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Patrick T. MacGregor

Single-Particle Structure of ^{29}Mg on the Approach to the $N = 20$ Island of Inversion

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Single-Particle Structure of ^{29}Mg on the Approach to the $N = 20$ Island of Inversion

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The Son is the image of the invisible God, the firstborn over all creation. For in him all things were created: things in heaven and on earth, visible and invisible, whether thrones or powers or rulers or authorities; all things have been created through him and for him. He is before all things, and in him all things hold together.

COLOSSIANS 1:15–17[1]

To my wife Ally, your unwavering support has helped me to produce this work and my love for you compels me to recommend other reading material, unless you've really run out of all other options.

Supervisor's Foreword

In recent years, it has been shown that the magic numbers in nuclei, corresponding to closed shells of neutrons or protons in the nuclear shell model, evolve with proton and neutron number. They are not as immutable as presented in undergraduate textbooks; some shell closures disappear, whilst others appear in nuclei away from the valley of β stability. To understand the mechanisms that drive this evolution of nuclear structure, physicists must study the structure of exotic nuclei, in particular, the characteristics of the individual nucleons within them, what is known as single-particle structure. Typically, this information is accessed by measuring direct nuclear reactions using accelerated beams of ions.

Direct reactions allow access to many nuclear properties. They are reactions that proceed via a single step, exciting just one degree of freedom in the residual nucleus. They can probe single-particle properties via the transfer of a single nucleon from a light ion to or from a nucleus of interest. Pairing properties can be investigated by transfer of a correlated pair and collective properties via inelastic scattering. To measure these reactions on short-lived nuclei, it is necessary to use "inverse kinematics" where the beam particle is the radioactive nucleus and the light ion is the target.

Radioactive ion beam facilities, such as ISOLDE at CERN, allow nuclear physicists access to exotic nuclei away from stability. Coupled to these facilities, the latest particle-detection techniques are required to study the structure of these nuclei via direct reactions in inverse kinematics. Solenoidal spectrometers are a novel device that offer the best charged-particle resolution compared to other techniques.

Patrick's thesis describes the first measurement made using a new solenoidal device, the ISOLDE Solenoidal Spectrometer at the ISOLDE facility. These measurements of the $d(^{28}\mathrm{Mg},p)^{29}\mathrm{Mg}$ reaction probe the evolution of nuclear structure along nuclei with $N = 17$ investigating the emergence of a new shell closure at $N = 16$, testing the modern effective shell model interactions, as well as illuminating the role that the finite geometry of the nuclear potential plays in observed systematics of single-particle energies. These data are important in constraining models in a rapidly evolving region of the nuclear chart. As well as the emergence of a new shell closure at $^{24}\mathrm{O}$ in lighter $N = 16$ nuclei, the heavier magnesium isotopes sit in a region of changing nuclear shape called the island of inversion, where the weakening of the $N = 20$ shell gap results in the onset of deformation in the nucleus. These phenomena are of topical interest in the field, and Patrick's findings will provide a key benchmark.

Patrick's thesis also provides a canonical reference for nuclear physicists on the use of solenoid spectrometers to study direct nuclear reactions in inverse kinematics and will provide a useful guide for years to come. He has covered in detail the kinematics of reactions in a solenoid field and the transformations required to extract the Q-value of the populated states in the reaction from the measured quantities.

May 2022

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The original version of this book inadvertently contained incorrect typesetting within Equations A.2, A.3, A.5, and A.9. This has now been rectified.

Abstract

The nuclear structure of ^{29}Mg was probed using the $d(^{28}\text{Mg},p)^{29}\text{Mg}$ transfer reaction to populate its single-particle states. The ISOLDE facility at CERN provided a 9.473 MeV/u beam of ^{28}Mg which was directed at a deuterated target within the ISOLDE solenoidal spectrometer. Exploiting the kinematic advantages of this technique allowed most states up to 5 MeV to be resolved and angular distributions of the reaction cross section to be obtained. The DWBA code DWUCK5 was used to obtain spectroscopic factors for these states. Additionally, some higher-lying excited states were identified, and their possible properties were proposed.

Theoretical calculations in this region broadly reproduced the observed behaviour in ^{29}Mg, as well as matching trends from other nuclides in the $N = 17$ isotones. These calculations indicate that the nucleon–nucleon interaction between protons and neutrons, with the tensor interaction as a key component, is driving the evolution of shell structure, with the filling of the $\pi d_{5/2}$ orbital of particular importance in this region. Finite geometry effects also play an important role in this evolution as the p orbitals approach the neutron-separation threshold and the energy spacing between them reduces.

