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Gamma ray detection with CHIMERA at LNS: results and perspectives

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Abstract. We describe the use of the 4π CHIMERA charged particle detector as a large efficiency γ-ray detector. The CsI(Tl) stage of the CHIMERA telescope is used to detect and identify γ-rays. The high detection efficiency and the sufficient energy resolution guaranteed by CsI(Tl) allows us to use the detector for the study of rare decays. Two examples are reported: the low probability gamma decay (<10%) of the Pygmy resonance of a radioactive nucleus as the ^{68}Ni; the measurement of the gamma decay probability of excited levels of ^{12}C as the Hoyle state at 7.65 ($\sim 10^{-4}$) MeV and the 3^- level at 9.64 MeV ($\sim 10^{-7}$), both important for the Carbon production in stars. Future experiments made possible at INFN-LNS by the availability of the new fragment separator FRAISE are also outlined.

1. Introduction

CHIMERA [1] is a charged particle 4π detector for heavy ions. It was installed at INFN-LNS Catania since the beginning of this century. It uses 1192 telescopes Si-CsI(Tl) to detect and identify particles with different techniques. The CsI(Tl) stage of the telescope is sensitive to both gamma rays and neutrons, in particular gamma rays are identified via pulse shape analysis of the signal [2]. The high detection efficiency and the sufficient energy resolution guaranteed by CsI(Tl) for gamma rays allow us to use the detector for the study of rare decays. One field of investigation that is limitedly tackled is for instance the gamma ray decay yield of levels excited over the threshold for particle emission. The large particle decay probability of such levels strongly suppresses the gamma ray decay branch though, this low probability is very important in many fields. As an example, in nuclear astrophysics, this decay branch is often the only way to produce a relatively "long living" nucleus after capture reactions. For instance, neutron capture reactions are extremely influenced by the presence of the so called pygmy resonance, located near the threshold for neutron decay. A first trivial effect of such resonance is that the neutron capture cross section is increased by its presence. A less evident effect of such resonance is that the gamma decay branch, dissipating the excitation energy, produces a nucleus at its ground state. In this way a longer living nucleus is produced, becoming available as a seed for further reaction steps in the slow or rapid, neutron capture processes in neutron rich environments. We recently measured the relatively low probability gamma decay branch (<10%) of the Pygmy resonance of a radioactive nucleus as the ^{68}Ni [3], following its excitation via isoscalar mode. We will discuss about it in the next paragraph.

Other reactions relevant for the astrophysical environments involve alpha particles capture. The 3-alphas reaction is particularly relevant, being the main source for the production of ^{12}C in the universe [4]. Also in this case the only way to populate a stable ^{12}C, after the capture reaction, is its gamma decay. The probability of such gamma decay branch is quite small respect to pygmy resonances. We are working to measure it through the decay of the Hoyle state at 7.65 MeV [5] and of the 3^- level at 9.64 MeV. For the decay probability of the Hoyle state there is a rather reliable evaluation obtained in the 70th of last century (decay probability 4×10^{-4} [6]), while for the 9.64 MeV level there is only an upper limit evaluation around 10^{-7} [7]. In order to measure such very low decay probabilities we profit of the high efficiency of the CHIMERA detector and of its performances in particle identification and energy resolution. The complete detection of all particles produced in the reaction allows the use of the so-called Complete Redundant Measurement method (CRM) enabling the necessary background suppression. Section 3 discusses this detection method and presents some preliminary results. The last paragraph outlines the measurements made possible at LNS by the new fragment separator FRAISE.

2. The gamma decay of the pygmy dipole resonance in ^{68}Ni

In many theoretical studies it was shown that the pygmy resonance has a peculiarity with respect to other dipole states. It shows at the same time both isoscalar and isovector characters [10]. This unique behavior is due to the fact that the resonance is generally excited in nuclei with a sizeable neutron excess. In such nuclei the radius of the proton and neutron matter is different and in the nuclear surface the presence of the neutron matter is dominant. The excitation and decay of the pygmy dipole resonance in ^{68}Ni excited by isovector mode (Coulomb excitation) were studied at GSI looking both to its neutron [8] and gamma ray [9] decay channels. Being the isoscalar excitation not experimentally studied above the threshold for particle emission for radioactive nuclei, we decided to search for it in ^{68}Ni using a low charge N=Z reaction partner as the ^{12}C. The ^{68}Ni was produced by fragmentation on a 250 μm thick ^{9}Be target of a primary beam of ^{70}Zn at 40 A·MeV, delivered by the Superconducting Cyclotron (CS) at INFN-LNS laboratory. The beam selection was performed by using the FRIBS@LNS fragment separator active since many years [11]. A cocktail beam was produced and the fragments were identified event by event by using the CHIMERA tagging system [12]. The beam was finally focused on a carbon target. The beam energy in the middle of the target was around 28 A·MeV. The reaction fragments produced were detected and identified by 4 prototypes of the FARCOS correlator placed from 2° to 7° [13]. Two stages of double sided silicon strip detectors with respective

