Nuclei far from stability: measurements with RISING

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Some of the most interesting Nuclear Structure physics cases and phenomena, addressed with experiments made with RISING, are presented and discussed. The RISING array is located at GSI and, since 2003, is active in gamma-spectroscopy experiments for the study of the properties of exotic nuclei. There are several topics which have been experimentally tackled by the RISING collaborations, among them focus is given to the problem of shell quenching and on the collective properties of neutron rich nuclei. Both aspects have an interest which goes beyond nuclear structure as they can affect, for example, stellar nucleosynthesis during the r-process in supernova explosion. In particular, four physics cases will be discussed moving from light to heavy nuclei. The first is connected to the ^{36}Ca nucleus, interesting for the study of isospin symmetry. The second is the study of the collective properties of ^{68}Ni and the search of the Pygmy Dipole Resonance and thus the determination of the symmetry energy slope parameter. The third topic is the structure of ^{130}Cd, a nucleus constituting a waiting point in the r-process. Finally, some preliminary results from an experiment on neutron rich Z~82 isotopes are presented. Some future perspectives in connection with the new PRESPEC international collaboration are also discussed.

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[1] Speaker

Introduction

The outstanding constrain in any advance in our comprehension of the nuclear physics is the fact that, generally, any nuclear reaction used to probe the properties of the nucleus is limited, both for the projectile and target, within the ensemble of stable nuclei. This imposes a severe restriction in the regions of the isotope table which can be experimentally explored and makes impossible a comprehensive study of the nuclear system [1,2].

The most straightforward experimental technique in nuclear physics would be that to measure the evolution of the nuclear properties, once fixed the atomic number, adding successively one neutron at a time, starting from the proton drip-line up to the neutron one. In this way a whole new universe of phenomena is expected to appear, like for example n-p paring effects, which could be observed only near the proton drip-line, or neutron skins which exists in neutron rich nuclei. Unfortunately, using only stable nuclei this kind of experiments is not generally possible [3,4] as, for example, the position of the neutron drip-line is known approximately up for nuclei with Z ~ 30 only. In general, one can say that there are extremely large areas of the nuclear chart which have been only slightly touched by experiments and an ensemble of nuclei, as large as the previous, which have never been produced so far. In this 'terra incognita' of unknown nuclei there is the key for a deep understanding of the nuclear structure and for the comprehension of the richness of subtle effect which, alone, do not characterize the nuclear behavior but contributes to make it one of the most complicated quantum many body system present in nature.

In the first section of this contribution two of the most interesting physics cases which have motivated the study of exotic nuclei will be discussed. In the second section the attention will focus on the RISING array, located at GSI. It is an example of an international collaboration which has assembled a powerful detection array for the study of the gamma-decay of exotic nuclei. In the third section a review of some of the results achieved by the RISING collaboration in more than 5 years of works will be done. Finally, some conclusions and perspective will be given.

1. Moving towards neutron or proton rich nuclei

The exploration of the nuclear chart regions which can't be reached using stable nuclei and targets started only few years ago, when newly built radioactive beams facilities started to provide beams of unstable nuclei [4]. At the moment, there are several facilities in the world which can provide beams of exotic nuclei and several laboratories are undertaking major upgrades either to build a brand new radioactive beam facility or to increase the present beam intensity (see for example ref [3,5-9]). In fact, the now available intensity of radioactive beams ($<10^5$ pps) is still several order of magnitude smaller than that of stable nuclei ($> 10^9$ pps). In spite of the low beam intensities, the very first results achieved have shown new and sometimes unexpected phenomena.

