Physics Letters B 782 (2018) 427–432

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Mapping the demise of collective motion in nuclei at high excitation energy

D. Santonocito [a,*], Y. Blumenfeld [b], C. Maiolino [a], C. Agodi [a], R. Alba [a], G. Bellia [a,e], R. Coniglione [a], A. Del Zoppo [a], F. Hongmei [a], E. Migneco [a,e], P. Piattelli [a], P. Sapienza [a], L. Auditore [c,d], G. Cardella [c], E. De Filippo [c], E. La Guidara [c], C. Monrozeau [b], M. Papa [c], S. Pirrone [c], F. Rizzo [a,e], A. Trifiró [c,d], M. Trimarchi [c,d], H.X. Huang [f], O. Wieland [g]

[a] INFN – Laboratori Nazionali del Sud, via S. Sofia 62, I-95123, Catania, Italy
[b] Institut de Physique Nucléaire, CNRS-IN$_2$P$_3$, Université Paris-Sud, Université Paris-Saclay, F-91406 Orsay Cedex, France
[c] INFN – Sezione di Catania, via S. Sofia 64, I-95123, Catania, Italy
[d] INFN – Dipartimento di Scienze MIFT dell'Universitá di Messina, V.le F. Stagno d'Alcontres 31, I-98166, S. Agata, Messina, Italy
[e] Dipartimento di Fisica e Astronomia dell'Universitá di Catania, via S. Sofia 64, I-95123, Catania, Italy
[f] Key Laboratory of Science and Technology for National Defence, China Institute of Atomic Energy, P.O. Box 275(46), Beijing 102413, China
[g] INFN – Sezione di Milano, via Celoria 16, I-20133, Milano, Italy

A R T I C L E   I N F O

Article history:
Received 11 January 2018
Received in revised form 3 May 2018
Accepted 18 May 2018
Available online 24 May 2018
Editor: V. Metag

Keywords:
Giant Dipole Resonance
Hot nuclei
Fusion reactions
Statistical Model

A B S T R A C T

High energy gamma-rays from the ^{116}Sn + ^{24}Mg reaction at 23*A* MeV were measured using the MEDEA detector at LNS – INFN Catania. Combining this new data with previous measurements yields a detailed view of the quenching of the Giant Dipole Resonance as a function of excitation energy in nuclei of mass A in the range $120 \div 132$. The transition towards the disappearance of the dipole strength, which occurs around 230 MeV excitation energy, appears to be remarkably sharp. Current phenomenological models give qualitative explanations for the quenching but cannot reproduce its detailed features.

Studies of the Giant Dipole Resonance (GDR) built on excited states have provided a wealth of information on the dynamics of nuclei at finite temperature [1–3]. One remaining open problem in the study of the evolution of GDR properties as a function of excitation energy is the origin of the suppression of the GDR gamma yield at high excitation energies. This effect was observed, for the first time, in the study of ^{40}Ar + ^{70}Ge @ 24*A* MeV reaction [4] where hot nuclei around 600 MeV excitation energy were populated and the gamma-ray spectrum measured in coincidence showed a sizeable strength reduction compared to standard statistical model calculations. The spectrum could be reproduced assuming an excitation energy $E^* = 320$ MeV suggesting the interpretation of the disappearance of the GDR with increasing excitation energy and the existence of a limiting temperature for the collective motion in nuclei with mass A ~ 100.

Further evidence for the suppression of the GDR γ yield at very high excitation energies in the same mass region was then found by different experimental groups investigating the reactions ^{40}Ar + ^{92}Mo at 21*A* and 26*A* MeV [5], ^{36}Ar + ^{90}Zr at 27*A* MeV [6] and ^{36}Ar + ^{98}Mo at 37*A* MeV [7] where hot nuclei were populated in an energy domain ranging from 260 to about 550 MeV. These results showed the limits of applicability of the standard statistical scenario in the description of the GDR decay from a very hot system, pointing to the need of a theoretical explanation for the quenching mechanism. A simplified approach to reproduce the gamma-ray spectra was to introduce a sharp ad hoc suppression of the gamma emission above a given excitation energy, the so called cutoff energy. In the analysis of the 27*A* MeV data the authors reproduced the spectra extracted at all the excitation energies using the same energy value of 250 MeV for the cutoff [8] which led the authors to conclude that $E^*/A \sim 2.2$ MeV represents a limit for the existence of the dipole vibration for $A \sim 110$ nuclei [8].

