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ULTRADIPOLE RADIATION FROM LOW–ENERGY HEAVY–ION REACTIONS*

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High-energy photon production in heavy-ion reactions at projectile energies around 10 MeV/u is discussed in the context of bremsstrahlung studies at $E_p/A \geq 20$ MeV/u. Recent results on the $^{12}C + ^{26}Mg$ reaction at 6, 8.5 and 11 MeV/u and the $^{12}C + ^{24}Mg$ reaction at 11 MeV/u studied by the Warsaw-Seattle-Cracow collaboration are summarized.

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1. Introduction

The intention of this talk is to present recent results on a high-energy γ-ray production following heavy-ion collisions at projectile energies around 10 MeV/u. The subject will be limited to the so called ultradipole radiation (UDR) or bremsstrahlung radiation, since the giant dipole resonance (GDR) decay has been widely discussed by previous speakers. The knowledge of the UDR parameters is of large importance also for statistical GDR decay studies at projectile energies higher than 5–6 MeV/u since in such case the bremsstrahlung is present in γ-ray spectra as a high-energy tail. Only

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a few experiments concerning the UDR studies at beam energies below 20 MeV/u have been reported in the literature [1–4]. As it is a school, some general remarks concerning bremsstrahlung emission at beam energies higher than 20 MeV/u, where systematic studies have been performed [5, 6], will be included. A brief presentation of the most recent experimental results on the UDR obtained by the Warsaw–Seattle–Cracow collaboration at the University of Washington tandem liniac will also be given. Finally, a short report will be presented on the construction of a new experimental set-up for high-energy γ-ray studies at the Warsaw Cyclotron, which started operation in 1994.

There are two main mechanisms for high-energy photon production in heavy-ion collisions at projectile energies between 10 and 100 MeV/u: statistical emission and dynamical emission. Statistical emission occurs from a hot, compound system: compound nucleus in the thermodynamical equilibrium or a hot-spot. A basic feature of statistical emission is that the system does not remember its dynamical origin. Besides the recoil of the emitting source, the statistical emission is independent of the dynamical character of the heavy-ion reaction. At projectile energies $E_p/A \approx$ 5–6 MeV/u and lower, statistical emission is practically the only source of high-energy photons, and most of the radiation comes from the statistical decay of the giant dipole resonance built on highly excited states [7, 8]. Characteristic shape of the γ-ray spectrum measured in an inclusive experiment is shown in Fig. 1. The low-energy component of the spectrum corresponds to γ-ray emission from the compound nucleus after it has cooled to near or below the threshold energy for particle evaporation. The high-energy component corresponds to γ-ray emission in direct competition with particle evaporation. The high-energy component is mainly connected with γ-quanta from the decay of the GDR in the initial compound nucleus and in nuclei formed after one particle evaporation.

In the case of statistical emission the angular distribution of the high-energy γ-rays must be symmetrical with respect to 90 ° in the frame of the emitting source, *i.e.* in the nucleus-nucleus (projectile-target) center-of-mass frame. In such a frame an angular distribution is usually characterized by $a_1(E_\gamma)$ and $a_2(E_\gamma)$ coefficients defined by the formula:

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

In the case of pure statistical emission $a_1(E_\gamma) = 0$, while $a_2(E_\gamma)$ typically exhibits an asymmetric shape centered near the GDR resonance energy, and determined by the deformation of the nucleus in which the GDR has been excited [7–9] (Fig. 1). In the laboratory frame, the angular distribu-