One of the major issues which have become evident in the study of exotic nuclei concerns the development of new shell or subshell structures. In fact, the spectroscopic data on the single particle structure in exotic nuclei, especially in the neighborhood of double magic nuclei (i.e. the energy of the first excited state in even-even nuclei or the $B(E2,2^+ \rightarrow 0^+)$ value), provide a sensitive probe for the study of sub(shell) structure development, E2 polarizability and the shape response of the magic core [10-11]. New shells and magic numbers has been observed in $N \gg Z$ light neutron-rich nuclei around N = 8, 20, 28 [12–14]. Very recently ^{24}O was proved to be double magic nucleus making N=16 a new shell closure [15-16] This is ascribed to the monopole part of the nucleon–nucleon residual interaction which causes a large monopole shifts of neutron single-particle orbits [18-21]. An alternative interpretation of the shell structure change along the N = 8, 20 and 28 isotonic sequences uses the weakening of the surface slope of the neutron potential due to the large neutron excess. One important consequence is that the well known Woods–Saxon shape of the mean field potential in nuclei close to stability is expected to change towards a harmonic oscillator type. This implies a reduction of the spin–orbit interaction and the strengthen of the harmonic oscillator magic numbers [17]. The scenario, for medium and heavy nuclei, is still practically unexplored. The presence of shell quenching for Z=50 and 82 or for the equivalent isotones N=50 and 82 is, at the moment, an open question which can be solved only through direct measurements.

A second extremely important phenomenon which appears in neutron rich nuclei is the change in the dipole response in neutron rich nuclei [22-24]. In fact, the large asymmetry in neutron and proton number induces a correspondent asymmetry in the energy levels filled by protons and neutrons and, consequently, a spatial separation in the filled orbitals [25]. The decoupling of the more weakly bound valence neutrons from the core is expected to manifests in a new collective excitation mode. In stable nuclei the nuclear dipole response is characterized by the isovector Giant Dipole Resonance (GDR), macroscopically, the out of phase oscillation of neutrons and protons; microscopically, a coherent superposition of many single particle-hole states. As the N/Z ratio increases an accumulation of E1 strength around the particle separation energy, commonly denoted as the Pygmy Dipole Resonance (PDR) is expected [26]. Qualitatively, this increase has been explained as due to the vibration of the neutron skin against an isospin saturated core and the name ‘Pygmy’ is due to the minor size of its strength in comparison with the GDR which dominates the E1 response. The experimental study of this low lying E1 strength, in the case of stable nuclei, has been done [27,28] with photon scattering experiments in different mass regions and in general it was observed that the low energy E1 strength (below and around the neutron binding energy) is larger than that due to the tail of the GDR. It was also found that this low energy strength increases with the N/Z ratio. The problem of how the E1strength evolves for nuclei far from stability in the neutron rich side is presently one of the interesting topics in nuclear structure since it provides information on the neutron skin and on the nuclear equation of state for asymmetric nuclear matter, relevant for the study of neutron stars [29,30]. In addition, the strength of the PDR is presently attracting a lot of attention as the dipole strength distribution affects reaction rates in astrophysical scenarios where photodisintegration reactions are important, i.e., in hot stars and stellar explosions [31].

2. The experimental setup RISING

As mentioned in the introduction there is, at the moment, a large effort in the construction or upgrading of experimental facilities capable to provide intense beam of unstable nuclei. In addition, a new generation of detector arrays has been built or is under construction in every laboratory where radioactive beams are or will be available. Such impressive activity is progressing worldwide in laboratories located in Japan, America and Europe [32-37]. However, in this contribution I'll concentrate on one particular experimental setup, RISING [38-40], which is located at GSI and has already a history of more than 5 years in the measurement of the properties of exotic nuclei with radioactive beams.

