BREMSSTRAHLUNG RADIATION IN HEAVY-ION COLLISIONS ^{18}O + ^{27}Al → ^{45}Sc AT 8.3 MeV/u*

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(Received November 20, 1999)

High energy γ-ray spectrum and angular distribution for the ^{18}O + ^{27}Al reaction at 8.3 MeV/u have been analysed assuming the statistical decay of giant dipole resonance and the nucleon-nucleon bremsstrahlung emission. Simple parabolic energy dependence of the inverse slope parameter $E_0(E_\gamma)$ has been proposed. The bremsstrahlung contribution was estimated also at 6 MeV/u and found to be negligible.

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

1. Introducion

High-energy γ-rays emitted in heavy-ion reactions at projectile energies in the range of $E_{\rm proj}/A = 6$–$15\,{\rm MeV}/u$ originate mostly from statistical GDR decay and nucleon-nucleon bremsstrahlung during the initial stages of the collision process. In mass–assymetric reactions, as ^{12}C + ^{24,26}Mg and ^{12}C + ^{58,64}Ni, those two types of γ-ray emission have been disentangled by the angular distribution measurment [1]. It was shown that the data, when properly analyzed, give an information on the GDR built on excited states as well as on the bremsstrahlung process. The ^{18}O + ^{27}Al reaction is nearly mass-symmetric, thus the a_1 coefficient extracted from the measured angular distributon is close to zero which makes the method less sensitive. The intention of this report is to estimate an amount of the bremsstrahlung cross section in the ^{18}O + ^{27}Al reaction at 8.3 MeV/u by using the same

* Presented by O. Kijewska at the XXVI Mazurian Lakes School of Physics, Krzyże, Poland, September 1–11, 1999.

method as for mass-asymmetric reactions, and to show how it may influence the extracted GDR parameters. The ^{18}O + ^{27}Al $\rightarrow$ ^{45}Sc reaction was already measured and analyzed at $E_{\rm proj}/A$ = 2.5–6 MeV/u [2] in order to study the nuclear shape evolution. It was found that at very high rotation the equilibrium shape undergoes a shape transition from oblate to triaxial, approximately prolate in agreement with the liquid drop model. The bremsstrahlung emission has not been included in the analysis since at so low projectile energies a negligible value of the bremsstrahlung cross-section was obtained from a very simple estimate. In order to conclude about the bremsstrahlung contribution in the ^{18}O + ^{27}Al reaction, the reaction has been measured for higher energy $E_{\rm proj}/A$ = 8.3 MeV/u [3] where importance of the bremsstrahlung process is larger.

2. CASIBRFIT assumptions

In this work, the measured data for the ^{18}O + ^{27}Al reaction at $E_{\rm proj}/A$ = 8.3 MeV/u [3] have been analyzed using CASIBRFIT code [4] which included statistical GDR decay and bremsstrahlung processes. In order to take advantage of the experimental constraint which is the $a_1(E_\gamma)$ dependence on E_γ energy, the angular distribution coefficients $A_0(E_\gamma)$ and $a_1(E_\gamma)$ have been fitted simultaneously in the fitting procedure as it was done for more mass-asymmetric reactions ^{12}C + ^{24,26}Mg and ^{12}C + ^{58,64}Ni [1]. The statistical decay has been calculated according to CASCADE code with the isospin correctly included, level density in the Reisdorf approach and the spin dependent moment of inertia. It was assumed that in the nucleon-nucleon CM frame the bremsstrahlung emission has an isotropic angular distribution and the total cross–section $\sigma_{\rm brem} = \sigma_0 \exp(-E_\gamma/E_0)$. An inverse slope parameter E_0 was allowed to vary with E_γ , since it was found necessary in order to reproduce the increase in $a_1(E_\gamma)$ with increasing γ-ray energy for mass–assymetric reactions [1].

3. BUU calculations

The character of the $E_0(E_\gamma)$ dependence was estimated qualitatively on the basis of BUU (Boltzmann–Uehling–Uhlenbeck) nuclear transport equation. BUU calculations have been performed for ^{18}O + ^{27}Al at $E_{\rm proj}/A$ = 8.3 MeV/u for different impact parameters b = 0 to 8 fm with the code supported by Wolf [5]. At this low projectile energy the time evolution of photon emission probability $P(E_\gamma, b, t)$ at various impact parameters b exhibits pronounced peak below 100 fm/c (Fig. 1) which is due mostly to the initial nucleon–nucleon collisions, and also some structure at a later time which we assume is already included in the statistical model calculations.