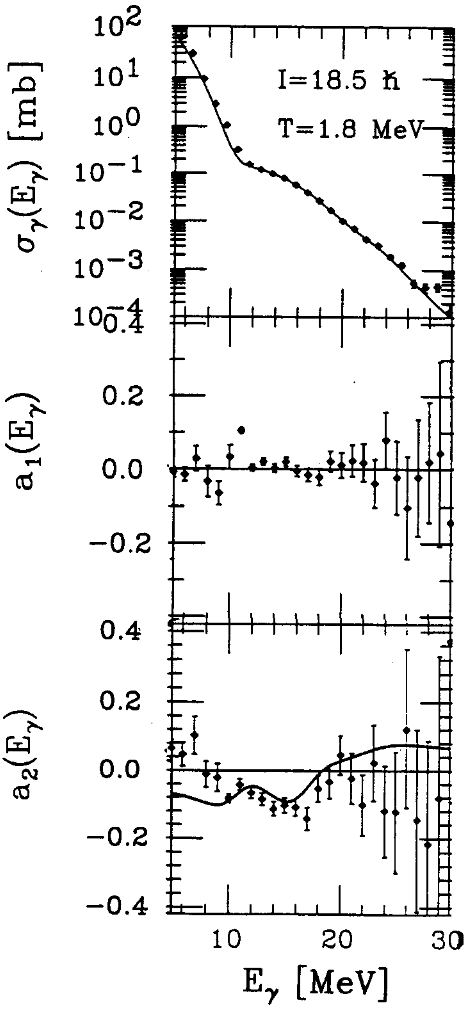

Fig. 1. Measured γ-ray spectrum (top), a_1 (middle) and a_2 (bottom) angular distribution coefficients for $^{18}O + ^{27}Al$ at $E_p = 72.5$ MeV. Solid line: least-squares-fitted statistical model calculations (top) and thermal shape and orientation fluctuation calculations (bottom) [9].

tion is forward peaked and its asymmetry results from the Doppler effect due to the recoil of the emitting source.

At projectile energies higher than $E_p/A \approx 5$–6 MeV/u statistical emission has been found to be not the only source of high-energy photons. An excess of photon yield over that expected on the basis of statistical decay has been observed in many studies on high-energy γ-ray production following heavy-ion collisions at energies 30-100 MeV/u [5, 6]. This additional "non-statistical" component in the γ-ray spectrum is especially visible for

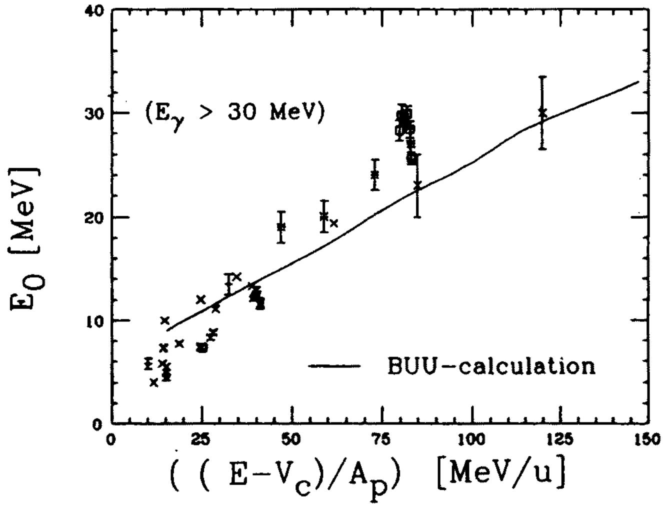

Fig. 2. The inverse slope parameter E_0 as a function of the Coulomb-corrected projectile energy (from Ref. [5]). Solid line: BUU calculations.

γ-ray energies exceeding the Giant Dipole Resonance region and this is why it is sometimes called ultradipole radiation. This radiation is also called bremsstrahlung radiation, since it is understood as γ-emission from electric charges moving with acceleration or deceleration in the nuclear field or in the Coulomb field. Such emission is dynamical in character and, contrary to statistical emission, it depends on the interaction between colliding nuclei.

2. Systematics of energetic photon production experimental data at $E_p/A \approx 20 - 100$ MeV/u

High-energy photon production following heavy-ion collisions at projectile energies $E_p/A \approx 20$–100 MeV/u has been studied systematically and the results are summarized in recent reviews [5, 6]. Some information relevant to the discussed subject is given below.

