GIANT DIPOLE RESONANCE STUDIED IN HEAVY-ION REACTIONS AT PROJECTILE ENERGIES 6–11 MeV/u* **

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(Received November 3, 2000)

High-energy γ-ray spectra and angular distributions from $^{12}C+^{24,26}Mg$, $^{12}C+^{58,64}Ni$ and $^{18}O+^{100}Mo$ reactions at few bombarding energies, between 5 and 11 MeV/u, were measured and analyzed by taking into account complete and incomplete fusion processes and bremsstrahlung emission. The GDR parameters were extracted as a function of the average excitation energy and the bremsstrahlung parameters as a function of $(E_{\rm proj} - V_{\rm c})/A$.

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

1. Introduction

During the last years we performed several experiments: $^{12}C+^{24,26}Mg$ [1–3], $^{12}C+^{58,64}Ni$ [4] and $^{18}O+^{100}Mo$ [5] in order to obtain information concerning the Giant Dipole Resonance (GDR) in the compound nuclei at final-state temperatures up to about 2 MeV. Heavy-ion reactions induced by high-energy projectiles must be used in order to produce a compound nuclei at such high excitation. At projectile energies above 6 MeV/u preequilibrium and bremsstrahlung processes become important and influence measured high-energy γ-ray spectra. Thus those processes have to be included in the analysis and their contribution depends on the projectile energy.

We present here details of the performed experiments, a method of data analysis and results obtained for reactions studied.

* Presented at the XXXV Zakopane School of Physics "Trends in Nuclear Physics", Zakopane, Poland, September 5–13, 2000.

** This work was partly supported by the Polish State Committee for Scientific Research (KBN) Grant No. 2 P30B 035 15 and by the United States Department of Energy.

2. Experiment

The data in all reported experiments were collected at the University of Washington Nuclear Physics Laboratory. High-energy γ-rays emitted in the reactions were measured at five angles with a single or triple large NaI-spectrometer set-up at few beam energies. Each of the detectors was surrounded by its own active plastic shield and a passive lead shield to suppress background γ-rays and cosmic radiation. The n-γ discrimination by the standard time of flight technique allowed a very good separation of the events induced by γ-rays produced in the target and by the neutrons. Multiplicities of low-energy γ-rays were measured in the 20 % efficiency multiplicity filter, which consisted of 22 small NaI detectors. Data with fold $\geq$0, 1, 2 or 4 cut, depending on the reaction and bombarding energy, were used in the analysis in order to eliminate noncompound nucleus background.

3. Data analysis

For all the reactions studied high-energy γ-ray spectra at five angles were fitted by the Legendre polynomials and the angular distribution coefficients $A_0(E_\gamma)$, $a_1(E_\gamma)$ and $a_2(E_\gamma)$ were extracted in the nucleus-nucleus CM frame:

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

Comparison of data extracted for each reaction at several projectile energies, reveals a large bremsstrahlung tail in the $A_0(E_\gamma)$ spectrum and a large positive $a_1(E_\gamma)$ coefficient value, which increases with projectile energy, and is clearly seen at γ-ray energies above 20 MeV. In order to obtain information concerning GDR, a simultaneous analysis of the high-energy γ-ray spectra ($A_0(E_\gamma)$) and angular distributions ($a_1(E_\gamma)$) at each projectile energy was done using CASIBRFIT [1] — a version of the CASCADE code in which the bremsstrahlung emission was incorporated besides the excitation and decay of the GDR. The code permits a separation of the statistical and nonstatistical contributions by performing fits to the experimental γ-ray spectra and using the fact that the two components differ in the $a_1(E_\gamma)$ coefficient.

In order to obtain information on the evolution of the GDR excitation, the dependence of the GDR parameters on the average final excitation energy and the final state temperature is studied. Unfortunately, the average excitation energy of the compound nucleus was often incorrectly estimated in GDR studies at projectile energies around 10 MeV/u, which led to wrong interpretation of the results.

