NEW RESULTS IN HIGH-ENERGY γ-RAY STUDIES FROM HEAVY-ION REACTIONS AT AROUND 10 MeV/u* **

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Recently measured data for the ^{12}C + ^{26}Mg reaction at 6, 8.5 and 11 MeV/u and for ^{12}C + ^{24}Mg at 11 MeV/u have been analysed using a new version of the CASCADE code allowing for simultaneous fitting of γ-ray spectra and angular distributions. The GDR parameters and bremsstrahlung parameters have been extracted. Comparison with BUU calculations are also discussed.

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1. Introduction

It is by now a well established experimental fact that in heavy-ion collisions at projectile energies $E_{\rm p}/A \leq$ 5–6 MeV/u, statistical emission is practically the only source of high-energy photons. For those collisions the γ-ray yield in the high-energy part of the spectra ($E_\gamma \approx$ 15–30 MeV) is due to statistical decay of the giant dipole resonance (GDR) built on highly excited states [1,2] and the angular distribution must be symmetrical with respect to 90° in the nucleus–nucleus (projectile-target) center-of-mass frame (n-n CM frame). In heavy-ion collisions at projectile energies $E_{\rm p}/A \geq$ 10 MeV/u an excess of γ-ray yield over that expected on the basis of statistical decay has been observed in many studies as a continuous background which decreases

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exponentially up to the highest measured photon energies [3]. It is especially well visible for γ-ray energies exceeding the GDR region, *i.e.* above $E_\gamma = 30$ MeV. These photons have been interpreted as due to nucleon–nucleon bremsstrahlung emitted during the initial stages of the collision process [3]. Measured angular distributions of high-energy photons beyond the GDR region can be reasonably fitted assuming an almost isotropic emission from a source moving with a velocity close to one-half of the beam velocity, suggesting an emission from a source moving with the nucleon–nucleon center-of-mass velocity (N-N CM frame). After transformation to the n-n CM frame the angular distributions exhibit an asymmetry with respect to 90°. At projectile energies around 10 MeV/u, both processes: statistical γ-ray emission and bremsstrahlung emission give important contributions to the measured total γ-ray cross section and angular distribution.

In order to extract realistic GDR and bremsstrahlung parameters from the measured data, simultaneous analysis of γ-ray spectra and angular distributions should be performed with an attempt to differentiate between statistical decay and nucleon–nucleon bremsstrahlung on the basis of angular distribution, which is possible when the collision is mass-asymmetric.

2. Modifications of CASCADE

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/Linac accelerator [4]. In order to estimate the importance of statistical and nonstatistical contributions in these reactions we have incorporated a parametrization of nucleon–nucleon bremsstrahlung emission into the CASCADE code and have expanded the fitting to the total cross section and a_1 coefficient.

Results of the experimental data (five angles) analysis consist of $A_0^{\rm exp}(E_\gamma)$, $a_1^{\rm exp}(E_\gamma)$ and $a_2^{\rm exp}(E_\gamma)$ coefficients in the n-n CM frame (Fig. 1). The $A_0^{\rm exp}(E_\gamma) \cdot a_1^{\rm exp}(E_\gamma)$ product is more directly related to theory than is $a_1^{\rm exp}(E_\gamma)$ then we use this value to compare with the theoretical expectation (in the n-n CM frame) $A_0^{\rm br}(E_\gamma) \cdot a_1^{\rm br}(E_\gamma) + A_0^{\rm cn}(E_\gamma) \cdot a_1^{\rm cn}(E_\gamma)$, where the statistical $a_1^{\rm cn}(E_\gamma) = 0$. Thus our fitting procedure of the theoretical calculations to the measured data includes: $A_0^{\rm br}(E_\gamma) + A_0^{\rm cn}(E_\gamma)$ to compare with $A_0^{\rm exp}(E_\gamma)$ and $a_1^{\rm br}(E_\gamma) \cdot A_0^{\rm br}(E_\gamma)/(A_0^{\rm br}(E_\gamma) + A_0^{\rm cn}(E_\gamma))$ to compare with $a_1^{\rm exp}(E_\gamma)$ in the fitting range up to the highest measured γ-ray energy E_γ. This is the idea of the new fitting code CASIBRFIT.

