Jacque Raynal, ECIS, and M_n/M_p values in radioactive nuclei

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Abstract

Jacque Raynal's coupled channels code ECIS has played an important role in the effort to search for shell effects in exotic isotopes using both intermediate energy Coulomb excitation and inverse kinematics proton scattering to probe their level structures and to extract neutron and proton excitation modes through their M_n/M_p values. It will continue to be an important tool as nuclei very far from the stable ones are produced in new exotic beam accelerator centers.

I. INTRODUCTION

The energy of the 2_1^+ state and the electromagnetic matrix element $B(E2; 0_{gs}^+ \to 2_1^+)$ are very useful in identifying even-even nuclei that have closed shells of either protons or neutrons. However, about forty years ago Bernstein, Brown and Madsen [?] demonstrated that the ratio of the neutron and proton transition matrix elements (generally written as M_n/M_p) for the $0_{gs}^+ \to 2_1^+$ transition provides a complementary way of testing shell closures in stable nuclei.

The quantity M_n/M_p has proven to be important for testing shell closures in radioactive nuclei as well. While the magic numbers 2, 8, 20, 28, 50, 82 and 126 for stable nuclei were identified seventy years ago [?], experiments with radioactive isotopes and beams have demonstrated that the magic numbers can be different in nuclei that are not located in the valley of stability. To make determinations of M_n/M_p in stable nuclei, results from experimental probes such as sub-Coulomb barrier heavy-ion scattering (Coulomb excitation) and inelastic proton scattering were compared with each other. To determine M_n/M_p in neutron- and proton-rich nuclei, these stable beam techniques were adapted into new techniques for use with radioactive beams – intermediate-energy Coulomb excitation and inverse kinematics proton scattering. The reaction code ECIS, developed by Jacques Raynal [?], played a critical role in enabling this transition to radioactive beam measurements so that shell effects could be explored outside of the valley of stability.

II. COULOMB EXCITATION

One important property of a nucleus is the strength of the excitation of its states through the electromagnetic process which can then be compared to existing nuclear structure models. One method of extracting these values since the mid-1950s for stable nuclei is by carrying out scattering with charged probes that are below the system's Coulomb barrier so that uncertainties in the nuclear interaction potentials do not add ambiguity to the extracted electromagnetic strengths. Generally, these experiments are carried out with accelerated beams of energy 5 MeV/nucleon or so, with the resulting deexcitation γ-rays or charged particles being detected in appropriate arrays. The difficulty with the study of the most exotic nuclei, those having larger neutron to proton ratios or vice versa than those along the valley of stability, is that these nuclei are produced most easily by the fragmentation process with resulting beam particles of interest having energies of 50 MeV/nucleon or so. This suggests that extraction of purely electromagnetic inelastic strength is not possible because there might always be a contribution from a poorly known or even completely unknown nuclear interaction.

However, Winther and Alder [?] showed in 1979 that under the right scattering conditions it was possible to observe relativistic Coulomb excitation. Three early works [? ? ?] used inverse scattering where the fragmented product nucleus was used to extract electromagnetic inelastic probabilities for the first 2^+ states in ^{32}Mg (N=20) and ^{42,44}S ($N = 26, 28$) at beam energies of 40-50 MeV/nucleon. These fast beam experiments were carried out by detecting the incoming particle with a particle detector that was in coincidence with a deexcitation γ-ray.

The possibility of using fast beams for Coulomb excitation rested on two assumptions. The first was that an angular range could be found where the scattering was purely Coulomb. The second was that the γ-ray detector had sufficient position resolution to allow the γ-ray emitted from the moving system to be Doppler corrected. It was the coupled channels code ECIS that allowed the first assumption to be investigated since it allows for a large number of partial waves in its computation as well as treatment of the Coulomb potential to the very large radii needed at these energies. These calculations showed that the scattering could be considered as purely Coulomb when the particle detector subtended a laboratory angle of less than 4°. Since the extracted experimental results depended on the ECIS calculation being done correctly there was a concern by one of us (KWK), who had done them, that there might have been an error in carrying them out. Luckily, during a visit to GANIL it became possible to ask Nicolas Alamanos to check these calculations. He verified that they were done correctly. As the reader will learn in another contribution, Nicolas Alamanos had learned the intricacies of ECIS from Jacques Raynal directly, which gave added weight to their veracity. A later question that arose was whether the deexciation gamma rays observed came from the first 2^+ state or perhaps from a low lying 3^- state. Here again ECIS was able to show that the probability of exciting a 3^- state was a factor of five lower than that for a 2^+ state.

