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High-energy gamma rays emission in coincidence with light charged particles from the ^{32}S + ^{74}Ge reaction at 210 MeV

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Abstract. High-energy γ-rays from the ^{32}S + ^{74}Ge reaction at 210 MeV bombarding energy were measured in coincidence with light charged particles detected in a large area hodoscope. Experimental results show that energetic γ-rays in coincidence with light charged particles are essentially emitted in the compound nucleus decay. The parameters of the giant dipole resonance (GDR) have been extracted from a lineshape analysis of the experimental γ-ray spectrum. The derived values of mean energy E_{D}, width Γ and strength S are in good agreement with results from previous experiments on Sn isotopes obtained by using different experimental techniques.

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1 Introduction

The measurement of the high-energy γ-rays emitted in heavy-ion reactions provides informations on the properties of nuclei at high temperature. Special interest is set on the energy range E_γ=10÷20 MeV, being related to the decay of the giant dipole resonance (GDR) built on highly excited states of nuclei [1]. In fact, the parameters characterizing the GDR (mean energy E_D, width Γ and strength S) depend on fundamental collective nuclear properties such as the symmetry energy, the size and the shape of the nuclei and the coupling of the collective motion to the surface vibration [2]. Furthermore, even at moderate temperature ($T \sim 2\div3$ MeV), γ-emission from GDR states mostly occurs in the first steps of the de-excitation chain and thus represents a direct probe of the initial compound system. A systematic study of the GDR parameters, as done in the A $\sim$ 110 mass region (Sn isotopes)[2-8], makes possible, in principle, to follow the evolution of collective nuclear properties as a function of angular momentum and temperature.

The main experimental difficulty in detecting high-energy γ-rays is related to their low multiplicity (approximately 10^{-3} high-energy photons per nuclear decay). For low bombarding energy, hard γ-rays are essentially produced in the decay of the compound nucleus (CN), therefore γ-emission from GDR states has been studied in inclusive experiments [2]. When the bombarding energy is increased, contributions to the total γ-ray spectrum coming from different reaction mechanisms start to be significant and more complex experimental techniques are required. A widely used technique consists in the measurement of the low-energy γ-rays multiplicity in coincidence with the hard γ-rays [3-5]. In this way, the contributions from central collisions are magnified by the rejection of the low multiplicity events, which are often associated with peripheral reactions. Some high-energy γ-rays measurements in coincidence with the evaporation residues (ER) were also performed at bombarding energies near or above the threshold ($\sim$10 MeV/amu) for the onset of the incomplete fusion [7-10]. Exclusive GDR measurements in coincidence with isomeric states or discrete γ-lines in residual nuclei are also available in the literature [6, 11, 12].

An alternative way to tag fusion-evaporation events is the detection of the light charged particles emitted during the CN decay. This technique has been successfully used in the past for lighter nuclei such as Cu and Ca isotopes [13, 14] and turned out to be more efficient compared to an evaporation residues coincidence measurement.

In this work, the same experimental method has been applied in the A $\sim$ 110 mass region to study the GDR at moderate temperature.

2 Experimental details

The experiment was performed at the XTU Tandem facility of the Laboratori Nazionali di Legnaro (Italy). A 210 MeV ^{32}S beam was focussed onto a 280 μg/cm^2, 95% enriched, self-supporting ^{74}Ge target. The ^{106}Cd compound nucleus was formed at total excitation energy E_x=134 MeV. The critical angular momentum for the fusion-evaporation channel is $J_{crit} \simeq 69\hbar$ as determined by the competition with fission.

A light charged particle hodoscope (LPH) was used as main event trigger. The LPH was made of eight silicon detectors (300 μm thick), each having a 4×6 cm^2 active area, divided into seven independent strips. The eight detectors were placed in a plane perpendicular to the beam axis, symmetrically with respect to the beam direction, at 8 cm from the target in the forward hemisphere. At this distance, the LPH covers the angular range between θ_{lab}=10^o and θ_{lab}=50^o. A 10 mg/cm^2 thick aluminized mylar foil was placed in front of the detectors to stop the scattered beam and the heavy (Z $>$ 2) reaction products. The readout of each of the 4 detectors nearest to the beam axis was carried out by using two preamplifiers reading 3 and 4 strips together. An unique preamplifier was used for each of the 4 more distant detectors, reading the 7 strips all together.