Statistical model calculations in CASIBRFIT are done as in a typical CASCADE version treating the isospin correctly (*i.e.* as an additional variable to excitation energy, spin and parity), with the level density in the Reisdorf approach (optionally), and the spin dependent moment of inertia. The existing version of the CASCADE code was expanded to γ-ray

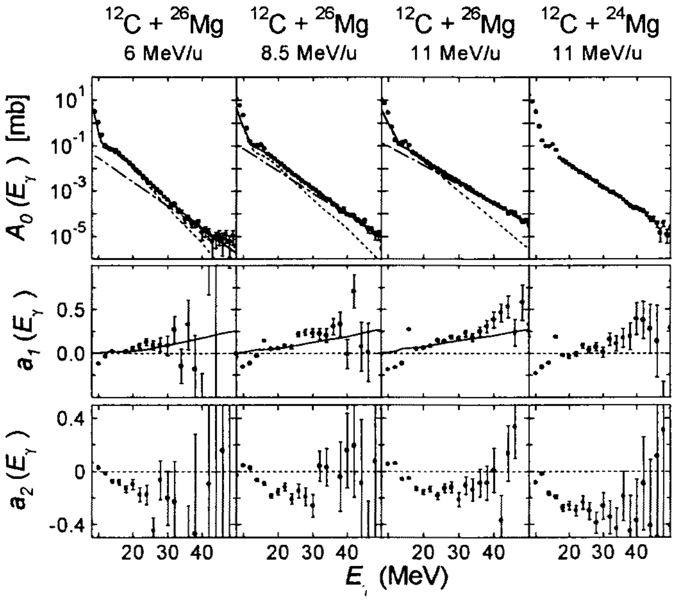

Fig. 1. Measured γ-ray spectrum $A_0^{\exp}(E_\gamma)$ (top), $a_1^{\exp}(E_\gamma)$ (middle) and $a_2^{\exp}(E_\gamma)$ (bottom) angular distribution coefficients for the ^{12}C + ^{24}Mg reaction at 11 MeV/u and the ^{12}C + ^{26}Mg reaction at 6, 8.5 and 11 MeV/u. Solid lines through the data show CASIBRFIT normal calculations: total results of the fit (top and middle, see text); dot-dash line: fitted bremsstrahlung contribution (top); short-dash line: fitted statistical model calculations (top).

energies $E_\gamma > 50$ MeV. The resulting γ-ray spectrum calculated in the n-n CM frame is folded with the detector lineshape (response function and efficiency) into $A_0^{\rm cn}(E_\gamma)$. The bremsstrahlung cross-section is also calculated in the n-n CM frame according to the analytic formula for five angles and folded with the detector lineshape. It was assumed that in the nucleon–nucleon center-of mass frame (N-N CM frame) the bremsstrahlung emission has an isotropic angular distribution. Thus after transformation to the n-n CM frame $a_1^{\rm br}(E_\gamma) \neq 0$. The angular coefficients $A_0^{\rm br}(E_\gamma)$ and $a_1^{\rm br}(E_\gamma)$ are extracted from the Legendre polynomial fit. Finally, the fitting function (f_1, f_2) is constructed from the fit parameters, *i.e.* GDR parameters: S_1, E_1, Γ_1, S_2, E_2, Γ_2 and bremsstrahlung (BR) parameters: σ_0 and E_0

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\begin{aligned}
f_1(\mathrm{GDR}, \mathrm{BR}) &= A_0^{\rm br}(E_\gamma, \mathrm{BR}) + A_0^{\rm cn}(E_\gamma, \mathrm{GDR})\,, \\
f_2(\mathrm{GDR}, \mathrm{BR}) &= a_1^{\rm br}(E_\gamma, \mathrm{BR}) \cdot \frac{A_0^{\rm br}(\mathrm{E}_\gamma, \mathrm{BR})}{A_0^{\rm br}(\mathrm{E}_\gamma, \mathrm{BR}) + A_0^{\rm cn}(\mathrm{E}_\gamma, \mathrm{GDR})}\,. \qquad (1)
\end{aligned}
$$

The fitting subroutine performs a least-square fit of (f_1, f_2) to $(A_0^{\exp}(E_\gamma), a_1^{\exp}(E_\gamma))$ simultaneously, using an algorithm which combines a gradient search with an analytical solution developed from linearizing the fitting function.

