Coulomb Excitation of Neutron-Rich Magnesium Nuclei

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Arguably, the most pressing issue in all of low energy nuclear structure physics is developing a clear understanding of very neutron rich nuclei. By extrapolation of present knowledge, we predict almost half of all the possible bound nucleon systems lie in this domain where they remain unknown and unmeasured.

In the most neutron rich nuclei, with twice as many neutrons as protons or more, conventional nuclear models of nucleons bound in a single mean field must be modified, either by retaining constant neutron-to-proton ratio and drastically reducing the charge density of nuclear matter, or by building up a neutron skin. Either way, the stability of the nuclei, the location of the neutron-dripline, and the underlying nuclear structure remain to be determined. At present, the details of how the large excess of neutrons is accommodated and how it modifies the potential and the effective interactions in that field lie in the realm of theoretical prediction. A wide variety of predictions exist, based on many different technical approaches, which reach differing conclusions on the topology of the mass surface, the location of shell gaps and single particle energies, the effective residual interactions, and on the expected collective modes.

The shape of nuclei has been found to be a property which is very sensitive to nuclear potentials and their single particle states. In recent times, sophisticated models have been developed to describe the shapes of nuclei at high spin and along the proton dripline. The polarizing effects on the mean field caused by the occupancy of particular states near the fermi surface has been thoroughly explored to a point of having excellent predictive power, as have issues involving how state occupancy changes with frequency, and the effects on pairing. Now, in the neutron rich domain, these models can be used "in reverse" as tools to extract information on the mean field and single particle states from experimental measurements of nuclear shapes.

Coulomb excitation of nuclei remains one of the most sensitive, precise and unambiguous techniques for measuring the properties of nuclei, including static moments and transitional matrix elements. It has taught us a great deal of what we know of nuclear structure. As a purely electromagnetic probe, the excitation probability of states can be exactly and directly related to the nuclear wave functions. The population of states can be chosen by altering the kinematics of the collisions. The excitation cross-sections are frequently large by nuclear standards, often in barns (10^{-28} m^2) Thus, it is a probe which is ideally suited for far-from-stability physics.

Several experimental variants of Coulomb excitation are useful. For low-intensity ISOL beams at energies below the classical Coulomb barrier, thick target experiments offer the largest yields. For collective nuclei, identification of the lowest states in nuclei should be possible with 100's particles/second, while precision experiments become possible with 10^4 of particles/second. Absolute yields can be checked against lifetimes extracted from Doppler line shapes. The deviation from pure Coulomb excitation, which is sensitive to the nuclear matter distribution (and thus nuclear potentials) can be precisely measured through measuring changes in Coulomb-nuclear interference with beam energy as the beam energy is raised and the nuclei get closer. Measuring reorientation gives the sign of the quadrupole moment. Above the barrier, where the absolute yield is more difficult to calculate due to coulomb-nuclear interference, there is strong inelastic multi-step excitation which can be used as a tool to reach high angular momentum states. In this "unsafe" regime the population of states can be an order of magnitude above traditional "safe" Coulomb excitation, so sensitive searches to locate new states can begin above the barrier, then be refined in pure electromagnetic follow-up experiments.

With more intense beams, about 10^5 particles per second and up, thin targets can be used, and the excitation probability of states can be explored as a function of impact parameter. Measuring all of the Rutherford scattered particles in a 4-π particle detector, and almost all the γ-rays in a modern array, can present the most complete picture of low-lying collective modes which can be achieved in nuclei. Again, the use of radioactive particles may require some modification of technique.

The Coulomb Excitation of magnesium (Z=12) isotopes provide an interesting case which is illustrative of the physics issues which can be addressed, and which can be used to compare what may be achieved with low energy ISOL-type beams at about 5MeV/u with what has been achieved with intermediate (50MeV/u) and high (400 MeV/u) energy Coulomb excitation at fragmentation facilities. Experiments have been performed on ^{32}Mg at 49 MeV/u at RIKEN [1] and on ^{28}Mg at 238 MeV/u at GSI [2].