The characteristic feature of non-statistical γ-ray spectra is an approximate exponential shape well described by the formula $\sigma_{UDR}(E_\gamma) = \sigma_0 \cdot \exp(-E_\gamma/E_0)$, where $1/E_0$ is a slope parameter. The inverse slope parameter E_0, measured at $E_\gamma > 30$ MeV and at $\theta_{lab} = 90°$ in order to suppress the Doppler effect, exhibits a systematic dependence on the projectile energy, and is nearly independent of the combination of projectile and target nuclei (Fig. 2). Observations also point-out that the cross-section for high-energy γ-ray production integrated over $E_\gamma > 30$ MeV is proportional to $[A_p \cdot A_t]^{2/3}$, where A_p and A_t are the projectile and the target mass, respectively. It suggests that the number of nucleons taking part in the collision is important in determining the measured cross section.

Measured angular distributions of high-energy γ-rays beyond the GDR region ($E_\gamma > 25$ MeV) typically exhibit a large angular asymmetry in the laboratory frame. Angular distributions are found to be consistent with γ-ray emission occurring nearly isotropically from a source moving with a velocity close to one-half of the beam velocity. After transformation to the nucleus-nucleus center-of-mass frame the asymmetry with respect to 90° will be forward-peaked, absent, or backward peaked (positive, zero or negative values of $a_1(E_\gamma)$) depending on whether the projectile mass is heavier, equal to, or lighter than the target mass. Thus an attempt to differentiate between statistical decay and nucleon-nucleon bremsstrahlung may be performed on the basis of angular distribution when the collision is mass-asymmetric.

3. Mechanisms of UDR emission

From the theoretical point of view emission of ultradipole radiation may proceed via several mechanisms. Usually two extreme processes are compared: a collective nucleus-nucleus bremsstrahlung and an incoherent nucleon-nucleon bremsstrahlung. A collective nucleus-nucleus bremsstrahlung emission occurs when the projectile nucleus radiates as a result of the initial deceleration by Coulomb repulsion between the projectile and the target considered as simple entities, and subsequent acceleration in the nuclear field of the target and final slowing down as the projectile approaches the target. Energy of the photons produced via this mechanism is proportional to the acceleration (deceleration) of the projectile. Emission probability of photons with the highest energy depends on the acceleration and is the highest in the initial stages of the collision, before the nuclei slow down.

The angular distribution of the emitted radiation depends on the projectile-target combination and in general has a complicated pattern [10]. However, if the effective dipole charge of the projectile-target system equals zero then, in the long wavelength approximation, the angular distribution will have only a quadruple term.

It seems that the collective nucleus-nucleus bremsstrahlung is not observed in heavy-ion collisions at projectile energies $E_\mathrm{p}/A \approx 20$ - 100 MeV/u. For example the observed dependence of the cross section upon the nuclear charges is much slower than predicted by the collective model.

The most important mechanism for high-energy γ-ray production in heavy ion collisions is bremsstrahlung emission due to individual nucleon-nucleon (N-N) collisions, *i.e.* collisions between individual projectile and target nucleons. In this process, photons are produced when charged protons are accelerated or decelerated by the nucleon-nucleon interaction. The dominant contribution comes from electric dipole emission due to neutron-proton collisions. Proton-proton collisions, which produce only electric quadruple radiation, are usually neglected.

The probability of photon emission in an individual N-N collision can be calculated using the classical bremsstrahlung formula and assuming nucleon scattering by a hard-sphere potential [11]. It gives as a result [12]:

$$\frac{d^2N}{dE_\gamma d\Omega_\gamma} = \frac{e^2}{4\pi^2\hbar c} \cdot \frac{1}{E_\gamma} \cdot |\Delta\beta|^2 \cdot (2 + 3\sin^2\theta), \qquad (2)$$

where $\Delta\beta$ is the change in the nucleon velocity resulting from a collision. According to this formula, γ-ray emission from individual N-N collisions has a strong dipole character in the frame associated with the emitting source, i.e. in the nucleon-nucleon center-of-mass frame. In order to calculate a distribution of γ-ray emission in a heavy-ion collision one has to integrate the above formula over all possible momenta of colliding nucleons. As a result the angular distribution averages out and the distribution becomes nearly isotropic in the N-N center-of-mass frame, i.e. in the frame moving with one-half of the beam velocity. In the nucleus-nucleus center-of-mass frame such a distribution will be forward peaked ($a_1(E_\gamma) > 0$) for collisions in which the projectile is lighter than the target.