Different theoretical models developed to explain the GDR behaviour at high excitation energy basically follow two main ideas,

* Corresponding author.
E-mail address: santonocito@lns.infn.it (D. Santonocito).

https://doi.org/10.1016/j.physletb.2018.05.052
0370-2693/

Table 1
Values of the energy removed in the pre-equilibrium stage of the reaction deduced from the analysis of light charged particle energy spectra and E^* of the hot compound nucleus for all the reactions investigated.

reaction	E_{beam}	E_{pre} (MeV)	E^* (MeV)
$^{116}Sn + {}^{12}C$	17A MeV	28±10	150±10
$^{116}Sn + {}^{12}C$	23A MeV	52±10	190±10
$^{116}Sn + {}^{24}Mg$	17A MeV	50±20	270±20
$^{116}Sn + {}^{24}Mg$	23A MeV	97±20	330±20

either a suppression of the GDR [9,10] or a rapid increase of the width [11–13]. The comparison of measured gamma-ray spectra with statistical model calculations, in which the different theoretical prescriptions were implemented [8], suggested that data are better described through an approach based on GDR suppression. A similar result was obtained in the mass region $A \sim 60 \div 70$ [14] through the study of the reaction ^{40}Ca + ^{48}Ca at 25A MeV. However a clear conclusion on the quenching mechanism was never reached due to the limited agreement between data and model predictions and to the fact that the limited set of data available focused on excitation energies well above the energy at which the quenching sets in. In order to be able to draw conclusions on the GDR quenching mechanism and to delineate the energy region where the quenching appears, a complete mapping of the evolution of the GDR properties as a function of excitation energy, from a region where the GDR retains its typical features up to a region where the quenching is clearly evident, was needed.

A study of the evolution of the GDR properties as a function of excitation energy in nuclei of mass region $A \sim 120 \div 132$ was undertaken at the Laboratori Nazionali del Sud (LNS) Catania using the MEDEA [15] multi-detector coupled to the SOLE [16,17] solenoid and the MACISTE [16,17] focal plane detector. In a first run, the reactions ^{116}Sn + ^{12}C at 17A and 23A MeV, and ^{116}Sn + ^{24}Mg at 17A MeV, were used to populate hot nuclei in an energy region between 150 and 270 MeV [17]. Evidence of an onset of a GDR quenching were found in the data set at $E^* = 270$ MeV [17]. However a single energy didn't allow a study of the shape of the GDR cutoff. Therefore in a second run the reaction ^{116}Sn + ^{24}Mg at 23A MeV was investigated with the same experimental setup to extend this study to higher excitation energies. Inverse kinematics were used to maximize the collection efficiency of evaporation residues on the SOLE focal plane detector. Light charged particles and gamma-rays were detected in the MEDEA detector, an array made of 180 BaF_2 scintillators 20 cm thick covering the polar angles from 30° to 170° degrees and the whole azimuthal angle, in coincidence with forward emitted ($\theta < 3°$) fusion-like residues focused by the magnetic field of SOLE solenoid on the focal plane detector MACISTE placed 16 m from the target. The time of flight of the recoils and their impact point on the focal plane detector were measured using three 30×40 cm^2 low pressure MACISTE Multiwire Proportional Chambers. Three Si–Si telescopes (50 μm–500 μm) 5×5 cm^2 each, were added on the focal plane in order to measure the Z and time of flight of the evaporation residues and to have a better control of the reaction dynamics.