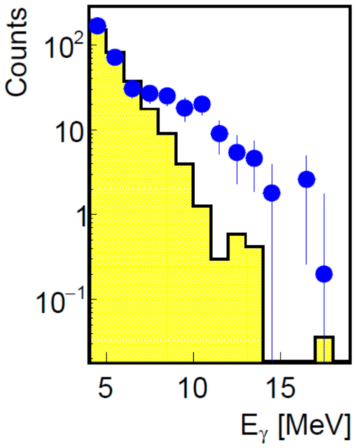

Figure 1 Gamma ray spectra detected in coincidence with ^{68}Ni (blue solid symbols) and with ^{66,67}Ni (filled histogram).

thickness of 300 and 1500 µm are coupled to a third stage of 4 CsI(Tl) detectors 6 cm thick - used to stop high energy light particles - in each FARCOS telescope. The CsI(Tl) of the CHIMERA sphere (Θ>30°) detected the gamma rays [14]. Due to the low beam intensity (about 20kHz total beam intensity was available during the experiment and the ^{68}Ni purity was about 30% of the cocktail beam) the large detection efficiency of the sphere was the key feature. Fig.1 shows the energy spectrum of the gamma rays detected in coincidence with the ^{68}Ni fragments produced in the reaction (solid symbols), compared with the energy spectrum of gamma rays detected in coincidence with ^{66,67}Ni fragments (filled histogram). The contribution of the pygmy resonance is observed in the region of 10 MeV in the case of coincidence with ^{68}Ni. In fact, since ^{66,67}Ni are produced after a neutron decay, typically, after such decay, there is no more excitation energy available to excite the pygmy resonance, hence no further gamma rays are emitted in that region. Similarly, if the pygmy resonance decays by gamma ray emission, a long living ^{68}Ni (29 s half-life) is produced and reaches the detector where it is identified in charge and mass by the outstanding identification capabilities of the FARCOS detectors.

More details on the measured angular distribution of the emitted gamma rays, showing their E1 character can be found in ref. [3]. No differences, within the limit of the low statistics, are observed comparing the spectrum of Fig.1 with the equivalent one measured at GSI exciting the resonance in the isovector mode [9]. In May 2020 a new experiment is scheduled aiming at increasing the observed statistics and directly comparing the decay spectra excited with both isoscalar and isovector modes. The comparison of the two modes with the same apparatus is important to reduce the uncertainty due to the detector response function.

3. Gamma ray decay of high excitation energy levels of ^{12}C.

As outlined in the introduction the 3-alpha process is the main responsible of the production of ^{12}C in the universe and this nucleus is the seed needed for the production of many other stable elements. They are in fact built by means of the capture of alpha particles by the ^{12}C nucleus. As outlined above, however, the ^{12}C is formed only when the excited levels, produced by the 3-alpha process, decay to the ground state by emitting gamma rays. The most important level that is excited in this reaction is the famous Hoyle state at 7.65 MeV [5]. This level is just near the threshold for alpha decay in the ^{12}C (7.22 MeV) so it can be populated by the relatively low energy alpha particles present in environments like the core of Red Giant Stars (from the point of view of nuclear physics their kinetic energy is low, just 9 keV average energy but it corresponds to a temperature of about 10^8 Kelvin that is a quite high if

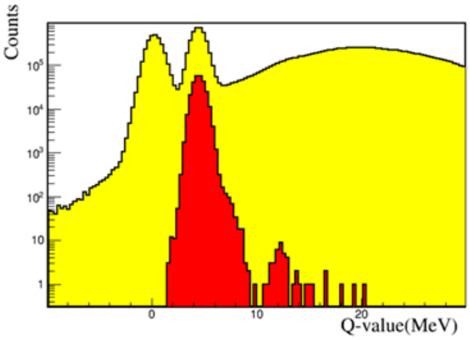

Figure 2 Q-value spectrum of two particles detected in coincidence (yellow). Same spectrum obtained requesting also the coincidence with one gamma ray.

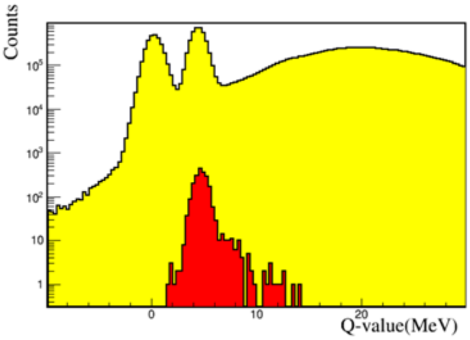

Figure 3 Same of Fig.2 but with red spectrum obtained requesting also the coincidence with two gamma rays.

compared with the internal sun temperature). This level has been extensively studied during the last century. A good review of its decay studies is given in ref. [6]. The probability of gamma decay of such level was extracted mainly with the technique developed by Chamberlin et al [15], detecting the scattered beam particle in coincidence with the ^{12}C surviving after the gamma ray decay step. This technique was accurate enough to extract the present accepted value of $4x10^{-4}$ with 5% error bar for the gamma decay width of the level [6]. However, this method did not allow to extract a precise value for the decay of the 9.64 MeV 3^- level that can be excited at higher temperature in more explosive environments (10^9 kelvin) [16]. In that case only a lower limit of 10^{-7} was extracted by Chamberlin [7] mainly due to problems given by ^{13}C impurities in the target. A new more sophisticated experiment is nowadays ongoing in Japan to improve this result [17] using a cryogenic proton target and the Grand Raiden spectrometer. We have demonstrated that a good background subtraction capability can be obtained also with the simultaneous detection of all emitted particles and gamma rays [18]. CHIMERA detector – thanks to its 4π angular coverage – has, in fact, the possibility to detect all charged reaction particles. Moreover, with its CsI(Tl), we can detect and identify, with large efficiency, all the gamma rays cascade. The background suppression power available with our detection system is proportional to the number of particles and gamma rays detected in coincidence. It also depends on the quality of constraints that we can exploit by imposing energy and momentum conservation.