The RISING collaboration includes 40 research groups mainly from Europe and has conducted several campaigns of γ-spectroscopy experiments making use of the radioactive beams produced with the SIS/FRS facility at GSI, Darmstadt. The experimental set-up [38-40] is based on the 15 Cluster detectors (105 HPGe capsules) which originally were part of the EUROBALL array [55-57] and on a system of charged particle detectors for the identification and tracking of the beam before and after the secondary target [38]. Depending on the experimental campaigns different geometries and additional detectors have been used in the setup to maximize the efficiency, the resolving power and the characteristic of the apparatus. The RISING array is, at the moment, the most efficient γ-ray detector system coupled to an in flight radioactive beam facility in the world. The physics program is very rich and has produced key experiments facing the quest of shell structure with its manifestation in single particle and collective modes, complex states as multi-particle excitation and high multipole transitions producing long lived states, symmetries, deformations, and shape coexistence. Recent experiments are still under analysis, but a large number of interesting results were already obtained, a few of which will be discussed in the following sections.

The RISING experimental setup was commissioned at the end of 2003 and two different experimental campaigns took place. The “fast beam campaign” used the relativistic ions from 100 AMeV up to 600 AMeV for Coulomb excitation or other nuclear reactions. The campaign took place in the period 2003-2005. The second experimental campaign, the “stopped beam campaign”, started in 2005 and ended in 2009. In this case the primary objective was to stop the rare isotopes inside a stopper placed in the center of the array in order to study their gamma and beta decay at rest.

In both RISING experimental campaigns the primary beam from UNILAC-SIS was used to produce, by fragmentation or fast fission reactions, the exotic species. The primary beams consisted of stable nuclei with an energy range between 400 to 1000 AMeV on a stable target (typically ^{9}Be or ^{208}Pb) with thicknesses of 1–4 g/cm^{2}. The target is placed at the entrance of the fragment separator (FRS) (see figure 1) which selects and transport the nuclei to the experimental hall for the implantation or a reaction on a secondary target [54]. Inside the FRS the nuclei far from stability are identified, on an event by event basis, in x,y position, mass, charge and energy by the use of various types of detectors placed at the intermediate and close to the final focal plane [38,54].

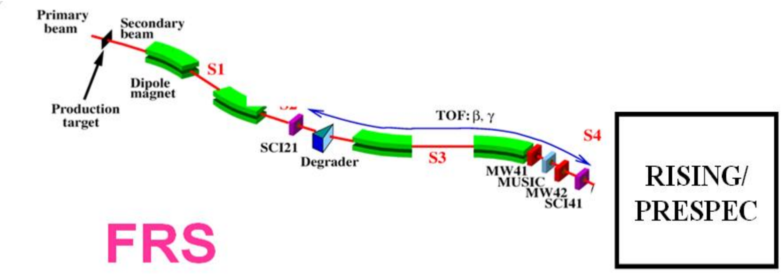

Figure 1: *A schematic view of the FRS facility. The primary beam from UNILAC-SIS arrives from the left and hits the primary production target. The detectors used for the identification of the exotic species collected, focused and transported in the FRS, are indicated in the plot. The location of the experimental array RISING/PRESPEC is indicated by the box in the right part of the figure.*

2.1 Selected physics cases from the "fast beam campaign"

In the "fast beam campaign", which made use of beam energies from 100AMeV up to 600 AMeV the HPGe detectors of the EUROBALL Clusters had been positioned at forward angles in order to maximize the effective solid angle affected by the Lorenz boost, and, at the same time, to minimize the Doppler broadening effect due to the opening angle of the detectors [38]. In this configuration additional detectors have been added to the clusters: i) the MINIBALL array [31] which was used for half of the campaign, ii) the HECTOR array [58-59] which consists of 8 large volume BaF_2 detector and was positioned at backward position for all the campaign and iii) the CATE calorimeter which was placed after the target [38,60-61]. The CATE array consists of modular ΔE–E telescopes arranged in a 3x3 geometry. Each telescope consists of a position sensitive silicon detector coupled to a CsI scintillator and is capable, on an event by event basis, to identify in charge and position the ions after their interaction with the target. As the exotic nuclei interact on a secondary target, in the "fast beam campaign" it is extremely important the identification of the isotopes after their interaction with the target. Consequently, the experiments have focused mainly on light-medium mass nuclei as only for these CATE has the proper resolution. The following list shortly summarizes the physics case tackled by RISING 'fast beam' experimental campaign [41-46]:

