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Search for E1 strength in $^{62,64}\text{Fe}$ around the threshold

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Abstract. The structure and nature of the pygmy dipole resonance (PDR) states below and above the neutron threshold is a recent open problem, particularly in exotic, neutron rich nuclei. Present experimental observations give only limited information on this subject. New experiments using different methods are needed. A recent measurement at the GSI laboratories on $^{62,64}\text{Fe}$ with the PRESPEC (2014) setup, following a past experiment with the RISING (2005) setup on ^{68}Ni , will contribute to solve the open questions. The setup located at GSI consists of the segmented HPGe detector array AGATA, scintillators (HECTOR), an Energy Loss / Total Energy time of flight measuring detector system called LYCCA and the fragment separator (FRS) apparatus. The experiment is based on relativistic Coulomb excitation together with the detection of the incoming and outgoing particles event by event. The detection of the produced γ -rays in the reactions, provides insight into the problem of the electric dipole response and E1 strength distribution around particle separation threshold.

1. Introduction

Giant resonances are among the basic building blocks of nuclear structure. Since they dominate the nuclear response, particularly above the particle binding energies, investigations of their main features such as centroid energy and resonance width have been carried on for many years in experimental nuclear physics. In the case of the simplest mode, the giant dipole resonance (GDR), a reasonable knowledge of its systematic features has been achieved. However, its fine structure, which carries unique information on the underlying nature of the mode and on the decay mechanisms, is still not known. A very interesting long-standing question is the nature of the so-called electric pygmy dipole resonance close to the neutron threshold in medium-to-heavy nuclei. When the pygmy strength is rather collective, it is also predicted that it might result from a neutron excess density vibration relative to the $N \approx Z$ core. A good understanding of the properties of soft E1 (or pygmy) modes is important, particularly in connection with exotic neutron-rich nuclei, because in that case the corresponding strength is expected to be higher than in stable nuclei. Furthermore, the presence of a resonance of E1 character close to particle threshold has important astrophysical implications, because it considerably modifies the equilibrium of the (γ, n) and (n, γ) reactions occurring in explosive nucleosynthesis scenarios. This knowledge is crucial for statistical reaction codes applied in network calculations and plays therefore an important role in the astrophysical r-process [1,2,3].

The E1 strength distribution around the separation energy depends mainly on the neutron excess [4]. At present, there's an ongoing discussion on the possibility of extracting information on the neutron skin from the pygmy resonance structure [5,6,7]. This quantity is related to the isospin-



dependent part of the nuclear equation of state (EOS), which, in turn, has relevant implications for the description of neutron stars. For this reason, there is an enormous effort aimed at determining the parameters that govern the asymmetric matter EOS, using both experimental and theoretical tools.

The first experiment searching pygmy states in the ^{68}Ni exotic nucleus, measuring γ -ray emission with the RISING setup [8], shows interesting results [9]. They allowed to deduce the neutron skin thickness [6] in a model dependent way. That work has motivated further investigations and thus new experiments regarding the search of the pygmy resonance in exotic ^{64}Fe and ^{62}Fe nuclei, using relativistic Coulomb excitation and the γ -tracking array AGATA, have been recently made.

2. Experimental set up and measurements

The experimental PRESPEC set up consisted in the combination of the GSI Fragment Separator (FRS) with the AGATA and HECTOR array systems [10] (figure 1). The segmented HPGe detectors of AGATA are equipped with electronics allowing the pulse shape analysis procedure which provides the position information with high resolution. To increase the efficiency and timing properties, the LaBr₃:Ce scintillator detectors were mounted around the target position. The setup used for γ -ray detection provided an excellent Doppler correction, good background reduction and good efficiency.