In order to populate the excited carbon levels, we studied at INFN-LNS the reaction alpha on carbon at 64 MeV using an alpha particle beam also produced by the CS. The scattered alpha particles were detected and isotopically identified by the CHIMERA telescopes by ΔE-E method [19]. The silicon detector of the CHIMERA sphere (from 30° to about 80°) detected and identified by means of the time-of-flight technique the recoiling carbon with energy from few MeV up to few A·MeV. Summing the energy of the two detected particles we extracted the Q-value spectra of the reaction in which we can identify the ^{12}C levels populated in the reaction. The yellow histograms of figures 2 and 3 shows such Q-value spectrum. In such plot two main peaks can be observed corresponding to the ground state and the 4.44 MeV level. Higher excited levels, over the threshold for particle decay, cannot be observed due to the low yield compared to the huge background. The red histogram shows the quality of the suppression produced by the CRM method adopted with the detection of all particles and at least one gamma ray. A suppression of 5 orders of magnitude of the elastic peak is obtained and the level at 12.7 (1^+), that was completely obscured by the background, can be observed. This level has in fact a rather large probability to emit one M1 gamma ray (more than 2% [20]) even if its population cross section is quite low due to its non-natural parity. It is important to underline that energy and momentum conservation play a fundamental role in the background suppression. In fact, apart the obvious request of mass identification for the Carbon recoil, firstly we require that the two coincidence particles must be detected on opposite sides of the reaction plane (momentum conservation). Moreover, we ask that the energy of the detected gamma ray is equal (within the experimental resolution) to the measured Q-value. The required detection of one gamma ray does not allow one to see in the spectrum the Hoyle state that, due to the 0^+ spin and parity, cannot decay to the Ground State (GS) by direct gamma emission, but must decay to the 4.44 MeV 2^+ level with an E2 transition and after, with a second E2 transition, to the 0^+ GS. Due to our limited energy resolution (sigma of the Q-value of the order of 0.7 MeV) however, the presence of the Hoyle state is suggested by the deformed high energy side of the 4.44 MeV level. Also the 9.64 MeV 3- has a larger probability to decay through E1 transition to the 4.44 MeV level and successive E2 transition to the GS with respect to the less favoured (by selection rules) E3 direct decay to the GS.

In Fig.3 the filled yellow histogram is compared with the one obtained requesting the detection of two gamma rays in coincidence (red histogram), with a total energy comparable to the detected Q-value. In this case the 4.44 MeV level is suppressed by about 2 orders of magnitude and the Hoyle state becomes more clearly visible. It is not surprising to observe in such spectrum also few events in the region of 12.7 MeV level. In fact, this level has also a Γ_1 probability (to the 4.44 MeV) around 10% respect to Γ_0 probability [20]. The larger efficiency for lower energy gamma rays of our device partially compensates the lower probability to detect two gamma rays, so we can observe such events for this level. More surprising is the presence of some structure in the region of 9.64 MeV. In this first test experiment the number of detected events with population of the 9.64 MeV level was not in fact high enough to observe this decay, assuming a probability of the order of 10^{-7}. Comparing the population of the Hoyle state measured looking at the 3-alpha decay channel and the one of the 9.64 MeV, we know that we detected only about 3 times more events from this last level than from the Hoyle state. Looking now to the gamma-decay yield in the energy region of the two peaks, one can see that there is only about a factor 30 between the two gamma decay probabilities. Assuming as true the value $4\cdot10^{-4}$ for the decay probability of the Hoyle state, this means that the decay probability of the 9.64 MeV level should be of the order of 10^{-5}. However, before confirming this observation we need to collect more data. The observed behaviour could be due to some statistical fluctuation. In July 2019 more data were collected on the same reaction stay tuned for new results.

4. Future perspectives.

An upgrade of the LNS facilities involving the CS and a new fragment separator called FRAISE [21] has been recently funded. The upgrading of the Superconducting Cyclotron has the main aim to increase the beam intensity up to 10 KW and is planned to last about two years. The new fragment separator called FRAISE will benefit of the higher beam intensity producing up to 3 orders of magnitude more intense exotic beams with respect to present FRIBS@LNS. With such intense exotic beams we can start a new extensive program of nuclear structure and reaction mechanism studies. Among these studies the investigation on the gamma ray decay of excited levels in exotic nuclei will play an important role allowing a better understanding of their structure and in particular of their role in astrophysical environments.

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