The probability of a photon emission in an individual N-N collision can also be calculated using the quantum Boltzmann-Uehling-Uhlenbeck (BUU) nuclear transport equation [13]. In this case, calculations are done in the momentum space. Nucleons in the projectile with their internal momentum distribution collide with nucleons in the target, also characterized by their internal momentum distribution. Fermi momentum for nucleons, *e.g.* in ^{12}C nucleus is $p_F \approx 220$ MeV/c, while in ^{118}Sn nucleus $p_F \approx 260$ MeV/c. The average relative momentum of the projectile and the target nucleons equals $p_{\rm rel}^{\rm N-N} = \sqrt{2m_{\rm n}(E_{\rm p} - V_{\rm C})/A}$, where $m_{\rm n}$ is the average nucleon mass, $V_{\rm C}$ is the Coulomb barrier. Thus at $E_{\rm p}/A = 40$ MeV/u the relative momentum is $p_{\rm rel}^{\rm N-N} \approx 272$ MeV/c and at $E_{\rm p}/A = 10$ MeV/u $p_{\rm rel}^{\rm N-N} \approx 136$ MeV/c. Therefore, it is possible that the relative motion of colliding nucleons couples with the Fermi motion of nucleons in the projectile and the target nuclei. This is illustrated in Fig. 3. Two spheres of Fermi momenta corresponding to the projectile and the target nucleons shifted by the average relative momentum per nucleon denote the initially occupied phase space. The final-state phase space, after emitting a high-energy photon, is limited to much smaller momenta. Pauli blocking severely inhibits high-energy photon production. States with low momentum are occupied before a collision and blocked because of the Pauli principle. Projectile and target nuclei are heated in the collision process and, thus, low-momentum states are partially available in the final state. Photons with the highest energy arise from the interaction of nucleons in the endcaps of the two Fermi spheres, since the nucleons in these regions have the largest acceleration. After photon emission those nucleons will tend to occupy states with momentum close to zero. However, there is large probability that these low-momentum states will be occupied, thus unavailable, and the interaction would not take place. In this way the general decrease of the cross section for high-energy γ-rays with increasing E_γ energy can be explained.

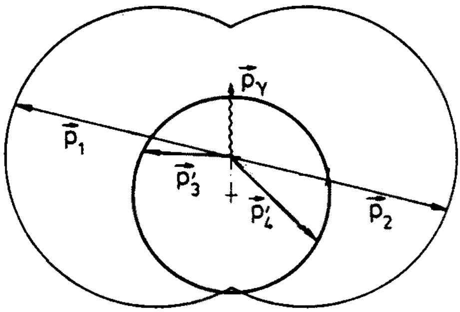

Fig. 3. Illustration of initial and final state phase space in a heavy-ion collision (from Ref.[5]).

In a complete treatment of the problem one should follow the evolution of the phase space distribution of projectile and target nucleons in time. Photon emission is possible at every stage of the collision. However, the dominant contribution to high-energy photon emission is from the first-chance neutron-proton collisions [5].