The obtained LPH segmentation allow, in principle, the simultaneous detection and identification of up to 12 light charged particles (LP). Nevertheless, the probability of detecting high fold LP events is rather small in the present case. Statistical model calculations for the ^{32}S + ^{74}Ge system predict an average multiplicity of 2 protons and 1.5 α particles. It has to be also noticed that in the present experiment a sensible fraction of the protons give signals below the LPH threshold yielding a reduced efficiency with respect to the α detection.

The high energy γ-rays were detected by four 10.2 cm $\times$ 10.2 cm cylindrical BGO scintillators, temperature stabilized and gain monitored, placed at θ_{lab}=90^o, 118^o, 135^o, 157^o and at a distance of 90 cm from the target position. Time-of-flight, with the start signal from the LPH, was used to separate γ-rays from fast neutrons. The energy calibration of the BGO detectors was obtained by using ^{60}Co and ^{137}Cs radioactive sources, the 7.4 MeV and 10.2 MeV γ-rays originating from slow neutron capture in Ge isotopes [15] and the reaction ^{2}H(^{11}B,nγ)^{12}C. The latter reaction populates the 15.1 MeV state in ^{12}C which decays to the ground state by a strong M1 transition. Doppler shift corrections for the BGO γ-ray spectra were also carried out.

Evaporation residues close to the beam axis were selected by means of an electrostatic separator, rejecting both the primary beam and the elastic-scattering events. The separator, basically a plane capacitor, was 50 cm long and was operated at 15 KV/cm. An entrance collimator allowed the selection of a slice of the kinematical cone around the beam axis from θ_{lab}=0^o up to about θ_{lab}=10^o, thus covering almost the total evaporation residues angular distribution, as resulting from Monte-Carlo statistical model calculations. The ER were detected in a set of 3 silicon strip detectors (similar to those used for the LPH) placed on a movable arm 117 cm downstream from the target position after the electrostatic separator. Identification of the ER was performed by measuring their energy and time-of-flight. The LPH provided the start signal for the time-of-flight measurements. The calculated ER detection efficiency was about 10% as determined from Monte-Carlo simulations. The same detection system was already used in an earlier experiment on the ^{32}S + ^{74}Ge reaction in which light charged particles spectra were measured in coincidence with ER [16].

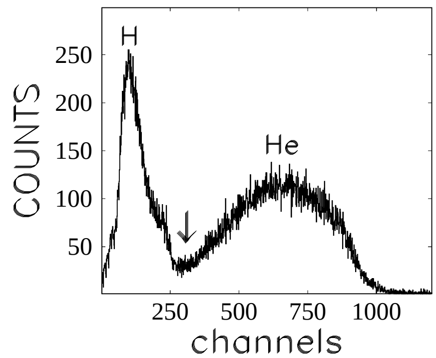

Fig. 1. Example of the LPH energy loss spectrum showing the separation between protons and α particles. The arrow marks the threshold for α particle discrimination

Double coincidences between high-energy γ-rays in the BGO detectors and light charged particles in the LPH (γ-nα events) and triple coincidences between high-energy γ-rays in the BGO detectors, light charged particles in the LPH and evaporation residues (γ-nα-ER events) have been collected.

The Monte-Carlo statistical model calculations, already mentioned in this section, have been an important tool in the analysis and in the interpretation of the LPH data. Simulations were carried out by means of the code CACARIZO [17], a Monte-Carlo version of the well known code CASCADE [18]. This code performs complete multistep statistical model calculations including an exact treatment of the spin coupling between compound nucleus and emitted particles. The geometry of the experimental set-up (LPH and ER detection system) has been folded into the original code to compare directly the simulations with the experimental results.