Similarly to what was observed in the study of the same reaction at lower beam energy [17], the time of flight spectrum of the residues populated in the reaction ^{116}Sn + ^{24}Mg at 23A MeV exhibits a broad distribution indicating the presence of complete and close to complete fusion events. A single velocity window centered around the center of mass velocity ($V_{CM} = 5.6$ cm/ns) was chosen in order to select events with a well defined excitation energy and data analysis of light charged particle and gamma-rays was performed accordingly.

From the analysis of time of flight spectrum the mass transfer from target to projectile was evaluated. This information was complemented with the analysis of the light charged particle energy spectra which were reproduced through a fitting procedure assuming the isotropic emission from two moving sources. This approach allowed the evaluation of the contributions coming from the equilibrated compound nucleus and pre-equilibrium emission and thus to estimate both the excitation energy and mass of the hot system populated in the reaction after the pre-equilibrium stage.

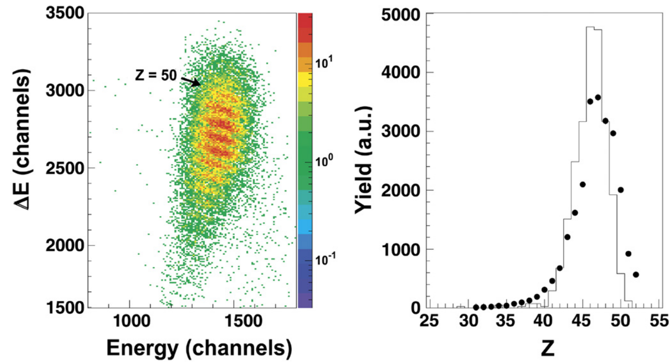

Fig. 1. Left) Evaporation residues ΔE-E correlation plot measured with Si–Si telescopes placed on the SOLE focal plane. Nuclei with different Z are clearly identified. Right) Evaporation residue experimental charge distribution measured on the focal plane is shown as full symbols. GEMINI++ simulations assuming in input the same average initial excitation energy, charge and mass of the hot system populated in the reaction, filtered with spectrometer acceptance are shown for comparison as full line. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

In order to deduce the excitation energy of the system a procedure similar to the one described in refs. [18,19] was undertaken. The initial momentum transfer from the projectile to the target was calculated assuming a complete fusion reaction and then the measured amount of pre-equilibrium emission, estimated from the fit of light charged particle energy spectra, was removed. Since neutrons were not detected in the experiment, the pre-equilibrium neutron multiplicity was assumed equal to the proton one. This is a reasonable assumption if the pre-equilibrium proton emission is mainly accounted for in terms of first chance np collisions [20,21] in the overlap region between colliding nuclei. This is supported by the experimental findings in this beam energy region [19,22–24]. In fact being the cross section $\sigma_{pp} = \sigma_{nn} = 1/3\sigma_{np}$ [25], pp and nn collisions contribute less to the total amount of pre-equilibrium protons and neutrons than np collisions. In the reaction investigated the light partner is an $N = Z$ nucleus and therefore the contributions coming from nn and pp collisions are expected to be the same. Such a scenario allows a reasonable description of both inclusive and exclusive data spanning a large range of incident energies (from 15A MeV to about 100A MeV) and projectile target combinations.

Using momentum and energy conservation the velocity, the mass and the excitation energy of the compound system can be deduced. Corrections for energy losses in the target and reaction Q-values were also taken into account. The procedure allowed to extract an excitation energy value of $E^* = 330 \pm 20$ MeV for the hot system produced with an average mass $A = 129$ and charge $Z = 56$. Errors on E^* include the error on fit parameters (temperature and multiplicity of the pre-equilibrium emitting source), and a factor of 2 indetermination on the estimated neutron multiplicity. The estimated values of the energy removed in the pre-equilibrium phase of the reaction and the excitation energy of the hot system are listed in Table 1 for all the reactions investigated.

The ΔE-E correlation plot measured with the telescopes yields the Z distribution of evaporation residues focused by SOLE on the focal plane (Fig. 1a). Loci associated to residues with Z between 33 and 52 can be clearly identified. The relative yields of the evap-