When GDR is built in a compound nucleus formed by complete fusion only, then the average excitation energy $\overline{E_i}$ preceding the GDR decay corresponds to the excitation energy averaged over decay steps and is lower than the initial excitation energy $E_{\rm init}$ by an energy lost due to particle evaporation prior to the GDR decay. The average final-state thermal energy defined as $\overline{E_f} = \overline{E_i} - \overline{E_{\rm rot}} - E_{\rm GDR}$ is related to the average final-state temperature by $T = [dln(\rho)/dE]^{-1}$, where ρ is the level density.

There is, however, experimental evidence that at projectile energies above 6 MeV/u an incomplete fusion is also present and its contribution has to be included in the CASIBRFIT calculations. In the incomplete fusion process the light clusters and nucleons are emitted before equilibration of a composite system and they carry away an energy ΔE_x and a momentum ΔL available in a collision. Thus, in such process, an equilibrated compound nucleus with the GDR built-in is formed with mass and excitation energy lower than in the complete fusion. The importance of incomplete fusion and bremsstrahlung processes increases with increasing relative velocity of the projectile and the target, so that both processes have to be correctly included in the analysis.

For the ^{18}O + ^{100}Mo reaction, the data needed to estimate incomplete fusion: α-particle and proton spectra in coincidence with high-energy γ-rays, and evaporation residues, were measured in a separate experiment [6]. Preequilibrium proton and α-particle multiplicities and average kinetic energies were then experimentally determined [5,6]. The neutron contribution was estimated by using model calculations [5]. The reduced initial excitation energy of the compound nucleus formed by incomplete fusion is lower than for complete fusion by the average energy lost by preequilibrium particle emission. The difference between the two is growing with the increasing projectile energy.

Similar estimates were done for ^{12}C + ^{58,64}Ni [4] and ^{12}C + ^{24,26}Mg [2] reactions basing on the literature data for incomplete fusion in ^{12}C induced reactions.

The average initial excitation energy, mass, and Z of the produced initial compound nuclei, corrected for the incomplete fusion loss, were used in the statistical model calculations with the Reisdorf level density description and a single Lorentzian GDR strength function. The bremsstrahlung cross section was parametrized by the exponential formula $\sigma_{\rm brem} = \sigma_0 \exp(-E_\gamma/E_0)$. An isotropic angular distribution of the bremsstrahlung radiation emitted in the nucleon-nucleon CM frame was assumed. We have found previously [1-3] that the $a_1(E_\gamma)$ coefficient could not be satisfactorily fitted, especially for the highest projectile energies studied ($E_{\rm proj} = 11$ MeV/u), when a constant inverse slope parameter E_0, independent of E_γ was assumed. We have found [2, 3] that the character of the $E_0(E_\gamma)$ dependence can be estimated by the BUU (Boltzmann–Uehling–Uhlenbeck) model calculations [7]. Such $E_0(E_\gamma)$ resulted in the slope of the bremsstrahlung spectrum increasing with E_γ, which was needed to reproduce the measured $a_1(E_\gamma)$.

4. Results and conclusions

The CASIBRFIT fits were performed for all the reactions studied. It was proved that the statistical and bremsstrahlung emissions in the ^{12}C+^{24,26}Mg [1–3], ^{12}C+^{58,64}Ni [4] and ^{18}O+^{100}Mo [5] reactions can be disentangled by simultaneous analysis of the high-energy γ-ray spectra ($A_0(E_\gamma)$) and angular distributions ($a_1(E_\gamma)$). The $E_0(E_\gamma)$ dependent on E_γ energy is necessary to reproduce the $a_1(E_\gamma)$ coefficient. The extracted value of $E_0 = E_0(E_\gamma = 30$ MeV) is in agreement with the systematics for higher projectile energies [8].

The dependence of the extracted GDR parameters on the average excitation energy corrected for incomplete fusion loss has similar character for all reactions studied [3–5] and is strongly influenced by the assumed amount of energy lost in preequilibrium emission. Thus, we recommend that the energy loss, so important in the analysis, should be estimated in a dedicated experiment, as it was done in [5].

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