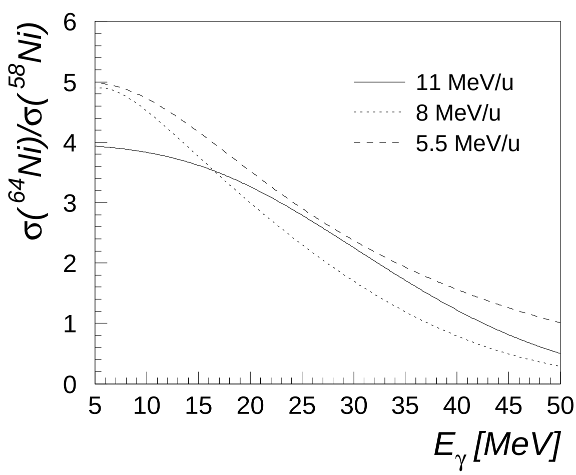

Fig. 4. Ratio of the fitted bremsstrahlung cross-section values for ^{12}C + ^{64}Ni reaction with respect to the ones for ^{12}C + ^{58}Ni reaction using CASIBRFIT code.

30 MeV is given by a product of the probability of γ-ray production in the individual first-chance n–p collision, the average number of first chance n–p collisions and the total reaction cross-section. Our estimates of that ratio, based on the presented analysis of the experimental data, are the most reliable at high γ-ray energies, $E_\gamma > 30$ MeV, where the bremsstrahlung cross-section clearly dominates over the statistical contribution. The ratio obtained around $E_\gamma = 30$ MeV for reactions studied at 5.5, 8 and 11 MeV/u

equals 2.4, 1.7 and 2.3, respectively, with the accuracy of about 0.2. Similiar effect was found in other cases when reactions with the same projectile but different target isotopes have been measured [10-12], and the ratio of cross-sections, for heavier and lighter target nuclei has been larger than expected by the semiempirical formula. In our previous studies of ^{12}C + ^{24,26}Mg at 11 MeV/u the ratio of experimental cross-sections was found to be 1.7 ± 0.1 compared with 1.03 from the formula. It was proposed [13] that this effect is a reflection of the differing nucleon momentum distributions in nuclei with different number of neutrons. In a nucleus with a larger number of neutrons there are more neutrons with a high momentum so that more high-energy photons can be produced in nucleon-nucleon collisions. Presentely, we have experimental evidence of such effect for two pairs of reactions and we have started its analysis.

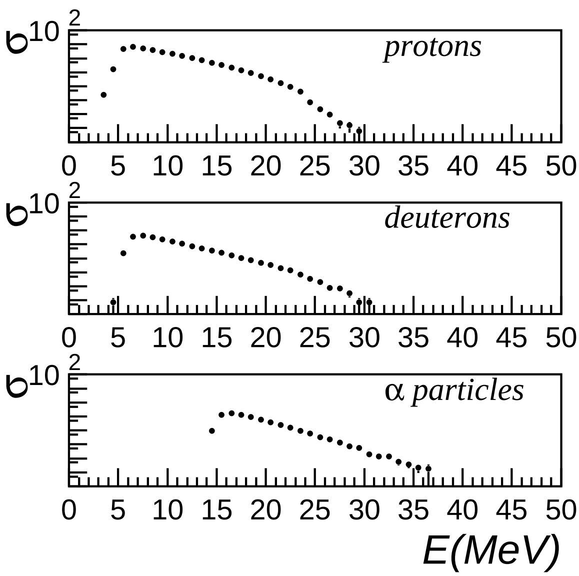

Fig. 5. Energy spectra for charged particles emitted in ^{20}Ne + ^{12}C reaction at 5.2 MeV/u measured with one Si-telescope positioned at 90°. Preliminary results.

4. Conclusions

The results of our study of the ^{12}C + ^{58,64}Ni reactions [4,5] together with ^{18}O + ^{100}Mo reaction results [3] show that all occurring processes have to be included in the correct analysis of the reactions. In order to have a reliable measure of the excitation energy, mass and charge of the decaying nucleus produced in heavy-ion reaction at bombarding energy above

6 MeV/u, light emitted particles should be measured and analyzed together with high-energy γ-rays. According to this we have already started a modification of the JANOSIK set-up which should allow the measurement of the energy spectra and angular distributions of light charged particles by the set of sixteen Si-telescopes attached to the JANOSIK set-up and placed around the target. Particle spectra for ^{20}Ne + ^{12}C reaction at 5.2 MeV/u have been measured with two Si-telescopes positioned at 50°, 90° and 130° (Fig. 5), to confirm the statistical character of the emission at this low projectile energy.

REFERENCES

[1] J.J. Gaardhoje, *Annu. Rev. Nucl. Part. Sci.* **42**, 483 (1992); G. Enders *et al.*, *Phys. Rev. Lett.* **69**, 249 (1992).

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

[3] M.P. Kelly, K.A. Snover, J.P.S. van Schagen, M. Kicińska-Habior, Z. Trznadel, *Phys. Rev. Lett.* **82**, 3404 (1999).

[4] Z. Trznadel, Ph.D thesis, Warsaw University, 2000.

[5] Z. Trznadel, M. Kicińska-Habior, M. P. Kelly, J.P.S. van Schagen, K.A. Snover, *Nucl. Phys.* **A687**, 198c (2001).

[6] M. Kicińska-Habior, Z. Trznadel, M. Kisieliński, M. Augsburg, D. Chmielewska, J. Dworski, A. Kordyasz, M. Kowalczyk, J. Kownacki, A. Krzyczkowska, J. Kwieciński, A. Maj, T. Matulewicz, J. Romanowski, Z. Sujkowski, Z. Żelazny, *Acta Phys. Pol.* **B28**, 219 (1997).

[7] D.J. Parker, J. Asher, T.W. Conlon, I. Naqib, *Phys. Rev.* **C30**, 143 (1984).

[8] Y. Schutz et al, G. Martinez, F. M. Marques, A. Martin, T. Matulewicz, R. W. Ostendorf, P. Bożek, H. Delagrange, J. Diaz, M. Franke, K. K. Gudima, S. Hlavac, R. Holzmann, P. Lautridou, F. Lefevre, H. Lohner, W. Mittig, M. Płoszajczak, J.H.G. van Pol, J. Quebert, P. Roussel-Chomaz, A. Schubert, R.H. Siemssen, R.S. Simon, Z. Sujkowski, V.D. Toneev, V. Wagner, H.W. Wilschut, G. Wolf, *Nucl. Phys.* **A622**, 404 (1997).

[9] W. Cassing, V. Metag, U. Mossel, K. Niita, *Phys. Rep.* **188**, 363 (1990).

[10] R.J. Vojtech, R. Butsch, V.M. Datar, M.G. Herman, R.L. McGrath, P. Paul, M. Thoennessen, *Phys. Rev.* **C40**, R2441 (1989).

[11] C.A. Gossett, J.A. Behr, S.J. Luke, B.T. McLain, D.P. Rosenzweig, K.A. Snover, W.T. Hering, *Phys. Rev.* **C42**, R1800 (1990).

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

[13] N. Gan, K.T. Brinkmann, A.L. Caraley, B.J. Fineman, W.J. Kernan, R.L. McGrath, P. Danielewicz, *Phys. Rev.* **C49**, 298 (1994).