III. INELASTIC PROTON SCATTERING

Shortly after the realization that one could extract electromagnetic excitation strengths via intermediate energy Coulomb excitation, it was realized that with an efficient particle detection system it might be possible to carry out inelastic proton scattering in inverse kinematics by detecting protons scattered from a plastic target in coincidence with the detection of the nucleus of interest in a magnetic spectrograph. Such experiments allowed the extraction of a quantity to extract a quantity that gives detailed information on the isovector/isoscalar character of the 2^+ state in these exotic nuclei even when incoming "beam" intensities were of the order of 10^4 particles per second.

More recently, inverse inelastic proton scattering experiments have been performed by passing a beam of the isotope of interest through a thick target (often solid hydrogen) and detecting γ-rays from the deexcitation of the states population in the scattering reaction using a high-efficiency array in coincidence with the detection of the beam particles in a magnetic spectrograph.

This work was based on the ideas of Bernstein, Brown and Madsen [**?**] who developed the tools for understanding the variation of structure as a function of neutron to proton ratios. Their work was developed to answer one of the most compelling questions about atomic nuclei: Do protons and neutrons always form a single fluid or do they behave differently under some circumstances? The giant dipole resonance, in which protons and neutrons form two fluids that oscillate opposite each other, was first observed in 1947 [**?**]. During the following decades, isovector giant resonances of higher multipolarities were found as well. These resonances, which are composed of coherent superpositions of particle-hole excitations across major shells, occur at high excitation energies. Low energy isovector states like the scissors ($M1$) mode [**?**] and higher multipolarity mixed symmetry states have been identified at energies under 5 MeV over the past 40 years.

However, differences in the motions of neutron and proton fluids in the lowest energy quadrupole and octupole excitations (the 2^+_1 and 3^-_1 states) are more subtle and generally occur when there is a shell or subshell closure for either the neutrons or protons. Bernstein, Brown and Madsen [**?**] systematically studied isovector effects in the 2^+_1 states of stable nuclei using multiple experimental probes that interact with the protons and neutrons in a nucleus differently. For example, electron inelastic scattering measures $E2$ and $E3$ proton

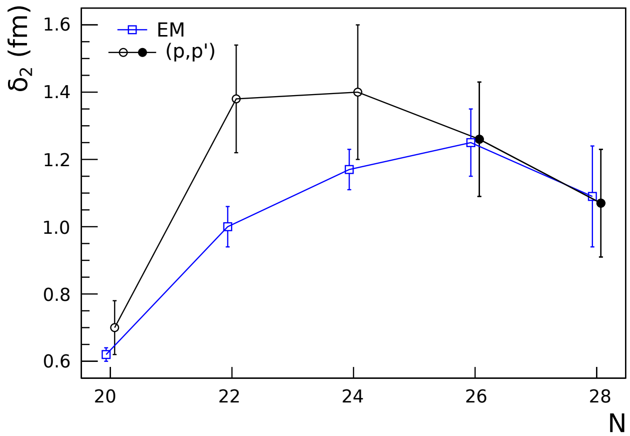

FIG. 1. (Color online) Proton-scattering and electromagnetic deformation lengths δ_2 for the $0^+_{g.s.} \rightarrow 2^+_1$ excitations of even-even neutron-rich sulfur isotopes. Proton-scattering deformation lengths are from Ref. [**?**] (open circles) and the present work (filled circles), and electromagnetic deformation lengths (open squares) are from Ref. [**?**].

transition matrix elements, while the inelastic scattering of protons at low ($<$ 50 MeV) energy predominantly measures the neutron transition matrix elements. Results from two experimental probes such as scattering of electrons and low energy protons can be folded into a result expressed as M_n/M_p, which is the ratio of the neutron and proton multipole transition matrix elements. If protons and neutrons are oscillating as fluids with the same amplitudes, that ratio is equal to N/Z. Bernstein, Brown and Madsen demonstrated that this is generally the case mid-shell. At shell closures, M_n/M_p generally deviates from N/Z.