- Relativistic Coulomb excitation of nuclei near ^{100}Sn
- Triaxiality in even-even core nuclei of N=75 isotones
- Shell structure of unstable doubly magic nuclei and their vicinity;
- Mirror symmetry of new (sub)shell closures : ^{36}S – ^{36}Ca
- E1 Collectivity in neutron rich nuclei ^{68}Ni

As previously mentioned, here the attention will be focused on the last three topics. Experimentally [62] it has been observed that the N=20 isotope chain shows evidence of two new sub(shells) closure for N=14 and N=16. In fact, ^{34}Si and ^{36}S show the typical features of double magic nuclei. This is similar to what was observed in much lighter nuclei where, in the so called ‘isle of inversion’, the N = 14 appear as a new magic number due to the switch of the $s_{1/2}$ and $d_{5/2}$ orbitals. In fact, between ^{20}C and ^{22}O the *s* and *d* orbitals inverts, creating a sub(shell) gap at N=14 in ^{22}O. This newly observed N,Z = 14(16) shell stabilization is expected to be symmetric with respect to the isospin projection T_z and may not or little be effected by neutron binding energy differences. The ideal site in the isotope table where to check such prediction is along the light Ca (Z = 20) isotopes which reflects in T_z the N=20 isotone chain (see left panel of figure 2). Nothing was known for ^{36}Ca as the lightest Ca isotope with detailed spectroscopy was ^{38}Ca. As the mirror nucleus of ^{36}Ca, namely ^{36}S, is known, the spectroscopic study of ^{36}Ca was a critical experiment in this mass region. The spectra in the right panel of figure 2 show the first excited state of ^{36}Ca measured for the first time with RISING [44]. Each plot shows the energy spectra as was separately measured by one of the three gamma detector arrays present in the experiment (EUROBALL CLUSTERS, MINIBALL and HECTOR). The measured mirror energy difference ΔE_M(EXP) E(2^+,^{36}S) – E(2^+,^{36}Ca) is extremely high, however it has been reproduced using an isospin symmetric USD based interaction using experimental proton and neutron SPE from the A = 17, T = 1/2 isospin doublet, which account empirically for the one-body part of Thomas–Ehrman and/or Coulomb effects. Such scenario is consistent with the expectation that proton rich Ca isotopes develop another “island of inversion” and the onset of inversion may start at N = 14 in ^{34}Ca already [44].

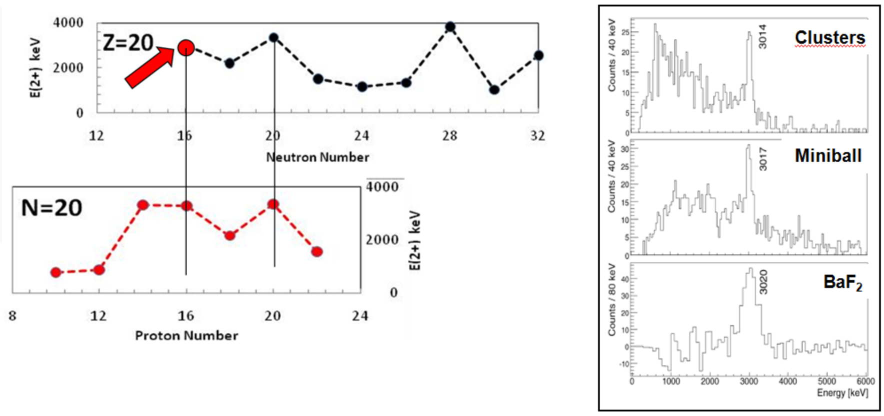

Figure 2: *Left Panel: the upper part of the figure shows the energies of the first 2^+ state in Ca isotope. In the bottom part the energy of the first 2^+ state in N=20 isotones are plotted. The lines which connected the two plots indicate the ^{40}Ca double magic nucleus and ^{36}Ca - ^{36}S. Right Panel: The energy spectra measured in the three gamma detector arrays of RISING corresponding to the first 2^+ excited state of ^{36}Ca (see ref [44])*