A semiempirical expression for a high-energy photon production cross section can be used [5, 6] in order to compare BUU calculations with the experimental data

$$\frac{d^2\sigma(E_\gamma > 30\mathrm{MeV})}{dE_\gamma d\Omega_\gamma} = \sigma_R \cdot \langle N_{\mathrm{np}} \rangle \cdot \frac{d^2 P}{dE_\gamma d\Omega_\gamma}. \tag{3}$$

The cross section is then given as a product of the probability of γ-ray production in the individual first-chance n-p collision $d^2P/dE_\gamma/d\Omega_\gamma$, the average number of first chance n-p collisions $\langle N_{\mathrm{np}} \rangle$, and the total reaction cross section σ_R. An estimate of the average number of n-p collisions can be made from the equal-participant model [10]

$$\langle N_{\mathrm{np}} \rangle = \frac{< A_F >}{A_{\mathrm{p}} A_{\mathrm{t}}} \cdot (Z_{\mathrm{p}} N_{\mathrm{t}} + Z_{\mathrm{t}} N_{\mathrm{p}}), \tag{4}$$

$$\langle A_F \rangle = A_{\mathrm{p}} \cdot \frac{5A_t^{\frac{2}{3}} - A_{\mathrm{p}}^{\frac{2}{3}}}{5(A_{\mathrm{t}}^{\frac{1}{3}} + A_{\mathrm{p}}^{\frac{1}{3}})^2}. \tag{5}$$

Probability of γ-ray production in the individual first-chance n-p collision depends on the elementary n-p-γ cross section and on the phase space distribution of the nucleons, and can be evaluated using the BUU equation.

The agreement between the BUU calculations done for $^{40}Ca + {}^{40}Ca$ and the experimental data for several reactions at projectile energies 20–100 MeV/u is satisfactory [5] (Fig. 2). The BUU calculations allow also to estimate a source velocity distribution for high-energy photon emission. Thus, one may argue that at projectile energies 20 - 100 MeV/u high-energy photon production is well described by incoherent nucleon-nucleon bremsstrahlung.

4. UDR from heavy–ion reactions at $E_p/A \approx 10$ MeV/u

Let us now consider how the high-energy photon production proceeds at lower projectile energies, around 10 MeV/u. The relative importance of Fermi motion of nucleons in colliding nuclei and Pauli blocking are expected to increase at these lower projectile energies, producing an increased sensitivity of the UDR yield to differences in the neutron-proton phase space distribution [4]. Conversely, the collective nucleus-nucleus bremsstrahlung process may become important for high-energy γ-ray production at lower beam energies since Pauli blocking will strongly limit high-energy γ-ray emission in N-N collisions. As it was already discussed, the nucleus-nucleus bremsstrahlung and the nucleon-nucleon bremsstrahlung processes should be easy to differentiate through a simultaneous measurement of the γ-ray spectra and angular distributions with extraction of the slope parameter and emitting source velocity. These are the general reasons for which studies of the high-energy photon emission following heavy-ion collisions at $E_p/A \approx$ 10 MeV/u become interesting. Such studies should also give information about an extrapolation of the n-p-γ probability and the $1/E_0$ slope to low projectile energies.

Among the few experimental studies of the high-energy γ-ray production following heavy-ion collisions at low projectile energies around 10 MeV/u, the measured data [1–4] seem to be consistent. It should be mentioned here that at projectile energies around 10 MeV/u, the contribution of statistical γ-ray emission at γ-ray energies above 30 MeV cannot be neglected. This is an additional difficulty, since this contribution has to be calculated using parameters which may change with projectile energy, *i.e.* with excitation energy of the compound nucleus. Simultaneous analysis of γ-ray spectra and angular distributions should be helpful in this procedure.

In the experimental studies of $^{12}C + {}^{92,100}Mo$ at $E_p/A = 9$-14 MeV/u [3] and $^{12}C + {}^{112,124}Sn$ at 7.5 and 10.5 MeV/u [2] an inverse slope parameter E_0 for the nonstatistical component in the γ-ray spectrum was estimated to be 4.1 ±0.2 MeV, which is in agreement with the systematics for higher projectile energies shown in Fig. 2. The velocity of the emitting source estimated on the basis of the measured angular distribution agrees within error with velocity of the N-N center-of-mass frame, suggesting emission from individual nucleon-nucleon collisions. Therefore, it seems that the high-energy photon production mechanism is here similar to that found for $E_p/A \approx$ 20–100 MeV/u. In ^{12}C + ^{112,124}Sn studies [2], the contribution of collective nucleus-nucleus bremsstrahlung was estimated and found to be 1–2 orders of magnitude lower than the measured cross section; its slope was also smaller than that observed experimentally.