The information gained from the nuclear structure will help to continue refining these interactions and provide a valuable benchmark for nuclear-structure studies around the border of the island of inversion. Similar experiments to study ^{30}Al and ^{31}Mg carried out recently will help to further the understanding of nuclear structure in this exotic region of the nuclear chart.

Acknowledgements

This work before you is the culmination of eight amazing years in Manchester, marking my progression from an inexperienced (and nerdy) teenager to a more competent (but still nerdy) adult. In that time, I have married, lost a lot of my hair and had a fantastic time learning about the wonderful world of physics. This journey has not been completed alone, and there are far too many people to thank.

My primary thanks must go to Prof. Sean Freeman and Dr. David Sharp, who have guided me through my Ph.D. with much patience and care. The depths of Sean's nuclear physics knowledge have been an invaluable resource for diagnosing my many mis-steps and helping me find further sources of information about a variety of topics. Despite his demanding duties as the head of department and now the head of ISOLDE, he has always found time to help me, for which I am immensely grateful. I hope my hyphenation and grammar have improved as a result of the many corrections you gave.

David has borne the brunt of my questions, poor writing and misunderstandings. His dedication to the field and to his students is commendable, and I have been the recipient of his wisdom and kindness. Despite juggling many responsibilities, he has always found time for me. We have enjoyed the slight delirium that accompanies night shifts on experiments more than once, and I hope we can continue to work together for a long time, though perhaps with better sleep in future.

Beth Cropper has been a constant source of bad jokes and another delightful person to share late-night shifts with on experiments. It has been a pleasure to get to know Katie Garrett, and it would have been lovely to work together in person more—I wish you both every success on the rest of your projects. I am also indebted to the wider Manchester nuclear physics group, past and present. Special thanks go to Stuart Szwec for helping me get started and to everyone who helped to turn our office into a mini-jungle and make it a fantastic place to work. In addition, my fellow student Sam Bennett and I have been together throughout our university experience, not only as housemates and laboratory partners, but also good friends. I am incredibly excited that you get to continue researching fission using ISS with Sean and David! (I should also confess that the peculiar behaviour of your disc drive was entirely down to me!)

Additional thanks go to the target group at Argonne National Laboratory and the team at ISOLDE, CERN who were able to deliver the beam and troubleshoot all of our issues whether convenient or not.

I could not have completed this project without the support of friends outside of nuclear physics. Special thanks to Amy, Ali, Lydia, Mike, Pawita and Parinya for your friendship (and amazing food!) throughout both good and bad times. Special thanks to Jack for fixing my laptop at pretty short notice, and to Carl for steadfastness, integrity and friendship—I am glad I can call you my friend.

My family cannot escape being mentioned in this discourse. I am indebted to my parents and grandparents, who have all sacrificed much ease and comfort to make me the man I am today. Stuart, my fellow physicist, twin and best friend has been an invaluable support to me for my whole life (literally). Matthew, Elizabeth, Angus and Cath have all supplied merciful distraction and relief often. 媽媽和爸爸: 多謝你們的愛和好意! 我好感激你們的支持. Abby, Ernest and Anna have welcomed me into their family with open arms and kindness, and I could not ask for better siblings-in-law.

However, my Ph.D. could not have been completed without my incredible wife, Ally. She has stood by me throughout this whole project, supporting me, challenging me, pushing me and being an all-round amazing person. I do not know how I could have finished this without her help through the numerous challenges that both Ph.D. and life have thrown at me.

Soli deo gloria.

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Contents

Abbreviations

CM	Centre of momentum
DWBA	Distorted-wave Born approximation
EBIS	Electron Beam Ion Source
ESPE	Effective single-particle energy
HELIOS	HELIcal Orbital Spectrometer
HIE-ISOLDE	High Intensity and Energy ISOLDE
HRS	High-resolution separator
IK	Inverse kinematics
IoI	Island of inversion
IPM	Independent particle model
ISOLDE	Isotope mass separator online (DE)
ISS	ISOLDE solenoidal spectrometer
KC	Kinematic compression
KS	Kinematic shift
LINAC	Linear accelerator
NK	Normal kinematics
PSB	Proton synchrotron booster
REX-ISOLDE	Radioactive beam EXperiment at ISOLDE
RF	Radio frequency