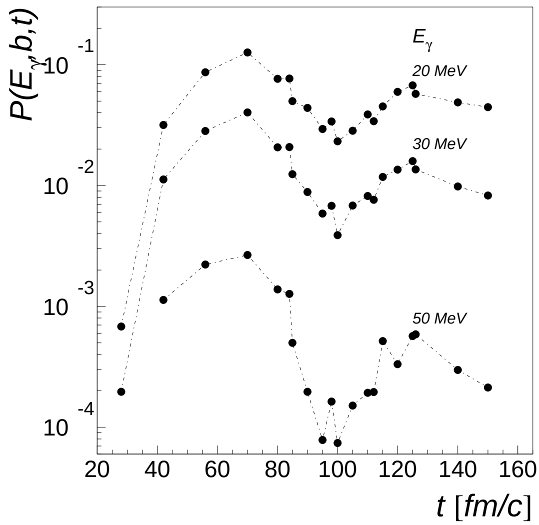

Fig. 1. Time evolution of photon emission probability at impact parameter $b = 2$ fm and photon energy E_γ.

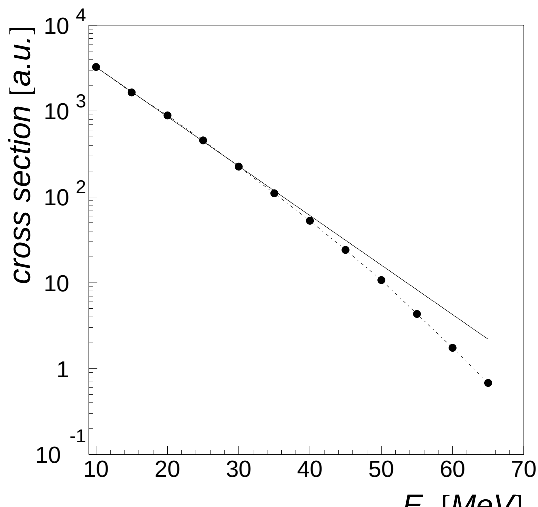

Fig. 2. Bremsstrahlung cross–section as a function of E_γ energy.

The BUU cross–section is then calculated as an integral over the time corresponding to the initial collisions and the whole range of impact parameter: $\sigma_{\rm BUU}(E_\gamma) = 2\pi \int P(E_\gamma, b, t) b db dt$. It was then 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. As it is seen in Fig. 2 the $\sigma_{\rm BUU}(E_\gamma)$ cannot be reproduced

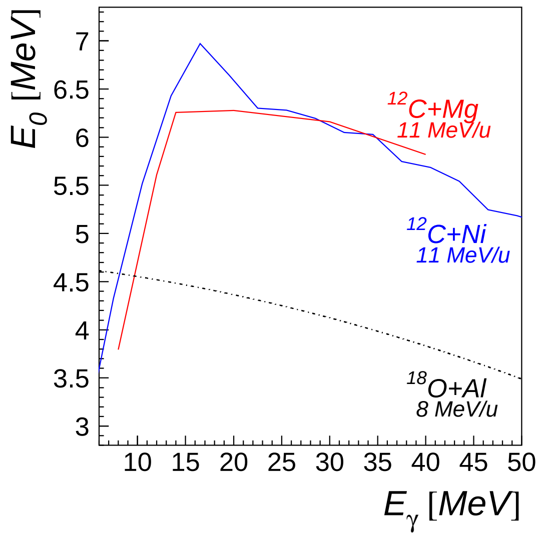

Fig. 3. BUU calculations: energy dependence of an inverse slope parameter E_0.

with a single E_0 value in the whole range of $E_\gamma = 10 - 65$MeV$/u$. The E_0 value extracted for different energy intervals changes by about 34%. This behavior can be compared with the results of similar analysis (Fig. 3) for ^{12}C + ^{24,26}Mg and ^{12}C + ^{58,64}Ni reactions studied earlier [1]. Similar $E_0(E_\gamma)$ dependence was observed experimentally for $Kr + Ni$ at higher projectile energies [6]. In this work a simple parabolic energy dependence is proposed to reproduce changes of $E_0(E_\gamma)$ value found from BUU calculations for ^{18}O + ^{27}Al reaction.