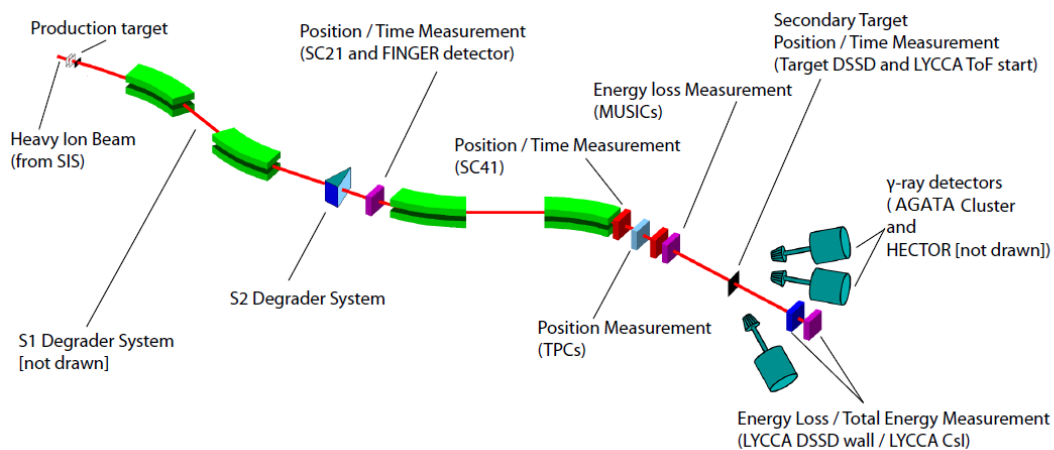


Figure 1. Schematic view of the FRS (sequence of 4 magnets on the left) together with the PRESPEC detectors (on the right). FRS is used for selecting the isotopes of interest. PRESPEC consist mainly in γ -ray detectors as HPGe segmented detectors (AGATA, mounted under forward angles), BaF₂ and LaBr₃:Ce scintillators (HECTOR, not shown and mounted additionally around the secondary target, mainly at backward angles) and an Energy Loss / Total Energy time of flight measuring detector system called LYCCA which detects and identifies the outgoing particles after the target.

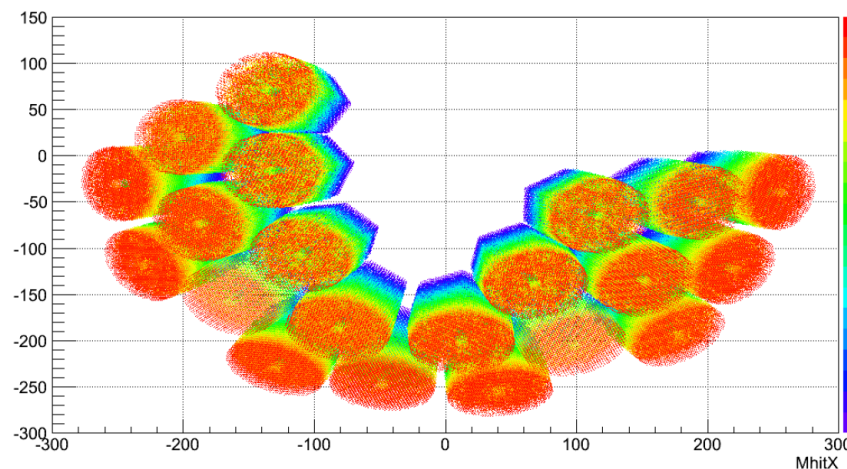


Figure 2. Perspective (x,y,z) plot of the measured γ -ray interaction points in the HPGe segmented detectors of AGATA. One can see the shape of the single detectors. The germanium capsules are mounted around the target position (in the centre at 0,0 coordinates). Every single interaction point, which contains additionally time and energy information, is coloured respectively to the local intensity. The spatial resolution around 5mm allows the reconstruction of the γ -ray interaction path with the help of tracking algorithms.

