Electric Monopole Transitions in ^{110}Pd

by

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Abstract

A measurement of the strength of the $E0$ transition between the 2_2^+ and 2_1^+ states, of the nucleus ^{110}Pd is proposed. Analysis will be undertaken of spectroscopic gamma-ray and internal conversion electron data obtained by inelastic scattering of an accelerated alpha particle beam off of a ^{110}Pd target. The $E2/M1$ mixing ratio will be determined from γ ray data collected using TIGRESS. The internal conversion coefficient for the transition will be extracted from the combination of TIGRESS data and internal conversion electron data collected by SPICE. These new data will be combined with literature half life and branching ratio information to determine the E0 transition strength for the first time.

Lay Summary

The lay or public summary explains the key goals and contributions of the research/scholarly work in terms that can be understood by the general public. It must not exceed 150 words in length.

Contents

List of Tables

List of Figures

Glossary

This glossary uses the handy `acroynym` package to automatically maintain the glossary. It uses the package's `printonlyused` option to include only those acronyms explicitly referenced in the LaTeX source.

Acknowledgments

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Chapter 1

Introduction

(The motivation in 5 sentences)

1.1 $E0$ Transitions

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1.2 Gamma-ray and Electron Spectroscopy

...

1.3 Palladium Isoptopes

...

Chapter 2

Theory

2.1 The Nuclear Shell Model

In the atomic model, orbiting electrons are subdivided into discrete shells wherein each shell is filled, beginning with the lowest energy level. This filling of shells must not violate the Pauli exclusion principle, which in this context stipulates that two or more electrons cannot occupy the same quantum state simultaneously. Similar evidence exists for a shell structure in the nucleus.

A prime example of this evidence is the two-neutron separation energy, S_{2n}, as a function of nucleon number, shown in Figure 2.1. The two-neutron separation refers to the energy required to remove two neutrons from a nucleus. It is the nuclear analogue to single electron removal from an atomic shell, with two nucleons considered due to pairing effects between nucleons. The S_{2n} values follow large steps downward following the closing of a nuclear shell, which occurs following nucleon numbers of 8, 20, 28, 50, 82 and 126. The nucleon numbers where these drops in S_{2n} occur are collectively known as the magic numbers.

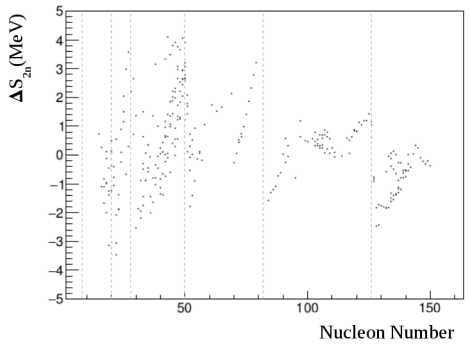

Figure 2.1: The difference between the experimental two-neutron separation energy, S_{2n}, parsed from the evaluated nuclear data sheets [**?**] and the value obtained from the semi-empirical mass formula [**?**]. The parameters used here are 15.5 MeV for the volume term, 16.8 MeV for the surface term, 0.72 MeV for the Coulomb term, 23 MeV for the symmetry term and 34 MeV for the pairing term [**?**]. The magic numbers of 8, 20, 28, 50, 82 and 126 are shown by the grey dashed lines where there are sudden drops. Image from Ref[**?**]

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2.2 Nuclear Reactions

2.3 The Mixing of Nuclear States

2.4 Collective Models of Nuclear Structure

This characteristic behaviour can be reproduced from theoretical modeling that replicates the approximate charge distribution of the nucleus, with the central region constant [**?**]. This potential, known as the Woods-Saxon potential, is of the form

$$V(r) = \frac{-V_0}{1+\exp[(r-R)]/a} \tag{2.1}$$

where the strength of the potential is a function of r, the radial distance from the origin. $R = A^{1/3}$ fm is the mean radius of a nucleus, A is the atomic mass num-

ber, $a = 0.524\,\text{fm}$ is the skin thickness (i.e. the radius of the nucleus in which the charge density decreases from 90% of its value to 10%), and V_0 is an adjustable parameter in order to replicate the correct separation energies [**?**]. Additionally, a spin-orbit coupling force must be included in the potential. This force is an interaction between the intrinsic nuclear spin of the nucleon, and its orbital angular momentum. In short, increasing degree of alignment between the nucleon's spin and angular momentum will increase the attractiveness of the potential. Substituting this complete potential into the three-dimensional Schrödinger equation

$$[\frac{-\hbar^2}{2m}\nabla^2 + V(r)]\Psi(r) = E\Psi(r) \tag{2.2}$$

yields a series of discrete energy levels for a nucleus that exhibit the characteristic energy steps following the magic numbers, as experimentally observed.

