Precise Coulomb excitation B(E2) measurements for first 2+ states of projectile nuclei near the doubly magic nuclei 78Ni and 132Sn

A Galindo-Uribarri 1,2
1 Physics Division, Oak Ridge National Laboratory, Oak Ridge TN, 37931, USA
2 University of Tennessee, Knoxville TN, 37996, USA
E-mail: uribarri@phy.ornl.gov

Abstract. Coulomb excitation is a very precise tool to measure excitation probabilities and provide insight on the collectivity of nuclear excitations and in particular on nuclear shapes. In the last few years radioactive ion beam facilities such as HRIBF opened unique opportunities to explore the structure of nuclei in the regions near the doubly magic nuclei 78Ni (Z=28 and N=50) and 132Sn (Z=50 and N=82). For this purpose we have developed specialized methods and instrumentation to measure various observables. There is also the opportunity to perform precision experiments with stable beams using exactly the same state-of-the-art instrumentation and techniques as with their radioactive ion beam counterpart. I describe some of the recent efforts at HRIBF to do more precise measurements using particle-gamma techniques.

1. Introduction
In the last few years various schemes to produce and accelerate nuclei far from stability have been developed, opening new and exciting opportunities to explore nuclear properties at extreme values of Z/N (with Z protons and N neutrons) and to better understand the forces that bind the nucleons together. In nuclear structure studies, the Radioactive Ion Beams (RIBs) can be considered as a tool that allows us to explore new regions in the nuclear chart and to study the shell structure and the gap evolution when the number of neutrons and protons changes providing a stringent test on the applicability of the theoretical models.
The use of RIBs for nuclear structure studies at low energy presents several experimental difficulties that require the development of methods and instrumentation. Each radioactive beam experiment presents its own set of problems and challenges due to the radioactive background from the beam, beam contaminants and the low beam intensity.
For many years, Coulomb excitation and transfer reactions have been used with stable beams and have provided a wealth of nuclear structure information. At the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory we have developed specialized instrumentation and techniques for performing these reactions in inverse kinematics with unstable beams. In particular we are using these two powerful techniques for the study of nuclear structure at low energies using neutron-rich RIBs near closed shells (e.g. 78Ni and 132Sn). While the primary focus of the HRIBF is the study of nuclear reaction spectroscopy and nuclear astrophysics using RIBs, there is also the opportunity to perform precision experiments with stable beams. Access to good quality beams from the facility and the newly developed powerful instrumentation provides unique opportunities to
perform systematic studies along isotopic chains using exactly the same instrumentation and techniques as with their RIB counterpart.

2. Coulomb Excitation and transfer reactions
Coulomb excitation is a purely electromagnetic excitation process of nuclear states due to the Coulomb field of two colliding nuclei. As such, it is a very precise tool to measure excitation probabilities and provide insight on the collectivity of nuclear excitations and in particular on nuclear shapes. At low beam energies, such as the ones we use at HRIBF, the interaction between the beam and the target nuclei is purely electromagnetic and predominantly populates the first excited state. Therefore, there is no need for corrections that account for feeding from the higher-lying levels, or potential nuclear-interference effects, as is the case of higher energy Coulomb excitation.

At HRIBF, we have made pioneer measurements of B(E2) values for several neutron-rich radioactive nuclei in the mass A = 80 and A = 130 regions [1,2]. We have repeated some of these measurements with increased statistics [3]. Also we are revisiting some of the reported measurements of B(E2) and quadrupole moments using stable beams along chains of isotopes such as Ni, Ge, Se, Sr, Sn, and Te to resolve some existing discrepancies. The approach has been to do safe Coulomb excitation reactions between various projectile-target combinations that allow for consistency crosschecks, to keep the corrections to the data to a minimum (e.g. electronics deadtime), and to extract and compare the results obtained using various independent techniques (e.g. normalization to Rutherford vs. normalization relative to the target well known B(E2) values). Together with the results obtained with RIBs (and using the same techniques) these revisited data will allow for a more meaningful comparison and a stringent test to theoretical predictions.