3 Light charged particle emission

When triggering on light charged particles, a possible contribution to the γ-ray spectra from two body reactions has to be considered. Some experimental observations reported in this section suggest that such contributions are negligible in the present case.

Figure 1 shows an example of energy spectrum measured by a single LPH detector. The two structures evidenced in this spectrum are associated to the detection of protons and α particles, according to their energy loss. Discrimination between protons and α particles is simply obtained by setting proper windows on the 12 LPH energy loss spectra. In this way protons and α hits are counted, allowing an event by event measurement of the charged particle fold.

The α fold distribution in coincidence with high-energy γ-rays (γ-nα events) and that obtained with the additional requirement of detecting an evaporation residue (γ-nα-ER events) are presented in Fig. 2. Because of the limited solid angle covered by the LPH, the decay channels contributing to a given nα event are those in which the number of emitted α particles is greater than or equal to the measured one. The fine structure of each nα peak represents the associated probability of detecting 0, 1, 2, ... protons in coincidence with nα particles. The relatively few counts of the 0α fold

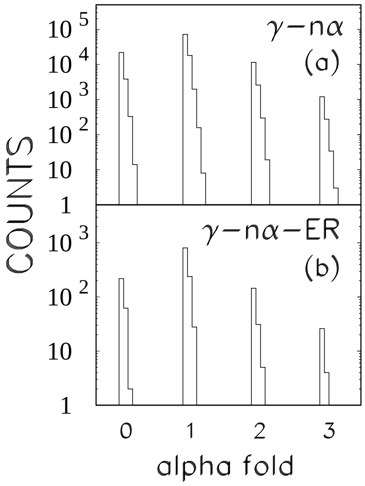

Fig. 2. Light charged particle fold distribution in coincidence with: (**a**) high-energy γ-rays (**b**) high-energy γ-rays and evaporation residues

Table 1. Experimental and calculated values of the $R_{1\alpha/2\alpha}$ ratios

	γ-nα (EXP.)	γ-nα-ER (EXP.)	Monte-Carlo (CALC.)
$R_{1\alpha/2\alpha}$	6.4±0.1	5.9±0.6	5.2

(only protons) with respect to the higher α folds are due to the reduced proton efficiency in the LPH (see Sect. 2).

In Table 1 the ratio between the number of events in the 1α and 2α channels ($R_{1\alpha/2\alpha}$) are reported in the γ-nα and γ-nα-ER cases together with the results of Monte-Carlo simulations. The two experimental values are very similar, showing that the α fold distribution results unchanged if the ER coincidence is required. The calculated $R_{1\alpha/2\alpha}$ value is also in reasonable agreement with the data.

In Fig. 3 are reported the high-energy γ-ray spectra in coincidence with the different α folds, whereas in Fig. 4 the presented γ-ray spectra have the additional ER coincidence requirement. The slope parameters T reported in Figs. 3 and 4 have been evaluated by fitting the γ-ray spectra in the energy region between 4 and 9 MeV with the exponential function exp($C - E_\gamma/T$). In Fig. 5 the slope parameters T in the γ-nα and γ-nα-ER cases are reported as a function of the α fold. It appears that, for a given α fold, the slope T of the γ-ray spectra is rather unchanged by the additional ER coincidence requirement.

The comparison between experimental data in the two classes of events (γ-nα and γ-nα-ER) shows no evidence of two-body reactions contribution to the measured γ - light particles coincidences. It is expected that the effect of such a contribution would give values of the slopes T and of the ratio $R_{1\alpha/2\alpha}$ different from those characterizing the ER channel. Fragments from two-body reactions are, in fact, produced with lower excitation energy with respect to that corresponding to the compound nucleus. In addition, results of statistical model calculations for the ^{32}S + ^{74}Ge reaction, show that the multiplicity of the light charged particles for two-body mechanism is considerably lower than that for the compound nucleus decay, also in the most favorable conditions, i.e.: *a)* maximum energy transfer in the collision and *b)* all the transfer energy stored as thermal excitation of the fragments [19].