3. Fit results and BUU calculations

Data from the $^{12}C + ^{26}Mg$ reaction at 6, 8.5 and 11 MeV/u have been fitted with CASIBRFIT code, assuming that the initial excitation energy of the compound nucleus is that calculated for complete fusion in each case and the velocity of the bremsstrahlung source equals the nucleon–nucleon center-of-mass velocity, β_{sNN}. Fit results for all studied cases when 5 parameters: $S, E, \Gamma, \sigma_0, E_0$ were varied are shown in Fig. 1. Fitted parameters are listed in Table I.

TABLE I

	$^{12}C + ^{26}Mg$ 5 MeV/u	$^{12}C + ^{26}Mg$ 8.5 MeV/u	$^{12}C + ^{26}Mg$ 11 MeV/u
S	1.0±0.4	1.0±0.2	1.0±0.1
E [MeV]	17.6 ±0.2	17.5±0.8	15.8±1.5
Γ [MeV]	14.8±0.5	14.5±1.1	12.9±0.7
σ_0	0.247±0.008	0.528±0.004	0.519±0.003
E_0 [MeV]	4.27±0.04	4.62±0.03	5.30±0.02

The quality of the spectral fits is good, however the $a_1(E_\gamma)$ calculation does not reproduce the data above $E_\gamma = 35$ MeV at 11 MeV/u.

We have found that the quality of the fit improves significantly when the E_γ dependent source velocity $\beta_s(E_\gamma)$ is used. Best results (Fig. 2) have been obtained with a quadratic dependence such that $\beta_s(E_\gamma)/\beta_{\mathrm{sNN}} = 0.934, 1.145$ and 1.491 for $E_\gamma = 20, 35$ and 50 MeV, respectively. The idea of the energy dependent source velocity may be understood in a simple manner. Photons emitted with the highest energy should result from the most energetic first-chance collisions for which the mean source velocity should be larger than in the case of less energetic subsequent step collisions.

The question may arise how the source velocity $\beta_s(E_\gamma)$ could be larger than β_{sNN}. It may be explained on the known basis that the bremsstrahlung photons are produced mostly during proton-neutron collisions between individual projectile and target nucleons and the intrinsic momenta of the proton and the neutron due to the Fermi motion of nucleons add to the relative momentum of the projectile and the target nucleons [3].

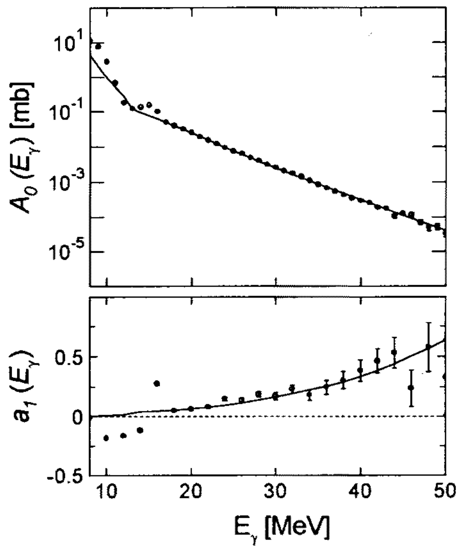

Fig. 2. Measured γ-ray spectrum $A_0^{\exp}(E_\gamma)$ (top) and $a_1^{\exp}(E_\gamma)$ (bottom) coefficient for the ^{12}C + ^{26}Mg reaction at 11 MeV/u (as in Fig. 1). Lines through the data: CASIBRFIT calculations with energy dependent source velocity.

Inverse slope parameters E_0 extracted from the fits and the mean value of the source velocity for bremsstrahlung photons have been compared (Table II.) with values predicted by the Boltzmann–Uehling–Uhlenbeck (BUU) nuclear transport equation [3] and calculated with BUU code written by Wolf [5]. Calculations of the γ-ray emission probability $P(b)$ have been done for several values of the impact parameter b in the range of 0 to 7 fm. The value of $P(b) \cdot b$ peaks around b= 4 fm. The impact parameter value corresponding to the maximum angular momentum of 25 $\hbar$ for complete fusion is $b_{\rm CF} = 4.3$ fm.