Another important result from the RISING Fast Beam campaign is related to the question on how the Giant Dipole Resonance (GDR) strength evolves when going from stable to more weakly bound exotic nuclei, with extreme neutron to proton ratio. This is an open problem that could not be tackled experimentally until recently. Theoretically, an accumulation of E1 strength around the particle separation energy is predicted as the N/Z ratio increases, the Pygmy Dipole Resonance (PDR) [26]. Unfortunately data in nuclei far from stability are extremely scarce. In fact, the PDR was investigated only in the oxygen isotopes $^{20-22}$O [64,65], in ^{26}Ne [66] and in the neutron-rich region around ^{132}Sn [24]. Using the RISING array, it was possible to investigate the low lying strength of the GDR in ^{68}Ni by measuring the γ decay produced by Coulomb excitation [46].

Such topic has collected very high interest beyond the nuclear structure field as it could change our understanding of the neutron capture process in the r-process. In fact, neutron-rich nuclei with loosely bound valence neutrons may exhibit very strong (γ,n) strength components (because of the PDR) near particle thresholds and thus very enhanced neutron capture rates (see for example ref. [31,67]). This means that the Pygmy Resonance can have a striking impact on the calculated r-abundance distribution.

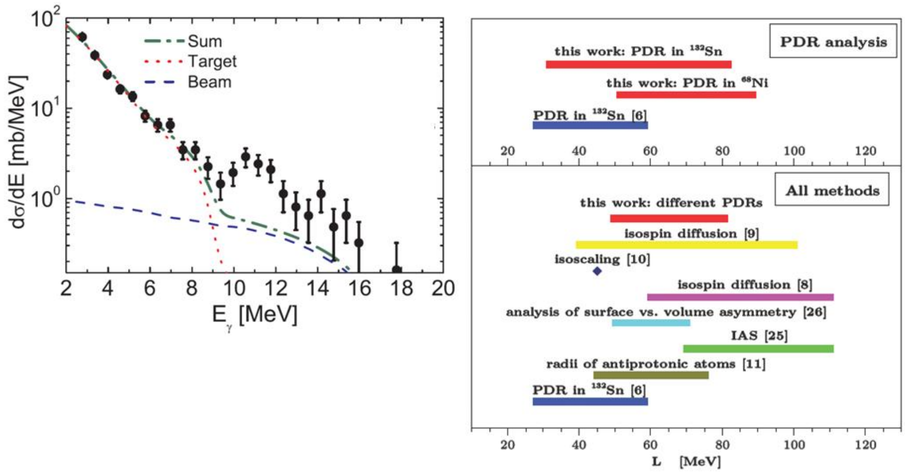

Figure 3: *Left Panel: the measured high energy spectra measured in the Coulomb excitation of* ^{68}*Ni at 600 AMeV. The three lines indicate the theoretical prediction (without the contribution of PDR) of the target and projectile emissions (from ref [46]). Right Panel: the summary of the available data on the derivative of the symmetry energy vs. nuclear density at saturation (L factor). The detailed values obtained in the analysis of PDR are in the upper part of the plot (from ref [30]).*