As stated earlier, shell effects have been one of the central themes of the research on nuclei with very large differences in neutron to proton ratios when compared with stable nuclei. By combining intermediate fast beam Coulomb excitation electromagnetic strengths to extract M_p with those derived from inelastic proton scattering to extract M_n it has become possible to explore the characteristics of nuclear excitations over a range of exotic nuclei not even envisioned 30 years ago.

IV. M_n/M_p NEUTRON-RICH SI AND S ISOTOPES

In a recent paper reporting experimental results on inverse kinematics proton scattering from neutron-rich exotic isotopes of sulfur and phosphorus, Riley *et al.* [**?**] compiled M_n/M_p results for 2^+_1 states obtained by combining intermediate energy Coulomb excitation results with proton scattering results for neutron-rich silicon, sulfur and argon isotopes. The experiments reported by Riley *et al.* used a solid hydrogen target and detected γ-rays from the deexcitation of the states populated in the reation using GRETINA in coincidence with beam nuclei detected in the National Superconducting Cyclotron Laboratory's (NSCL) S800 magnetic spectrograph. ECIS was used to extract deformation lengths $\delta_{p,p'}$ for the 2_1^+ states in ^{42,44}S from the $2_1 \rightarrow 0_{gs}^+$ γ-ray cross sections. Those deformation lengths, as well as some from previous experiments in the region, are shown in Figure 1.

The M_n/M_p values are calculated from the deformation lengths determined in proton scattering and the proton deformation length δ_p (determined from an electromagnetic probe such as intermediate energy Coulomb excitation) using the equation [**?**]

$$\frac{M_n}{M_p} = \frac{b_p}{b_n}\left(\frac{\delta_{(p,p')}}{\delta_p}\left(1 + \frac{b_n}{b_p}\frac{N}{Z}\right) - 1\right), \tag{1}$$

where b_n/b_p is the ratio of the sensitivities of the inelastic proton scattering reaction to the contributions of neutrons and protons to the excitation being measured. For beam energies of less than 50 MeV/nucleon in inverse kinematics experiments (or incident proton energies of less than 50 MeV in normal kinematics experiments) $b_n/b_p = 3$. Above 100 MeV/nucleon, $b_n/b_p = 1$ [**?**]. Between 50 and 100 MeV/nucleon, the energy range in which experiments have been performed at the National Superconducting Cyclotron Laboratory recently, there is considerable uncertainty about b_n/b_p. For their proton scattering data on ^{42,44}S, which were taken at 62 and 70 MeV/nucleon, respectively, Riley *et al.* used $b_n/b_p = 2 \pm 1$. This contributed considerable uncertainty to their final values of M_n/M_p.

The physics motivating these studies is the collapse of the N=28 major shell closure in N=28 isotones lighter than ^{48}Ca, in which the neutron shell closure is strong. In single closed shell nuclei, M_n/M_p for 2_1^+ states generally varies from the collective model value N/Z. As the compilation of M_n/M_p values given by Riley *et al.* in Figure 2 shows, the M_n/M_p value for the 2_1^+ state in the doubly magic nucleus ^{48}Ca is much larger than N/Z – showing that the neutron contributions dominate the 2_1^+ excitation in this nucleus.