4. Results of the CASIBRFIT calculations

The CASIBRFIT calculations for ^{18}O + ^{27}Al reaction have been done with a double Lorentzian GDR strength function because of large deformation of ^{45}Sc suggested by the results at 2.5 - 6 MeV$/u$ [2] and by the measured $a_2(E_\gamma)$ coefficients at 8.3 MeV$/u$. An energy dependent $E_0(E_\gamma)[\mathrm{MeV}^{-1}] = E_0^0(1 - 0.0024E_\gamma - 0.000055E_\gamma^2)$, where E_γ and E_0 in MeV, was used according to the results of the BUU calculations. The fits were done with 6 variable parameters: $S_1, \Gamma_1, S_2, \Gamma_2, \sigma_0, E_0^0$ and fixed values of E_{GDR1} and E_{GDR2} chosen as found at lower excitation energies of ^{45}Sc [2]. High-energy γ-ray spectrum, the $a_1(E_\gamma)$ coefficient, and the GDR strength function, fitted as well as experimental are shown in Fig. 4. The GDR parameters extracted from the best fit, with and without the bremsstrahlung process included, are shown in Table I.

TABLE I

Fitted bremsstrahlung and GDR parameters

σ_0	E_0(30 MeV) [MeV]	$\langle E_{\rm GDR}\rangle$ [MeV]	$\frac{E_{\rm GDR1}}{E_{\rm GDR2}}$	S_1+S_2	$\frac{S_2}{S_1}$	$\frac{\Gamma_2}{\Gamma_1}$
0	—	18.1	1.55	0.90±0.10	0.31±1.01	1.18±2.1
0.79±0.06	4.4±0.5	18.1	1.55	0.89±0.10	0.31±0.58	1.56±1.28

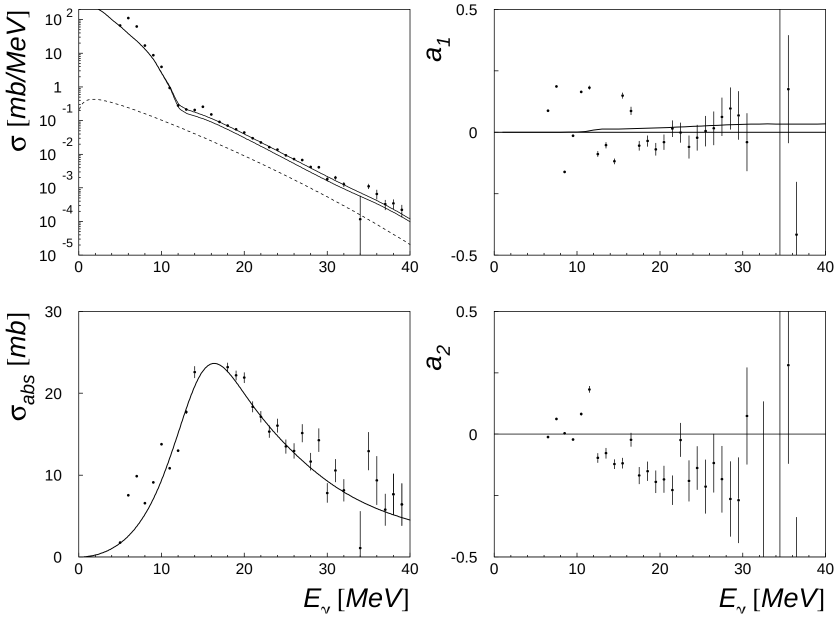

Fig. 4. CASIBRFIT calculations for ^{18}O + ^{27}Al at $E_{\rm proj}/A$=8.3 MeV/u: Measured and fitted γ-ray spectrum $\sigma(E_\gamma)$ (upper solid line — total, lower solid line — statistical contribution, dashed — bremsstrahlung contribution), $a_1(E_\gamma)$ coefficient, absorption cross-section $\sigma_{abs}(E_\gamma)$ and $a_2(E_\gamma)$ coefficient.

5. Conclusions

It can be seen that the GDR parameters extracted from the data for ^{18}O + ^{27}Al at $E_{\rm proj}/A = 8.3$ MeV/u are only slightly influenced by inclusion of the bremsstrahlung process. Only the width of the second GDR component is significantly increased. The inverse slope parameter $E_0(E_\gamma = 30$ MeV) extracted from the fit is in agreement with the systematic [7]. The bremsstrahlung contribution was also estimated at 6 MeV/u and it was found to be negligible. We plan to continue this analysis in order to estimate an influence of a possible incomplete fusion process on the GDR parameters.

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