Tanihata et. al. [3] have suggested that the most neutron rich nucleus in each isotope chain will have a neutron number which corresponds to a spherical shell-gap, and deformed shell gaps should not play any role in determining the location of the dripline. In the case of magnesium isotopes this is expected to mean that ^{40}Mg$_{28}$, where the two-neutron separation energy becomes zero, will be spherical. This expectation is contradicted by Hartree-Fock-Bogoliubov calculations [4] and relativistic mean field calculations [5] which seem to indicate super deformed (β~0.6) ground states in ^{36,38,40} Mg, which are the most bound configuration right up to the dripline. The spherical N=28 shell gap is reduced by the nearby unbound continuum, so the deformed Z=12 proton shell gap is the dominant shape-driving influence. The HFB calculations also suggest that the magnesium isotopes are the first case where a significant neutron skin develops. The skin is deformed, but less asymmetric that the proton distribution. This should lead to a low-lying component of the isovector giant quadrupole resonance. Thus, several departures from conventional nuclear structure are expected.

At present, nothing is known beyond ^{32}Mg, though present predictions of beam yields indicate experiments near the dripline, beyond A=36, should be feasible with the projected RIA facility.

Magnesium isotopes have already played a part in the story of neutron rich nuclei far from stability and radioactive beam physics. The heaviest isotopes (A>28) were found to have anomalous masses, which were suggested to arise from the onset of deformation and a breakdown of the N=20 spherical shell closure. The first excited state was found to be at only 885 keV, far lower than the other N=20 isotones. Motobayashi et al [1] measured the Coulomb excitation probability of the first excited state, convincingly demonstrating that large (β~0.5) prolate, deformation was indeed the cause of the “anomaly”, arising as fp-shell configurations became more bound than the traditionally anticipated spherical shell model configurations. This type of “breakdown” of magic numbers is now known in other regions of nuclei and does not require any “new” dripline physics. However, the observation did stimulate a wide variety of theoretical investigations aimed at a broader understanding of all bound magnesium isotopes, currently expected from A=20 to 40. It also demonstrated the technical feasibility of Coulomb excitation of radioactive beams.

A classic set of stable beam Coulomb excitation measurements of sd-shell nuclei were made by Schwalm and Warburton [6,7]. They set the scale for what may be achieved using ISOL-type radioactive beams. These thick target experiments were aimed at minimizing systematic errors, and yielded transitional B(E2) matrix elements at the 1-2% level, extracted by both lifetime determinations and absolute yields. In addition, the static moments of states were determined, through reorientation, and the onset of Coulomb-nuclear interference was determined. In short, if the technique is modified for low-intensity radioactive beams, these experiments will form the core of precise and unambiguous studies which will reveal the structural properties of dripline nuclei.

Two experimental issues deserve examination. Firstly, with the anticipated beam intensities from RIA, what statistical accuracy may be reached, as one moves from stability? Secondly, How does the radioactivity of the beam hamper the measurement? The first issue can be addressed by calculation. Using the calculated [4] matrix elements, and location of low-lying states, the electromagnetic yield can be exactly predicted as a function of energy. Combining this information with the known stopping properties of magnesium isotopes in lead then provide a reliable estimate of the anticipated production rates, which can be folded with detector efficiency, predicted beam intensity and running time to give the statistical quality of the experiment. In short, with expected yields, a GRETA-like gamma-array, and a 100hr experiment, ^{36}Mg (where the large deformation is expected to start) could achieve 1% statistical precision, ^{38}Mg 10%, and the dripline nucleus ^{40}Mg would have a few counts. Only in the last case would intermediate energy fragmentation provide a superior result. The issue of buildup of activity, which with a 10^7 particle/ sec beam of mean life of 1 sec gives secular equilibrium intensity of millicuries of activity, requires attention. Behind the excitation target, which needs to be thick enough to maximize excitation, recoils should stop in a gas catcher and be transported away from the experiment. This should lower countrates by 1-3 orders of magnitude depending on the details of the decays. In addition, to further suppress the activity, time correlations between beam particles and gamma-rays must be examined to eliminate background sources. It is worth noting parenthetically that the “activity problem” is less severe than for neutron poor radioactivities, as the intense 511 keV positron annihilation radiation is missing.