However, for the even-even $N = 28$ isotones with lower Z values – ^{46}Ar and ^{44}S – M_n/M_p is within experimental uncertainty of N/Z. That indicates that the $N = 28$ major shell closure is reduced in strength (likely for ^{46}Ar and ^{44}S) or has collapsed altogether, which likely doesn't occur until $Z = 14$ (^{42}Si). Furthermore, in the open shell neutron-rich nuclei ^{40}S, ^{42,44}Ar and ^{36,38}Si M_n/M_p is within experimental uncertainty of N/Z – or very close to

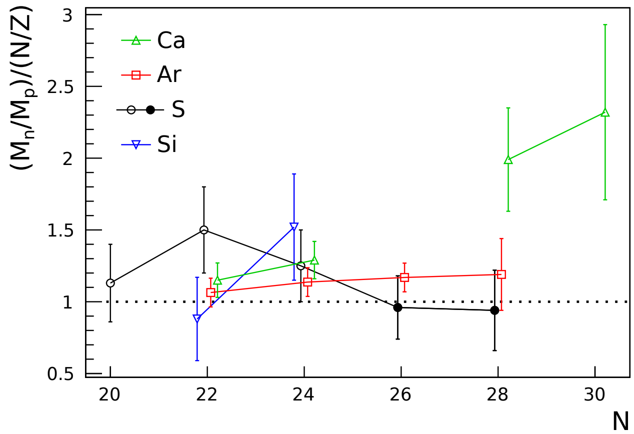

FIG. 2. (Color online) Ratios of neutron to proton transition matrix elements M_n/M_p expressed relative to N/Z for even-even neutron-rich calcium, argon, sulfur, and silicon isotopes from Refs. [**?** **?** **?** **?** **?** **?**] (open symbols) and the present work (filled circles).

that.

While Ref. [**?**] uses global optical model potentials and standard collective form factors for its ECIS analysis, ECIS can also accommodate microscopic folded potentials. Marechal et al. [**?**], whose experiment used an array of particle telescopes and a magnetic spectrograph, performed a microscopic analysis of their ^{40}S(p,p') data with ECIS in addition a collective form factor analysis. The microscopic analysis suggested that the neutron-rich sulfur isotopes have neutron skins. However, Marechal et al. pointed out that more detailed angular distributions would be required to confirm the presence of such skins.

V. M_n/M_p IN PROTON-RICH ^{30}S AND ^{34}AR

The technique of probing for shell effects by using inverse kinematics proton scattering and an electromagnetic probe to determine M_n/M_p is useful on the proton-rich side as well. Khan *et al.* [**?**] measured inverse kinematics proton scattering on the proton-rich radioactive nuclei ^{30}S and ^{34}Ar using particle telescopes and a magnetic spectrograph and determined M_n/M_p values using both phenomenological and microscopic ground state and transition densities (the phenomenological analysis was performed with ECIS). In both nuclei, they found that M_n/M_p is consistent with the isoscalar value N/Z; that is, both behave (unsurprisingly) like midshell nuclei.

Khan *et al.* were particularly interested in whether their microscopic calculations predicted proton skins in ^{30}S and ^{34}Ar or whether evidence for such skins could be discerned in their data. There was no indication of a proton skin in the data, but in addition the microscopic calculations themselves did not predict proton skins.

VI. M_n/M_p IN NEUTRON-RICH ^{20}O

When Jewell *et al.* [**?**] and Khan *et al.* [**?**] performed their measurements of the ^{20}O(p,p') reaction in inverse kinematics using particle telescopes and magnetic spectrographs, it was already known that the heaviest bound oxygen isotope is ^{24}O - only four neutrons away, even though ^{20}O is only two neutrons heavier than stable ^{18}O. The measurement by Jewell *et al.* was performed at 30 MeV/nucleon at the NSCL and observed the 2_1^+ state. Khan *et al.* performed their measurement at 43 MeV/nucleon and observed both the 2_1^+ and 3_1^- states. The phenomenological analysis of the 2_1^+ state by Jewell *et al.* found $M_n/M_p = 2.9(4)$, much larger than the N/Z value of 1.5, indicating that the valence neutrons dominate that excitation. This result is also much larger than the corresponding result for ^{18}O, M_n/M_p=1.50(17), which is close to the value of $N/Z = 1.25$ expected for an isoscalar transition.