In experiments at low beam energies the high-energy γ-ray production cross section has been measured in few cases for different target isotopes and the same projectile [2–4]. It was found that the cross section for heavier target nucleus is larger. The ratio of the yields for heavier to lighter isotope ($R_{\exp(\mathrm{Mo})} = 1.5 \pm 0.2$ [3], $\mathrm{R}_{\exp(\mathrm{Sn})} = 1.8 \pm 0.2$ [2]) is nearly constant with E_γ and is larger than the expected scaling factor corresponding to the ratio of the average number of the first-chance n-p collisions ($R_{N_{\mathrm{np}}(\mathrm{Mo})} = 1.02$, $R_{N_{\mathrm{np}}(\mathrm{Sn})} = 1.03$). A similar isotopic target effect has been found in the recent studies of ^{12}C + ^{112,124}Sn at 10 MeV/u [4] where it was proposed that this effect is a result of the different nucleon momentum distributions. The neutron momentum distribution in ^{112}Sn and ^{124}Sn nuclei is shown in Fig. 4. In a nucleus with a larger number of neutrons there are more neutrons with a high momentum and, thus, more high-energy photons can be produced in nucleon-nucleon collisions. Momentum distributions for protons are the same in both nuclei.

Recently, we have studied high-energy γ-ray emission in the ^{12}C + ^{26}Mg reaction at 6, 8.5 and 11 MeV/u and the ^{12}C + ^{24}Mg reaction at 11 MeV/u, using ^{12}C beams from the University of Washington tandem liniac. Inclusive γ-ray spectra and angular distributions have been measured in a large NaI(Tl) crystal with plastic anticoincidence and lead shields. Coincidence γ-ray spectra have been also measured using a multiplicity filter consisting of 23 small (3"x4") NaI(Tl) crystals. These reactions have been chosen in order to study the UDR at relatively low projectile energy for light targets and mass asymmetric entrance channel, as well as to check importance of bremsstrahlung at projectile energy about 6 MeV/u in collisions leading to $A \approx 40$ nuclei which have been previously studied [9] in a more symmetric entrance channel. Two different Mg isotopes have been chosen because in the ^{12}C + ^{24}Mg reaction an effective dipole charge is zero and possible contribution of the nucleus-nucleus bremsstrahlung vanishes. Additionally, in the ^{12}C + ^{24}Mg reaction the projectile and the target have isospin $T = 0$, so the statistical contribution should be low due to the pure isovector character of the GDR excitation. Thus, significant contribution

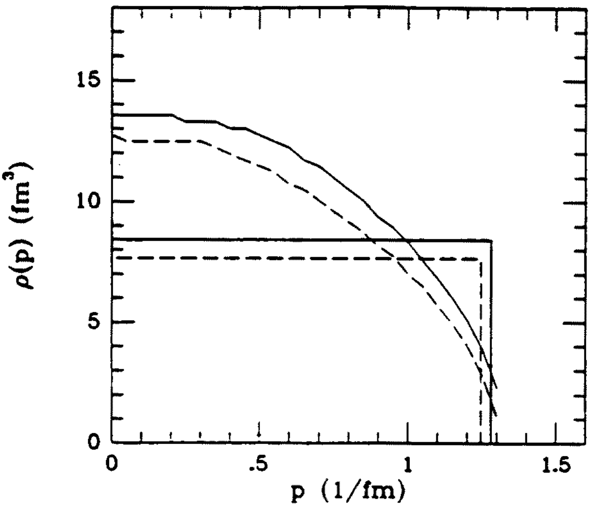

Fig. 4. Calculated momentum distribution of neutrons in ^{112}Sn (dashed line) and ^{124}Sn (solid line) in Thomas-Fermi and sharp sphere approximations (from Ref. [4]).

of the nucleon-nucleon bremsstrahlung emission should be seen in the ^{12}C + ^{24}Mg reaction. Finally, in case of ^{12}C + ^{26}Mg there are two more neutrons in the target nucleus. That is not a large change in the phase-space distribution but the percentage change is similar comparing with heavier targets. Hence it was interesting to check if any difference in the measured cross section for those two isotopes will be visible.