Another very successful program at HRIBF has been the study of transfer reactions using particle-gamma techniques [4]. Transfer reactions give direct access to the microscopic shell structure of nuclei. One-nucleon “pickup” (p, d) and one-nucleon “stripping” (d, p) reactions are useful spectroscopic tools in inverse kinematics with RIBs. Their advantages include simplicity on the interpretation and large transfer cross-sections for single particle (or hole) states. Techniques for performing the above reactions in inverse kinematics with unstable beams are being developed however, substantial development is still required in both targets and detection systems to fully exploit the potential of transfer reactions in hydrogen isotopes. Alternative approaches include the use of heavy ion transfer reactions with RIBs which we are exploring at HRIBF as a technique to study the structure of nuclear states inaccessible or difficult to populate in light ion reactions. It is possible to reach the same final nucleus by using a wide variety of different projectiles and by transferring different numbers of nucleons. Much may then be deduced concerning the structure of a state simply from its population or non-population in a series of different reactions. An attractive feature of heavy ion reactions below the Coulomb barrier is their insensitivity to the nuclear interaction between the cores simplifying the analysis.

Another approach we are pursuing is to develop techniques that allow us to measure more sensitive observables. The use of a polarized target in transfer reactions for example would allow the measurement of observables such as the analyzing power which gives an unambiguous determination of the total spin J [5].

The use of RIBs to do both Coulomb excitation reactions and transfer reactions presents serious challenges associated to their low intensities, potentially high backgrounds in the gamma-ray and charged particle detectors caused by the radioactivity of the beam, and isobaric contamination. Some of these problems can be solved with specially designed detection systems, as described later, and with good quality beams.

3. Beam production
The RIBs are produced using the Isotope Separator On-Line (ISOL) approach. The ISOL method requires two accelerator systems, a driver accelerator to produce radioactive atoms at rest and a post accelerator to accelerate them to energies of interest. The two accelerators are coupled by a target-ion
source (TIS) and a high-resolution mass separator. Facilities that use the ISOL method include HRIBF at ORNL in USA, ISAC-TRIUMF in Canada, and ISOLDE at CERN. HRIBF has a great advantage over other ISOL facilities that it has access to excellent quality beams for many stable species in a wide range of energies.

At HRIBF (Figure 1), the $K = 100$ Oak Ridge Isochronous Cyclotron (ORIC) serves as the driver, accelerating intense beams (up to $20 \mu A$) of light ions ($p$, $d$, alphas) for the production of radioactive isotopes, and the folded-geometry 25MV tandem accelerator serves as a post accelerator for the RIBs [6]. This accelerator is the highest operating voltage electrostatic accelerator in the world capable of producing beams from very low energies up to $15$ MeV per nucleon for light nuclei and up to $5$ MeV per nucleon for heavier masses. The ISOL method involves a thick target maintained at high temperatures ($T \sim 2200$ °C) to promote the rapid transfer to the actual ion source. Once ionized in an ion source the ions can be extracted by electric fields and then mass analyzed with magnets before its injection into a post-accelerator which takes them to the energy required by the experiment. HRIBF is the first facility to produce post-accelerated beams of heavy neutron-rich nuclei. In fact, the majority of the RIBs available at HRIBF are on the n-rich side (Figure 2). They originate from the fission spectra of $^{235}U$ bombarded with protons of energy of about $50$ MeV. The production target for n-rich nuclei consists of UC$_2$ mixed with graphite.

![Figure 1. Schematic layout of HRIBF, an ISOL facility at Oak Ridge National Laboratory whose main components are a K=110 cyclotron (ORIC) serving as a “driver”, a 25MV Tandem as a post-accelerator, two target/ion-sources (IRIS1 and IRIS2) for RIB production, an injector for stable ion species (ISIS) and various experimental stations. The majority of the Coulomb excitation experiments were performed at the RMS target station.](image)