Motobayashi et. al. conducted an important intermediate energy (49 MeV/u) Coulomb excitation experiment at RIKEN on ^{32}Mg which demonstrated the power and limitations of the fragmentation technique. Using a beam of 300 particles/second, and re-identifying surviving inelastically scattered ^{32}Mg nuclei emitted at a few degrees in the laboratory in a silicon detector telescope, the gamma-rays associated with Coulomb Excitation on a 350 mg/cm^2 ^{208}Pb target was measured in an array of NaI(Tl) detectors. The paper is important as it carefully outlines the sources of uncertainly in data reduction. The excitation cross section for the first excited state at 885 keV was measured to be 91±14mb corresponding to a B(E2) of 454±78 e^{2}fm^4, or a deformation of β=0.51. Excitation of higher states, through multi-step excitation, is suppressed, due to the rapid nature of the collisions. The measurement is of 16% accuracy, 10% of which is statistical, the remainder being systematic uncertainties. Thus, even with a much more intense beam, many of the uncertainties would remain, and it would appear that attaining 10% precision would be challenging. It is also important to note that every particle, ingoing and out, needs identification, so while a beam 10 times more intense would have been most advantageous, a beam 100 times more intense, >10^4 particles/second would have presented countrate problems.

Wan et. al. have also conducted a similar experiment at on ^{28}Mg fragments at GSI using beams of 210 to 280 MeV/u. Beam intensities were about 200 particles /sec. The Coulomb excitation cross-sections remain rather constant with beam energy (actually, they fall slowly at high energies, due to relativistic corrections), being measured to be 43±1 mb for the first excited state of ^{28}Mg which lies at 1473 keV. Again, this paper presented a very careful analysis of the advantages and pitfalls of high energy Coulomb excitation. The biggest advantage over the intermediate energy experiments is the increased range of the beam particles, and consequently the opportunity for using even thicker targets to enhance count rates. In this experiment a target of 940 mg/cm^2 of ^{208}Pb was used. On the negative side, the atomic Bremsstrahlung background, which rapidly rises both in energy and intensity and has a cross section of >10^3 barns for low-energy photon production, begins to present a formidable barrier. (which will become even more problematical at 400 MeV/u, with contributions to energies above 1 MeV). Multi-step excitation is even more suppressed. Finally, a simulation shows the effect of the relativistic boost which folds the gamma ray flux into forward direction and presents difficulty in precise Doppler correction, or in reconstructing angular correlations.

Summary

Precise (~1%) Coulomb excitation experiments can be made in neutron rich nuclei with RIA beams. Even approaching the dripline, 10% measurements should be possible. These studies should be far superior to measurements which can be achieved with fragmentation facilities. With ISOL beams, both static and transitional moments can be measured. However, sensitive experiments with fragmentation beams can be made. Using intermediate energies, about 50 MeV/u, offer the best probability for progress. For germanium-type resolution, relatively thin targets must be used, so measurements at the 10-20% level can be made one or two isotopes further from stability than ISOL experiments, and using thick targets the dripline nuclei might be studied. In fragmentation, low energy gamma-rays below 200 keV are difficult to detect. Precise measurements, better than 10% accurate, or measurement of any multi-step excitation leading to higher states, or measurement of static quadrupole moments seem extremely difficult. The use of 400 MeV/u beams for Coulomb excitation, seem to be very problematical, due to the intense bremsstrahlung background.

References

[1] T. Motobayashi et al. Phys. Letts. B346 (1995) 9-14

[2] S. Wan et al. Euro. Phys. J. A6 (1999) 167-174

[3] I. Tanihata et al. Nucl. Phys. A583 (1995) 769

[4] J. Terasaki et al. Nucl. Phys. A621 (1997) 706-718

[5] Z. Ren et al. Phys. Letts. B380 (1996) 241

[6] D. Schwalm and E.K. Warburton Nucl. Physics.

[7] D. Schwalm et al. Nucl. Phys. A192 (1972) 449