There are two different experimental techniques available for the measurement of the dipole strength in radioactive exotic nuclei. One consists in the complete kinematical reconstruction of the breakup products produced in the secondary target [68]. This technique does not need high intensity beams but it is currently limited by the fact that it cannot give any information below the particle binding energy. The technique used in the RISING measurement, using a 600 AMeV ^{68}Ni, consists in the measurement of the gamma-decay of the Coulomb excited projectiles. Such method, even though requiring high beam intensity, produces directly the E1 strength distribution and it is sensitive both below and above the particle binding energy [69-71]. In such kind of experiments, a critical factor is the capability to disentangle dipole states from others (mainly quadrupole states) which could be excited in the Coulomb scattering reaction. In this aspect the GSI experimental facility is unique as it can provide exotic beams at relativistic energies and this selects the Coulomb excitation of only dipole states. In fact, the dipole cross section increases with the beam energy while for quadrupole states the behavior is opposite. The plot in the left panel of figure 3 shows the measured high energy gamma-ray spectrum emitted by Coulomb excited ^{68}Ni at 600 AMeV as was measured by RISING. Between 10-12 MeV is evident the presence of additional strength than that expected from GDR, namely a PDR state. The Pygmy state exhausts approximately 5% of the EWSR strength [45]. The properties of the isovector Giant Dipole Resonance, in particular that of PDR, [26] could additionally provide constraints on the size of the neutron skin and on the slope parameter L of the symmetry energy, namely, the term which represents the derivative of the symmetry energy vs. nuclear density at saturation [26,29,30,72,73]. In fact, recently, it has been proposed a technique which is capable to extract, from the measured strength of the PDR, the nuclear skin thickness ($\Delta R=R_n-R_p$) and the value of L (see right panel of figure 3). The extracted values of ΔR in the case of ^{208}Pb, ^{132}Sn and ^{68}Ni and the value of L are perfectly consistent with that extracted using different techniques.

2.2 Selected physics cases from the “stopped beam campaign”

In the “stopped beam campaign”, the HPGe detectors of the EUROBALL Clusters had been positioned in two different geometries. The first, with a magnet in the target position, had the HPGe detectors positioned around the implantation target in a plane orthogonal to the magnetic field. This geometry was optimized for g-factor measurements [47]. The second geometry was extremely compact to maximize the efficiency of the array. The extremely high number of HPGe detectors gave to the apparatus i) high granularity to minimize the blinding effect induced by the prompt gamma flash, namely by the gamma and X rays produced during the implantation of the exotic species into the stopper and ii) an absolute full energy efficiency of ~ 25% at 300 keV and ~ 12% at 1332 keV, which is the highest ever achieved in such kind of arrays [40]. In a third part of the campaign the passive stopper was substituted by an active stopper which was constituted by several layers of DSSD detectors for the additional measurement of the electrons coming from the beta decay of the implanted exotic ions [74].

In this configuration, differently from what was done in the “fast beam campaign”, the mass region which was deeply analyzed was that of medium-heavy neutron rich nuclei [47-53], the production of which is practically a unique feature of the GSI experimental accelerator setup. Additionally, a flagship experiment focused on ^{100}Sn and measurements in proton rich Ni and Tc isotopes were also performed [75-79]. As in the previous section, here the attention will be focused on the open problem of the evolution of the shell structure in exotic nuclei, in particular in the N=82 isotone chain and in the neutron rich Z=82 region [80-85].

The region below the doubly magic nucleus ^{132}Sn is extremely important in stellar nucleosynthesis because of the A ~ 130 peak of the solar r-process abundance distribution. As happened in the case of neutron rich Nickel isotopes the assumption of a quenching of the N ~ 82 neutron shell closure leads to a considerable change/improvement in the global abundance fit in r-process calculations [86,87], in particular, a filling of the abundance plot around A ~120 – 140. Recent spectroscopic observations in nuclei close to ^{132}Sn, in fact, have been interpreted as the first experimental evidence of a shell quenching of the N =82 shell closure in ^{130}Cd [88,89]. The quenching seams to appear much closer to ^{132}Sn than that predicted by any calculation. In the experiment, performed using the RISING array, ^{130}Cd isotopes have been produced i) with a