The radioactive $^{62,64}\text{Fe}$ beams were produced by fragmentation of the primary ^{86}Kr beam delivered by the SIS synchrotron at GSI at 700 or 900 AMeV and focused on a Be target. The ions of interest were selected and transported with the fragment separator FRS, (figure 1). The settings of the FRS were chosen to accept secondary fragments with a magnetic rigidity corresponding to a certain mass-over-charge ratio. This provided a beam cocktail containing the ions of interest in large fraction. The different nuclei contained in the secondary beam were identified uniquely according to their nuclear charge and mass number on an event-by-event basis. The beam cocktail was then impinging on the Au target (2 g/cm² thick) or Pb target (1 g/cm² thick), which were surrounded by the γ -ray detectors (see figure 1). The incoming isotopes of interest were selected using a reconstructed ID, mass versus charge (AoQ-Z) plot, while the outgoing ions were selected using the LYCCA-array placed at zero degree [10 and references therein] γ -ray spectra were measured. On an event-by-event basis the incoming and outgoing beam particles were identified and very small deflection angles far below the grazing angle were selected. This guarantees pure Coulomb excitation mechanism. A selection of an impact parameter that is larger than 13 fm strongly suppresses the nuclear contribution to the reaction [8]. After Doppler correction for the radiation emitted from the projectile at 70% of the speed of light only the projectile γ -ray emission mainly produces detectable structures. The information from the pulse shape of the signals from the AGATA detectors leads to a very precise information of the position (figure 2), which is crucial if one wants to minimize the Doppler broadening of the measured spectral lines. The effect in the γ -ray spectra when one uses or not the PSA analysis is shown in figure 3, one sees that the γ -ray tracking helps to increase the peak to total ratio in the spectrum and lowers the background. Especially at lower energies where a high atomic background and statistical gamma decay from beam induced excitations is present.

With AGATA we measured the first 2^+ state in ^{64}Fe at 746 keV. The energy and strength of this state is known, so it can be used as a benchmark to estimate the strength of possible higher lying E1 states in the same nucleus.

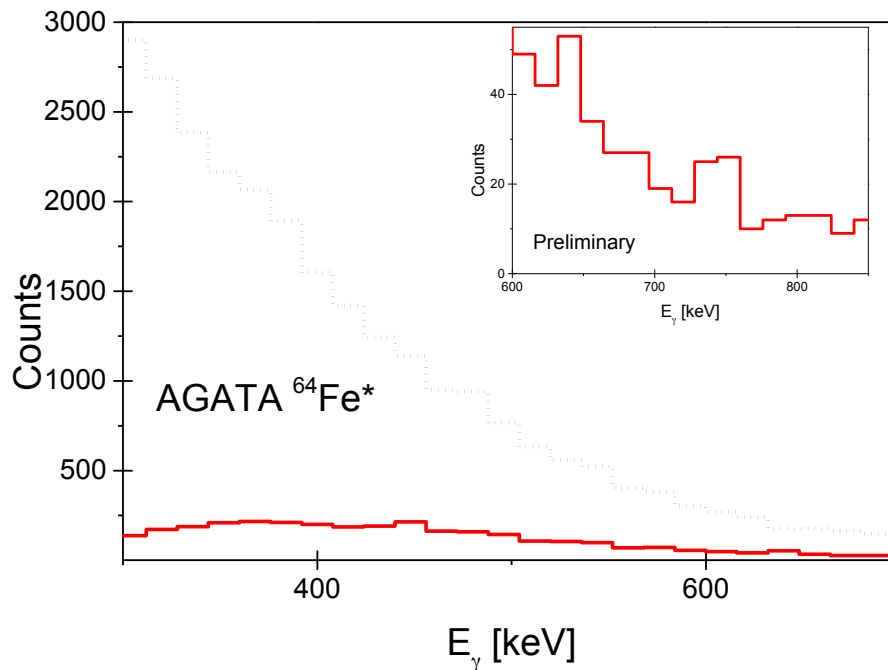


Figure 3. Doppler corrected γ -ray spectra measured in AGATA from Coulomb excited ^{64}Fe beam ($E_{\text{beam}}=400\text{A MeV}$ and $v/c=0.7$) at very small scattering angles. The dotted line is the result obtained using only the position information whereas the continuous line is obtained using tracking algorithms. The peak structure between 700 and 800 keV (in the inset) corresponds to the decay of the first 2^+ state in ^{64}Fe .