The measured inclusive γ-ray spectra and preliminary statistical model CASCADE calculations are shown in Fig. 5. In Fig. 6 the experimental spectra are compared with simple calculations assuming that the total cross section is described by the $\sigma = \sigma_0 \cdot \exp\,[-E_\gamma/E_0]$ component only, with an inverse slope parameter E_0 fitted to the data, and with an angular distribution assumed isotropic in the nucleon-nucleon CM system. The fitted E_0 parameter is in agreement with the systematics for higher energies. Also, a_1 coefficient for higher projectile energies is in good agreement with the pure UDR mechanism. From those two figures it is clear that while at the lowest projectile energy, $E_{\rm p}$ =73 MeV, statistical emission is the main source of γ-rays up to E_γ = 30 MeV, at two higher energies an excess of the cross section above the statistical component may be associated with the N-N bremsstrahlung.

It is intriguing that the ratio of the γ-ray yield for ^{26}Mg and ^{24}Mg targets is nearly constant with E_γ above E_γ = 20 MeV and equals 1.7 ± .1 when the scaling factor corresponding to the average number of first-chance n-p collisions is 1.03. Is it the result of the different phase-shape distribution? More detailed calculations are needed to answer this question.

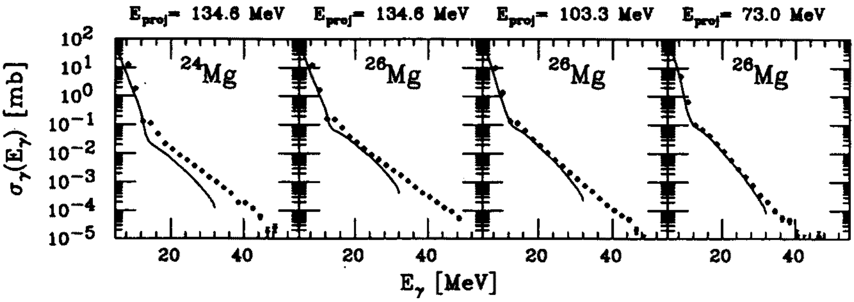

Fig. 5. Measured γ-ray spectra and preliminary statistical model calculations (solid line) for $^{12}C + ^{24}Mg$ at 11 MeV/u and $^{12}C + ^{26}Mg$ at 11, 8.5 and 6 MeV/u.