4. Particle-gamma detection: experimental considerations

A large solid angle particle-gamma combination has proven a very powerful tool in nuclear spectroscopy, because of the ability to choose the excitation energy and angular momentum, isolate different exit channels, identify charged particles, and measure their multiplicities, angular correlations, and energy spectra with very large efficiencies [7]. Using charged particle arrays, the momenta of the particles detected can be used to reconstruct the reaction kinematics in each event, thus enabling a considerable reduction of the Doppler broadening of the peaks of the $\gamma$-ray spectra [8]. Use of these arrays also greatly improves the reaction channel selectivity through energy-conservation constraints [9]. Important discoveries can be attributed directly to the use of $4\pi$ charged particle arrays...
in conjunction with large gamma spectrometers: (i) the discovery of band termination and collective states in $^{64}$Zn[7]; (ii) the experimental and theoretical study of collective properties of $^{48}$Cr at high spin [10-12]; superdeformation in the mass $A=40$ region in $^{36}$Ar [13] and $^{40}$Ca [14], to name a few.

At HRIBF, we have developed particle-gamma instrumentation and techniques to perform Coulomb excitation reactions and transfer reaction studies (Figure 3).

![Figure 2. HRIBF Post-accelerated Beams. Section of the chart of nuclides showing intensities of 3 MeV/A beam-on-target of neutron-rich beams at the HRIBF. In addition to about 80 stable ion beam species, about 175 RIB species are available (32 proton-rich species and 143 neutron-rich species).](image)

For Coulomb excitation experiments the gamma-rays emitted by the projectile and target were detected in a gamma-detector array (CLARION) and the target nuclei were detected with a charged particle array with minimum absorbers (BAREBALL). A fraction of the beam was sampled using an axial ionization chamber or Bragg curve detector placed at zero degrees to determine and monitor any change in the beam composition. Most importantly the Bragg detector was also used to measure beam energy loss in the target (Figure 4). This way we know precisely to better than 1% in a target in/out sequence the energy loss of the beam in the specific target used avoiding an important source of error. Tests have been performed with the Bragg detector to measure target thickness homogeneity and energy loss variations due to intense beam bombardment.

![Figure 3. HYBALL array of CsI(Tl) crystals mounted inside the CLARION gamma-ray spectrometer. Each clover detector is surrounded by a BGO Compton-suppression shield.](image)
Germanium, selenium, tin and tellurium isotopes have been Coulomb excited by bombarding light targets (e.g. $^{12}$C, $^{27}$Al, $^{24}$Mg, and $^{50}$Ti) of about 1 mg/cm$^2$ thickness using "safe" energies. Criteria to establish the maximum bombarding energy where the interaction between the nuclei is dominated by Coulomb forces ("safe" energy) is discussed in references [15-17].

**Figure 4.** Superimposed Bragg curve detector energy spectra for various charge states. The broader peak at 139.2 MeV corresponds to the beam going through the target. We used a setup that allows target in/out sequence to measure the beam energy loss in the specific target used in the experiment. Different charge states of beam with same analyzing magnet settings were used to calibrate the Bragg counter response.

5. Precise B(E2) measurements using Coulomb excitation

The Coulomb excitation process has an advantage over other nuclear reactions in that the electromagnetic interaction is well understood and the theory of the interaction has been well developed. Under the proper "safe" conditions the projectile nucleus and the target are never close to each other for the nuclear force to play a role and the excitation is accomplished purely through Coulomb interaction. In principle it is possible using modern experimental techniques to determine in a model-independent way the $M1$, $E1$, $E2$ and $E3$ matrix elements connecting low lying collective nuclear levels populated by electromagnetic excitation. There are several prescriptions for achieving "safe" Coulomb excitation conditions but the best approach is to experimentally investigate them by bombarding at various energies. This is particularly important when the reaction partners involve deformed or very light nuclei.

Coulomb excitation has many advantages as a mechanism for excitation of nuclear states reaching very neutron-rich radioactive species, as the projectile itself can be excited. Large cross-sections are involved helping to achieve good statistics in the measured data even for weak RIBs. By contrast, very neutron-rich compound nuclei formed in fusion-evaporation reactions will tend to evaporate several neutrons bringing the residual nuclei towards the valley of stability.

Experimental B(E2) values for several of the isotopic chains in the mass $A = 80$ and $A = 130$ regions have been measured with different techniques and experimental conditions, and show considerable spread (see compilation of B(E2) values in the “Raman Tables” [18]). I show an example in Figure 5 of the spread of B(E2) values for the N = 40 $^{72}$Ge. It is important to determine these values precisely for some stable nuclei as some of these “well-known” B(E2) values have been used as a calibration measurement or reference for the determination of B(E2) values of radioactive species.