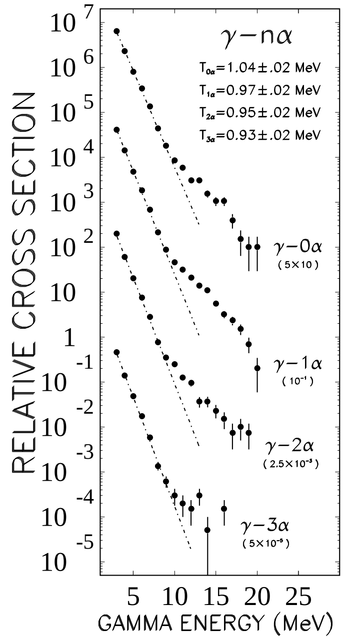

Fig. 3. Spectra of γ-rays detected in coincidence with different numbers of α particles in the hodoscope LPH

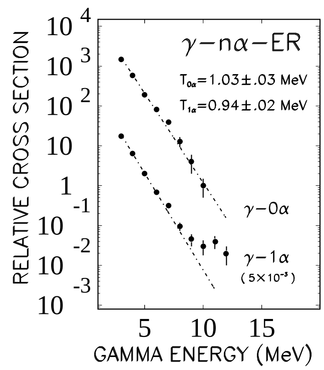

Fig. 4. Spectra of γ-rays detected in coincidence with both light charged particles in the LPH and evaporation residues

As a final remark, we note that the emission of light charged particles also decreases the total excitation energy available for γ-emission. The possible contamination of the γ-ray spectrum in coincidence with charged particles should, then, decrease with increasing number of coincident α particles.

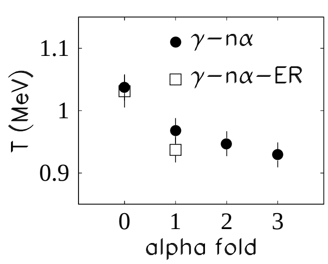

Fig. 5. Slope parameter T of the γ-ray spectra as a function of the measured α fold

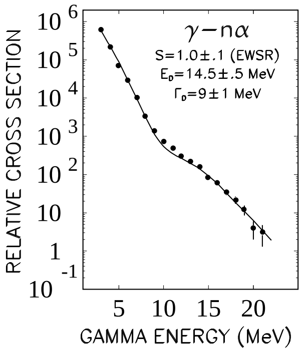

Fig. 6. γ-ray spectrum in coincidence with the light charged particles detected in the LPH. The solid line is the result of the CASCADE statistical model calculations

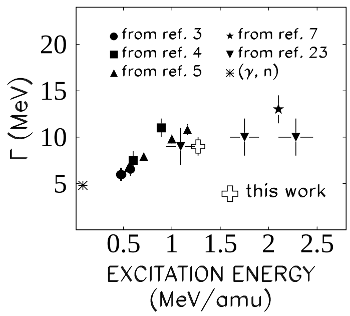

Fig. 7. GDR width Γ as a function of the excitation energy per nucleon. Results of Ref. 23 have been obtained in deep inelastic scattering measurement. The value relative to (γ, n) measurement is taken from Ref. 24

4 Gamma-ray energy spectrum lineshape analysis

The γ-ray spectrum summed over all BGO detectors and α folds was used for the lineshape analysis reported in this section.

The GDR parameters were determined by fitting the γ-ray sum spectrum in the energy region $E_\gamma \geq 12$ MeV with a single Lorentzian distribution of the GDR strength function, using a modified version [2] of the computer code CASCADE. The BGO detector response function was folded into the calculations. The set of the statistical model input parameters were derived from a previous measurement [16] on charged particle emission in the ^{32}S + ^{74}Ge reaction. In particular, the value a = A/7.5 MeV^{-1} for the level density parameter has been used. We stress that level density parameter values ranging from A/7.5 to A/9 MeV^{-1} have been already employed for the analysis of the γ-ray spectrum in the Sn region [3-8].