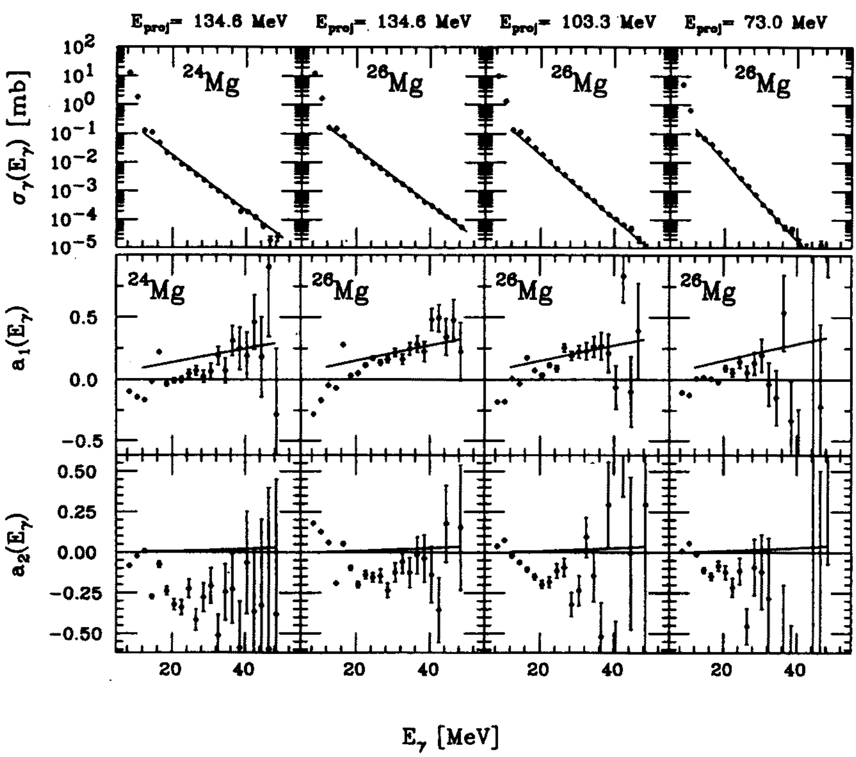

Fig. 6. Measured γ-ray spectra and angular distribution coefficients for $^{12}C + ^{24}Mg$ at 11 MeV/u and $^{12}C + ^{26}Mg$ at 11, 8.5 and 6 MeV/u. Solid line: fitted exponential spectrum shape and calculated a_1 and a_2 coefficients for angular distribution isotropic in the nucleon-nucleon CM system.

In the last minute of my talk I would like to mention that in Warsaw–Cracow collaboration we are building the experimental set-up at our Warsaw Cyclotron U-200P in order to study high-energy γ-rays from heavy-ion reactions. Presently we have a large BGO detector (10cm$\times$10cm) belonging to the Niewodniczański Institute of Nuclear Physics in Cracow which will be used to measure high-energy γ-ray spectra at different angles. We have also built a multiplicity filter consisting of 28 detectors: 10 BaF_2 crystals (5cm$\times$5cm) which we were able to borrow for a long-term use from our friends at Chalmer Techniska Hogskola in Goteborg and 18 small NaI(Tl) crystals received from Soltan Institute for Nuclear Studies in Świerk. The total efficiency of the filter measured at 1.17 MeV from ^{60}Co source with a large target chamber (which limits the closest detector-target distance to 16 cm) allowing for target cooling is around 10 %. For different type of experiments in which more precise angular momentum definition is required also a more compact target chamber will be built. In the near future we hope to receive a large NaI(Tl) detector for which we will build an anticoincidence and lead shields. In this set-up we plan to study a statistical GDR decay as well as a bremsstrahlung radiation.

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REFERENCES

[1] G. Breitbach. G. Koch, S. Koch, W. Kuhn, A. Ruckelshausen, V. Metag, R. Novotny, S.Riess, D. Habs, D. Schwalm, E. Grosse and H. Stroher, *Phys. Rev.* **C40**, 2893 (1989).

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

[3] 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).

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

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

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

[7] K.A. Snover, *Ann. Rev. Nucl. Part. Sci.* **36**, 545 (1986).

[8] J.J. Gaardhoje, *Ann. Rev. Nucl. Part. Sci.* **42**, 483 (1992).

[9] M. Kicińska-Habior, K.A. Snover, J.A. Behr, C.A. Gossett, Y. Alhassid, N. Whelan, *Phys. Lett.* **B308**, 225 (1993).
[10] D. Vasak, *Phys. Lett.* **B176**, 276 (1986); D. Vasak, B. Muller, W. Greiner, *J. Phys. G* **11**, 1309 (1985).
[11] H. Nifenecker, J.P. Bondorf, *Nucl. Phys.* **A442**, 478 (1985).
[12] S.J. Luke, PhD Thesis, University of Washington, Seattle 1992.
[13] G.F. Bertsch, S. Das Gupta, *Phys. Rep.* **160**, 189 (1988).