TABLE II

Reaction	$E_{\rm lab}$ [MeV]	$(< E_{\rm lab} > -{\rm V_c})/A$ [MeV/u]	$E_0^{\exp}$ [MeV]	$E_0^{\rm BUU}$[MeV] b=0	b=3.9
^{12}C + ^{26}Mg	134.6	9.7	5.3	8.5	7.3
^{12}C + ^{26}Mg	103.3	7.1	4.8	8.0	6.8
^{12}C + ^{26}Mg	73.0	4.5	4.5	6.9	6.3
^{12}C + ^{24}Mg	134.6	9.7	–	9.0	7.6

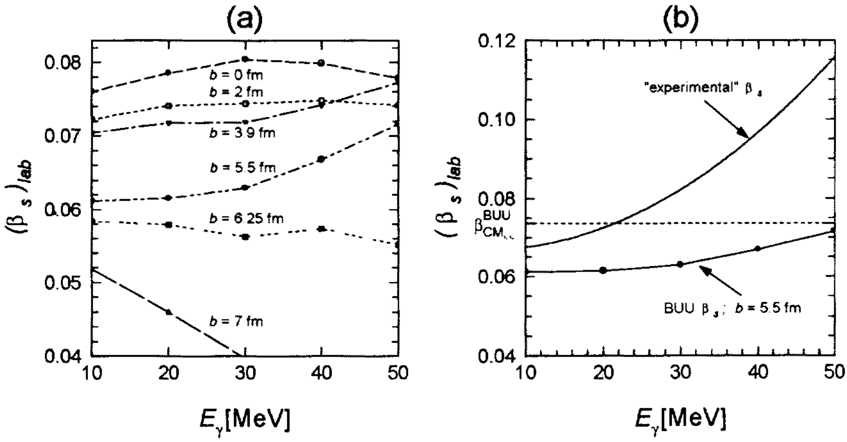

Fig. 3. (a)Energy dependence of the mean source velocity β_s for the ^{12}C + ^{26}Mg reaction at 11 MeV/u calculated with BUU code for different impact parameter values $b = 0 - 7.0$ fm. (b) Energy dependence of the mean source velocity for the ^{12}C + ^{26}Mg reaction at 11 MeV/u used in the best-fit calculations with CASIBRFIT and calculated with BUU code for $b = 5.5$ fm.

The parameters E_0 obtained with BUU code are essentially in agreement with other BUU calculations [3], however they are larger than systematics for experimental nucleon–nucleon bremsstrahlung data at these low projectile energies. The $E_0(b)$ value calculated at given b decreases with increasing impact parameter. However, for values of $b \leq b_{CF}$ corresponding to complete fusion for ^{12}C + ^{26}Mg reactions, the slope of the γ-ray spectra calculated with BUU code is too small to reproduce the experimental data. Average E_0 at 11 MeV/u was extracted from the fits of the exponential formula $\sigma = \sigma_0 \cdot \exp(-E_\gamma/E_0)$ to the BUU cross-section $\sigma_{BUU}(E_\gamma) = 2\pi \int_0^{b_{max}} P(b)bdb$ and equals 7.4 MeV. The required value of $E_0^{exp} = 5.36$ MeV can be obtained with b=6.3 fm, corresponding to an angular momentum of 31.7 $\hbar$.

The mean velocity, β_s, of the emitting source can be estimated from the source velocity distribution calculated with BUU. These distributions are symmetrical around the mean value of β_s, which depends on photon energy E_γ and on impact parameter. Energy dependence of β_s for different impact parameters of b = 0–7.0 fm is shown in Fig. 3a. The quantity β_s increases with increasing E_γ only for b = 3.9–5.5 fm. Even for these β_s values the E_γ dependence of β_s is slower than estimated from CASIBRFIT fits (Fig. 3b).

There is a possibility that the energy dependence of the γ-ray production probability per n-p collision assumed in the BUU calculations at 30–100 MeV/u projectile energy [3] leads to error at lower projectile energy. We tried a different formula for this probability which seems to give agreement at around 10 MeV/u [6] but it does not change the results significantly.

4. Conclusions

At the present stage the BUU calculations does not seem to reproduce the data. More detailed calculations are in progress.

It is also worth mentioning that the experimental $a_2^{\rm exp}(E_\gamma)$ coefficient for ^{12}C + ^{24}Mg at 11 MeV/u has a large negative value, presumably indicating very large deformation of the compound nucleus in which GDR was built. It may also suggest another mechanism for γ-ray emission. We observe different behaviour for data from the ^{12}C + ^{26}Mg and ^{12}C + ^{24}Mg reactions at the same energy 11 MeV/u. The data for the $N = Z$ ^{24}Mg target have not been successfully fitted yet. The ratio of the integrated cross sections for $E_\gamma > 20$ MeV for ^{12}C + ^{26}Mg compared to ^{12}C + ^{24}Mg equals 1.7 ± 0.1, whereas the BUU result is 1.2.

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