According to earlier works on Sn isotopes at excitation energies beyond 100 MeV [4, 5], an electric Isoscalar Giant Quadrupole Resonance (ISGQR) as well as an electric Isovector Giant Quadrupole Resonance (IVGQR) have been taken into account in the statistical calculations, with GQR parameters from systematics [20]. Nevertheless, GQR contribution to the calculated spectra turned out to be negligible [5].

The derived best fit values of the GDR parameters are: $E_{\rm D}$=14.5$\pm$0.5 MeV, Γ=9$\pm$1 MeV and S=1.0$\pm$0.1 in terms of the Energy Weighted Sum Rule (EWSR). The calculated spectrum corresponding to the best fit parameters is shown in Fig. 6 together with the experimental one.

The results of GDR measurements in the A $\sim$ 110 mass region [3-8] have already shown that the mean energy of the resonance remains almost constant at a value of $E_{\rm D}\simeq$15 MeV with increasing total excitation energy of the nucleus. On the contrary, the width Γ was observed to increase from 6 to about 10$\div$11 MeV as the excitation energy is raised up to 130 MeV [3-6]. Beyond this point, the width increase is very small [7, 8].

The broadening of the GDR width at the lowest excitation energies is generally interpreted as arising from nuclear deformation effects induced by the angular momentum [21]. Thermal fluctuations, which allow the sampling of nuclear shapes different from the equilibrium one, were also calculated [21] and their influence was found to be less important. Furthermore, in a recent γ anisotropy measurement [22], a strong angular momentum dependence and a very weak sensitivity to temperature changes was evidenced, thus reinforcing the interpretation given in Ref. 21.

The saturation of the width Γ at the highest bombarding energies was observed to be consistent with a limitation of the angular momentum that can be transferred to the hot compound nucleus surviving to fission [7]. This result also support the theoretical picture [21] of a strong spin dependence of the GDR total width.

At the excitation energy explored in the present work ($E_x \simeq$ 1.3 MeV/amu) the GDR total width starts to saturate. The value Γ=9$\pm$1 MeV extracted from the present lineshape analysis of the γ-ray spectrum nicely agrees with previous experimental results as illustrated in Fig. 7. In particular, the data of Chakrabarty et al. [5] are relative to excitation energies comparable with our work. In Ref. 5 a slightly wider Γ value was determined. This can be either due to the different CN populated or to the experimental technique employed (coincidences with a low-energy γ-ray multiplicity filter), or even to the different level density (a=A/9 MeV^{-1}) used in the statistical model calculations of Ref. 5.

5 Summary

High-energy γ-rays from the ^{32}S + ^{74}Ge reaction at 210 MeV have been measured in coincidence with light charged particles detected in a large area hodoscope (LPH).

In the high-energy γ-ray spectrum, we have found no signature of contributions from two-body mechanisms when triggering on light particles, therefore the compound nucleus emission seems to be the dominant channel as already observed in A=40$\div$60 nuclei [13, 14]. Preliminary results on high-energy γ-rays - LP coincidences are also available in literature for very light nuclei (A=30) [25], showing that in this case contributions different from CN formation have to be included.

The advantage of the γ-rays - LP coincidences technique is related to the minor constraints on beam intensity and target thickness with respect to a coincidence experiment in which a direct evaporation residues detection is involved. A good geometrical efficiency for light particles detection can be obtained with the possibility of having a sufficient detector granularity. This granularity also allow to keep reasonably low the counting rates for each detector.

The technique can be applied in all cases characterized by a sufficiently high average light charged particles multiplicity in the CN decay. This depend on the N/Z ratio of the compound systems as well as to their thermal excitation and angular momentum distribution.

GDR parameters extracted from the lineshape analysis of the high-energy γ-ray spectrum in coincidence with light particles are in good agreement with previous results in Sn isotopes [3-8] obtained by means of different experimental methods.

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