3. First results

A first result of the measurement is the proof that highly segmented HPGe detectors can perform the pulse shape analysis and tracking of the γ -rays in a relativistic Coulomb excitation experiment in the presence of a high background rate.

A preliminary analysis of the AGATA (figure 4) and LaBr3:Ce data (not presented in this paper as the analysis has still to be finalized) showed in both different detectors an accumulation of strength in the γ -ray energy spectra (figure 4) below threshold. This seems to happen not only in the ^{64}Fe nucleus but also in ^{62}Fe at slightly different energies. The strength distribution shows the typical shape and strength as expected [11,12]. On the basis of the angular distribution of these structures the E1 character may be demonstrated. Preliminary simulations with the GEANT Monte Carlo code and calculations of the cross section with an eikonal, Coulomb excitation approach together with branching ratio simulations and past measurements [9,13] appear to support the thesis of the E1 character of these structures. However, confirmations with higher statistics need to be obtained. Further analysis work is in progress.

4. Conclusion

After obtaining interesting results in 2005 with the RISING set up at GSI laboratories on the pygmy dipole state in ^{68}Ni , new measurements were made again at GSI in 2012 and 2014 with the AGATA-PRESPEC set up to search for pygmy states and to measure the low lying E1 strength distribution in the exotic $^{64,62}\text{Fe}$ nuclei.

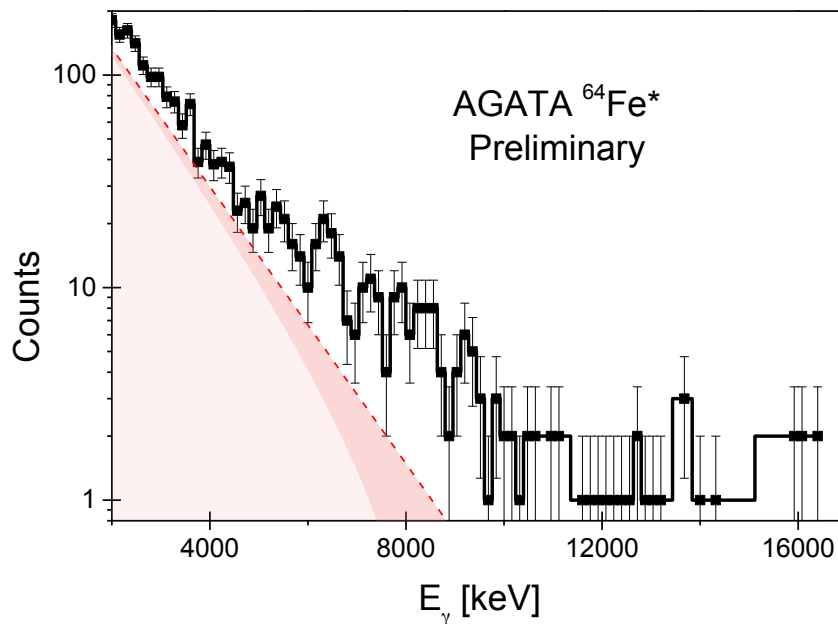


Figure 4. Preliminary Doppler corrected high energy γ -ray spectra for $^{64}\text{Fe}^*$ measured with AGATA using pulse shape analysis and tracking techniques. One can note a number of peaks sitting on an exponential background, which mainly comes from target excitation [9, ref. therein]. Width and shape of the peaks are similar to typical E1 strength distribution below the threshold [11,12].

The preliminary results obtained in these measurements contain interesting signals for the investigation of the pygmy states. Structures are present in the region 5-8 MeV in the measured γ -ray spectra and these structures seem to have an E1 character as this is the dominant excitation mode at these high beam energies. The structure shows similar strength distributions as seen in stable Fe isotopes [13] and a comparison with the yield obtained for the first 2^+ state shows that these E1 states would follow approximately the strength rule given in [12]. We also plan to extract from the data information for the region above the neutron threshold of 7.4 MeV up to the GDR region. This experiment is expected to provide the first and unique information for the E1 strength in the exotic $^{62,64}\text{Fe}$ nuclei, important for the modelling of the r-process path.

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