6-proton knockout from ^{136}Xe projectiles accelerated to 750 AMeV by the SIS impinging on a 4 g/cm^2 Be target and ii) from the fast fission of a ^{238}U beam at an energy of 650 AMeV on a 1 g/cm^2 Be target. A total number of ~ 6300 ^{130}Cd have been obtained from the two different techniques and it was possible to measure the gamma-ray spectra emitted by excited ^{130}Cd in single and in gamma-gamma coincidences (left panel of figure 3) [80]. The 1325 keV transition was assigned as that from the first 2$^+$ level. It is important to notice that this energy is much higher than that inferred from ref. [88] which was used as indication of shell quenching. The right panel of figure 4 shows the level scheme of ^{98}Cd (N=50, Z=48) and ^{130}Cd (N=82, Z=48). The two scheme are extremely similar giving no evidence, supported by theory, for a N = 82 shell quenching in this nucleus. It is worthwhile stressing also the fact that ^{130}Cd is the most neutron-rich N = 82 isotone for which information about excited states have been measured.

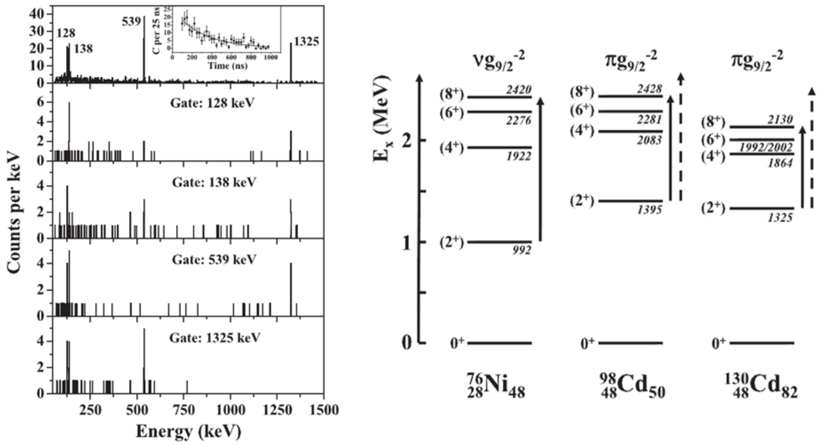

Figure 4: *Left Panel: the delayed gamma-ray spectrum measured in coincidence with the ^{130}Cd ions. The inset shows the time distribution between the ion implantation and the detection a gamma-ray from ^{130}Cd [80]. Right Panel: the level scheme of ^{130}Cd extracted from the RISING data compared to the known level schemes of ^{76}Ni [92] and ^{98}Cd [93]. The data are from ref [80].*

As was previously discussed, for neutron-rich N = 20 and N = 28 isotones it is now well-established that the neutron shells fade away. There are hints that also the N = 50 shell is weakened when going towards neutron-rich nuclei while in the case N=82 experiments does not provide any hints up to ^{130}Cd. Similarly, in the case of Z=82, data does not provide, up to now, that evidence. However, data on neutron-rich lead isotopes are rather scarce. In fact, it is rather difficult to populate these nuclei using classical deep-inelastic collisions [90]. The alternative approach offered by radioactive beam facilities, using the fragmentation of Uranium [91], has populated only heavy lead isotopes up to mass A = 215 with reasonable cross sections and gave spectroscopic data up to ^{212}Pb. However, using this technique, if isomers are present, it would be possible to study the structure of neutron rich nuclei around Z=82 by implanting the exotic species produced in the primary reaction into an active or passive stopper and measure the delayed gamma rays which followed the isomer decay.