Khan *et al.* performed a phenomenological analysis of the 2_1^+ state in ^{20}O as well (using ECIS), reproducing the result of Jewell *et al.*. However, Khan *et al.* also performed a microscopic analysis of the scattering to the 2_1^+ state, and obtained $M_n/M_p = 3.25(80)$ - in agreeement with the phenomenological analyses performed by both groups.

The result of Khan *et al.* for M_n/M_p for the transition to the 3_1^- state in ^{20}O provides an interesting contrast to the results for the 2_1^+ state. While the phenomenological deformation parameters β_2 determined by Jewell *et al.* and Khan *et al.* were much larger than the corresponding value in ^{18}O, the β_3 value determined by Khan *et al.* was very similar to the corresponding value in ^{18}O.

Khoa [**?**] reanalyzed the ^{20}O 2_1^+ state data of both Jewell *et al.* and Khan *et al.* using a folding model and concluded that the M_n/M_p value was an even more remarkable 4.2(3). However, the most important conclusion of all of this work on the 2_1^+ state in ^{20}O is that this state has a structure that is very different from that of the corresponding state in ^{18}O, which is only two neutrons away.

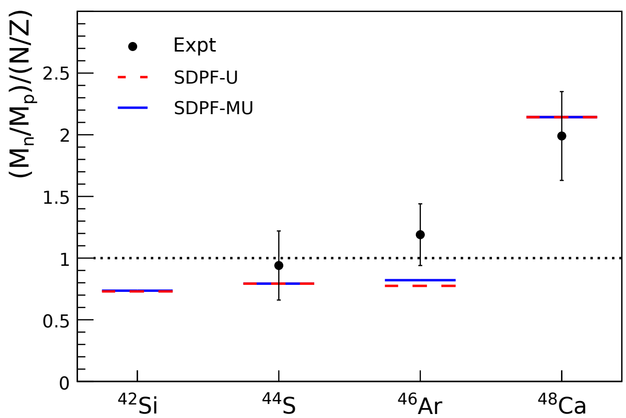

FIG. 3. (Color online) Ratios of neutron to proton transition matrix elements M_n/M_p expressed relative to N/Z for even-even $N = 28$ isotones from Ref. [**?**] and the present work compared with shell model predictions, described in the text.

VII. M_n/M_p AT FRIB

The Facility for Rare Isotope Beams (FRIB) will improve access to radioactive isotopes, both by producing higher quantities of beams that were low-intensity at facilities like the NSCL and by providing beams of isotopes that were not produced in practical quantities at all at the NSCL.

However, M_n/M_p values determined via inverse kinematics proton scattering experiments at FRIB will gain considerable precision for a reason that is not widely appreciated. The beams produced via fragmentation at FRIB will have high enough energies (greater than 100 MeV/nucleon) that the proton scattering reactions studied with these beams will be isoscalar – that is, they will have $b_n/b_p = 1$ [**?**]. The large uncertainty in b_n/b_p that existed in the 50-80 MeV/nucleon range for recent NSCL experiments will no longer cause large uncertainties in M_n/M_p results.

This new precision will allow the exploration of questions like the one illustrated in Figure 3 [**?**]. Shell model calculations with the SDPF-U and SDPF-MU interactions predict that the M_n/M_p values for ^{42}Si, ^{44}S and ^{46}Ar differ from N/Z. Because of the uncertainty in b_n/b_p for the inelastic proton scattering energies for recent NSCL experiments, available results do not have the precision to determine whether these predictions – which seem surprising for nuclei that are not supposed to have a shell closure – are correct. The new precision resulting from the higher beam energies at FRIB will make it possible to determine whether these shell model predictions are correct.

VIII. CONCLUSION

The capabilities of Jacque Raynal's coupled channels code ECIS have played a critically important role in the effort to identify shell effects in exotic isotopes through the determination of M_n/M_p values for 2_1^+ states with intermediate energy Coulomb excitation and inverse kinematics inelastic proton scattering experiments. The code - and Raynal's work - will remain important for generations of experiments at FRIB.

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