We have measured the B(E2) values of a series of radioactive beams of Ge, Se, Sn and Te isotopes [1,2,19]. Our approach has been to get a comprehensive picture of the shell structure in these regions by studying a series of properties of low lying states ($E(2^+)$, $B$(E2), g-factors and quadrupole
moments). The beams, instrumentation and techniques developed specifically for this purpose have allowed us to systematically study the behavior of these observables along isotopic and isotonic chains using both stable and radioactive nuclei under almost identical experimental conditions.

We have successfully developed a technique to Coulomb excite a RIB, in which scattered light target nuclei are detected at forward angles and are used both as a clean trigger for selecting $\gamma$-rays and to normalize to the integrated beam current through Rutherford scattering. Due to the relatively high velocity of the reaction products, especially in inverse kinematics reactions, the $\gamma$-rays will be emitted from fast moving nuclei (Figure 6). Therefore, the energy of the $\gamma$-ray will depend on the observation angle with respect to the velocity vector of the emitting nucleus following the Doppler Effect equations.

Figure 5. Compilation of B(E2) values for $^{72}$Ge (N = 40) from Reference[18].

A very successful research program at the HRIBF ISOL facility is the Coulomb excitation study of n-rich Ge and Se isotopes [2,19]. These results, together with those from CERN's ISOLDE on Zn [20] are providing direct information on the shell closure at N = 50 [21]. In the mass A = 130 region we have measured the B(E2) for even-even isotopes of $^{126-134}$Sn and $^{132-136}$Te. Highlights include the first Coulomb excitation measurement of $^{132}$Sn which shows the strongest shell closure among the magic nuclei. The results revealed a surprisingly large B(E2) value, further supporting the close similarity between this nucleus and its heavier analog, $^{208}$Pb [22].

Figure 6. Schematic of the Coulomb excitation in inverse kinematics of the radioactive $^{78}$Ge nuclei bombarding a carbon target. The gamma-rays are detected using the HPGe detectors from the CLARION array and the carbon recoils are identified using the CsI(Tl) detectors of the BAREBALL array.
Pioneer experiments were done to measure g-factors of exotic nuclei using the technique of recoil-in-vacuum (RIV) [23]. A transient field g-factor measurement on the first excited state in $^{132}$Te using Coulomb excitation has been carried out [24]. Very recently Coulomb excitation experiments where done with $^{124}$Sn (stable) and $^{126,128}$Sn (unstable) to obtain high precision B(E2) values and the first determination of a static quadrupole moment for the $2^+$ state of unstable Sn isotopes [25]. Extension of these measurements to lighter Sn isotopes is underway and would be very valuable for a better understanding of nuclear structure along the Z = 50 shell closure between $^{100}$Sn and $^{134}$Sn (Figure 8).

Similarly we hope that the detailed spectroscopic study of the evolution of the N = 50 shell closure will soon be within reach of experiments for the entire isotonic chain from the very neutron-rich $^{78}$Ni (Z = 28) to the self-conjugate $^{100}$Sn (Z = 50). Our studies of $^{82}$Ge and more recently $^{84}$Se together with the $^{80}$Zn studied at ISOLDE plus revisited measurements on the available N=50 stable isotones allow an excellent opportunity to investigate the role of the proton f $^5/2$, p $^3/2$, p $^1/2$, and g $^1/2$ orbitals in the evolution of the N=50 shell.

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Recent experiments at HRIBF include, Coulomb excitation of $n$-rich nuclei along the $N = 50$ shell closure and $Z = 50$ shell closure, the static quadrupole moment of the first $2^+$ in $^{78}$Ge and $^{126-128}$Sn and g-factor measurements of a few $n$-rich isotopes. It is expected that precise measurements of Coulomb excitation using particle gamma-techniques, with both stable and radioactive beams, will provide crucial tests of theoretical predictions, such as the evolution of shell structures in neutron-rich nuclei.

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