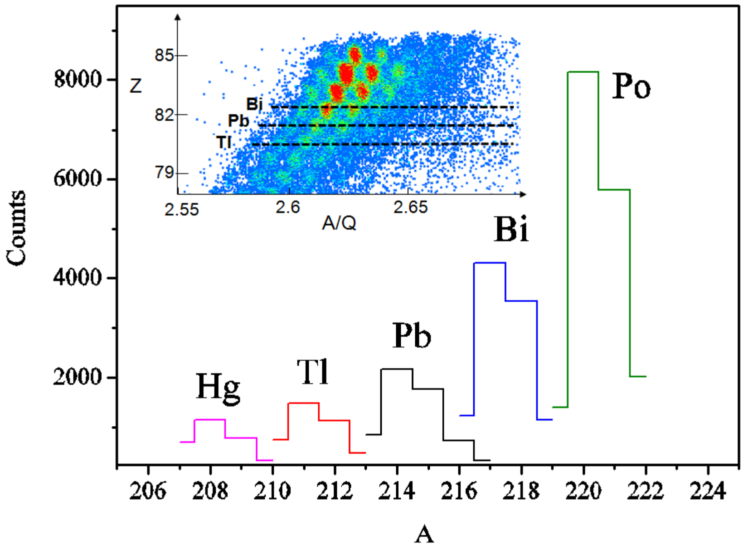

Figure 5:*The number of ions implanted in the absorbers which have been measured in coincidence with a gamma ray or a beta decay. The data are a subset of the total statistics and they are relative for the setup optimized for 215Pb. In the inset the A/Q vs Z measured spectra is given*

One of the last experiments of the 2009 RISING campaign consisted in the exploration of such neutron rich region where isomers are expected to occur abundantly as we are near the shell closure with single-particles occupying high-j orbitals close to the Fermi surface. The inset of Figure 5 shows the Z vs A/Q spectrum measured during part of the experiment, after a preliminary analysis. The neutron rich lead isotopes are indicated by a dashed line. The plot of figure 5 summarizes the amount of data collected during the experiment using a FRS setup optimized for ^{215}Pb. The different curves show the total amount of ions which have been measured (in coincidence with gamma or beta decay) during the experiment. It was possible, in fact, to acquire both the isomer gamma decay and the coincidence between implantation and beta decay of the implanted ions. The figure clearly shows the wealth of data that has been collected. When the analysis will be completed, the data will give a new deep insight on beta decay lifetimes and level structures of neutron rich isotopes in the Z=82 mass region at least up to ^{216}Pb.

3 Perspectives: AGATA in RISING/PRESPEC

In 2009 the international collaboration RISING enlarged with new institutes and nations and changed its name in PRESPEC. A major upgrade has been done in the detectors and in the electronics which has increased the sensitivity and the potentiality of the experimental apparatus. The CATE detector, placed after the target for the ions identification, has been substituted by the LYCCA-0 [93] detector developed inside the HISPEC collaboration. This detector has a much higher granularity than CATE (>80 CsI scintillators instead of the 9 mounted in CATE). A fast scintillator will be placed in front of the Silicon detectors for a TOF measurement which, together of the total energy measurement in CsI, will allow a much more clean identification in mass of the ions after their interaction with the target. The electronic of HPGe detectors has been substituted with digital one increasing the throughput of data and a similar upgrade has been done also in the FRS electronics. In a near future, in mid 2011, a second phase of the PRESPEC campaign will take place. In fact, the gamma-tracking array AGATA [33,34,94] (equipped with the then available number of detector units), will be installed in the PRESPEC setup to increase the detection sensitivity by at least another order of magnitude. Together with the anticipated upgrade of primary beam intensity at GSI, PRESPEC will provide unique capabilities to be exploited by the European nuclear structure community over the coming years continuing the successful program of the RISING project.

Acknowledgement

The experimental RISING and PRESPEC campaigns constitutes an excellent training ground for young physicists, offering them the opportunity both to obtain interesting physics results and to prepare well the experiments with the next generation of radioactive beams. Because of that the author is indebted to the RISING/PRESPEC collaboration and in particular to all the young students which have been the core of the apparatus. In particular, the author wants to thanks Angela Bracco, Oliver Wieland, Giovanna Benzoni and Roberto Nicolini.

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