2.5 Gamma Decay

, such that the intensities of the transitions can be obtained from

$$\lambda(E2) = \frac{\delta^2}{1+\delta^2} \tag{2.3}$$

$$\lambda(M1) = \frac{1}{1+\delta^2} \tag{2.4}$$

2.6 Gamma-ray Angular Distributions

$$\begin{aligned} A_\eta(J_i L_1 L_2 J_f) = \frac{1}{1+\delta^2}[&f_\eta(J_f L_1 L_1 J_i) + \\ &2\delta f_\eta(J_f L_1 L_2 J_i) + \\ &\delta^2 f_\eta(J_f L_2 L_2 J_i)] \end{aligned} \tag{2.5}$$

$$\rho^2(E0) = q^2 \times \frac{\alpha_K(E2)}{\Omega_K(E0)} \times \frac{BR(E2_\gamma)}{\tau} \tag{2.6}$$

$$\rho^2(E0) = \frac{1}{\Omega(E0)\tau(E0)} \tag{2.7}$$

where $\Omega(E0)$ is an electronic factor from atomic theory, $\tau(E0)$ is the partial mean life time of the $E0$ transition [**?**].

2.7 Internal Conversion Decay

2.8 $E0$ Transitions

While the electronic factor can be obtained from BrIcc [**?**], $\tau(E0)$ must be obtained from

$$\rho^2(E0) = q^2 \times \frac{\alpha_K(E2)}{\Omega_K(E0)} \times \frac{BR(E2_\gamma)}{\tau} \tag{2.8}$$

where $\Omega_K(E0)$ is an electronic factor from atomic theory, τ is the lifetime of the parent state, and $BR(E2_\gamma)$ is the branching ratio of the $E2$ γ ray transition. These latter two components are known values available on NNDC [**?**].

$$\tau(E0) = \frac{\Sigma\lambda_r}{\lambda_r(E0)} \cdot \tau \tag{2.9}$$

where λ_r is a relative decay constant and $\tau = T_{1/2}/\ln(2)$; $T_{1/2}$ is the half-life. [**?**]. This calculation requires a summation over every available decay mode from the parent state.

Chapter 3

Experimental Techniques

3.1 Experimental Details

Chapter 4

Techniques used for TIGRESS and SPICE Data Analysis

4.1 Peak Fitting

4.2 Calibration of Detection Efficiency

4.3 Simulated SPICE Efficiency

4.4 Determining Internal Conversion Coefficients

4.5 Determining $E0$ Transition Strengths, $\rho^2(E0)$

The internal conversion coefficient, α is obtained from the ratio of counts, A, multiplied by the absolute efficiencies, ε, i.e.

$$\alpha_K = \frac{A_e}{A_\gamma} \cdot \frac{\varepsilon_\gamma}{\varepsilon_e} \tag{4.1}$$

Where the γ-ray efficiency, ε_e, is known from previous measurements with the TIGRESS array, and the electron efficiency is calculated by normalization to measurements of α_K for select transitions of pure $E2$ multipolarity. These measurements, having known internal conversion coefficients, are used to construct a normalization efficiency curve. Electron efficiency is calculated by

$$\varepsilon_e = \frac{A_e}{A_\gamma} \cdot \frac{\varepsilon_\gamma}{\alpha_{\text{theory}}} \tag{4.2}$$

Here α_{theory} is the theoretical internal conversion coefficient obtained from BrIcc.

(simulation, geant, scaling)...

The ratio of intensities between $E0$ and $E2$ transitions from a common initial state, q^2, is given by

$$q^2 = \frac{\alpha_{\text{exp}}(1+\delta^2) - \alpha(M1)}{\alpha(E2) \cdot \delta^2} - 1 \tag{4.3}$$

where α are theoretical conversion coefficients obtained from BrIcc [**?**], and α_{exp} is an experimentally determined value of the internal conversion coefficient (i.e. ratio of $E0+M1+E2$ electrons vs. $M1+E2$ γ rays). Using these experimental inputs, $\rho^2(E0)$ may be calculated from

$$\rho^2(E0) = q^2 \times \frac{\alpha(E2)}{\Omega(E0)} \times W_\gamma(E2) \tag{4.4}$$

where $\Omega(E0)$ is an electronic factor from atomic theory and $W_\gamma(E2)$ is the $E2$ transition rate, a previously measured value available from NNDC.

A number of the input values, particularly the mixing ratio and the electron efficiency.

In determining the electron efficiency, ε_e, various fitting methods are applied. With the exception of linear fitting, these functions yield asymmetric error for the resultant absolute coefficient, α_K, value. Hence, the upper and lower error bound calculations use the asymmetric error values of the mixing ratio, δ, as well as for the absolute coefficient, ε_e.

The mixing ratio, δ, carries an asymmetric uncertainty value. The traditional approach of error propagation as outlined will necessitate taking the larger value between the Δ_+ and Δ_- error, yielding a symmetric uncertainty value. This approach, while practical for most purposes, can produce a result that is unnecessarily biased with respect to the alternative of a Monte Carlo method. In this measurement in particular, the traditional approach is insufficient as it can result in unphysical regions being included within the 1σ uncertainty.

4.5.1 Monte Carlo Method

Each experimental value used as an input is assumed to be a normal distribution with a mean and width given by (μ, σ). A simulation is performed, in which each event results in a calculation of $\rho^2(E0)$ using input values chosen at random from each distribution of (μ, σ). These calculations, each instance being an iteration of Equation 4.4, fill a distribution of $\rho^2(E0)$ values. An example distribution for the $2_2^+ \rightarrow 2_1^+$ transition in ^{110}Pd is shown in Figure 4.1.
Mean Estimator, Red Line

4.5.2 Neyman Construction

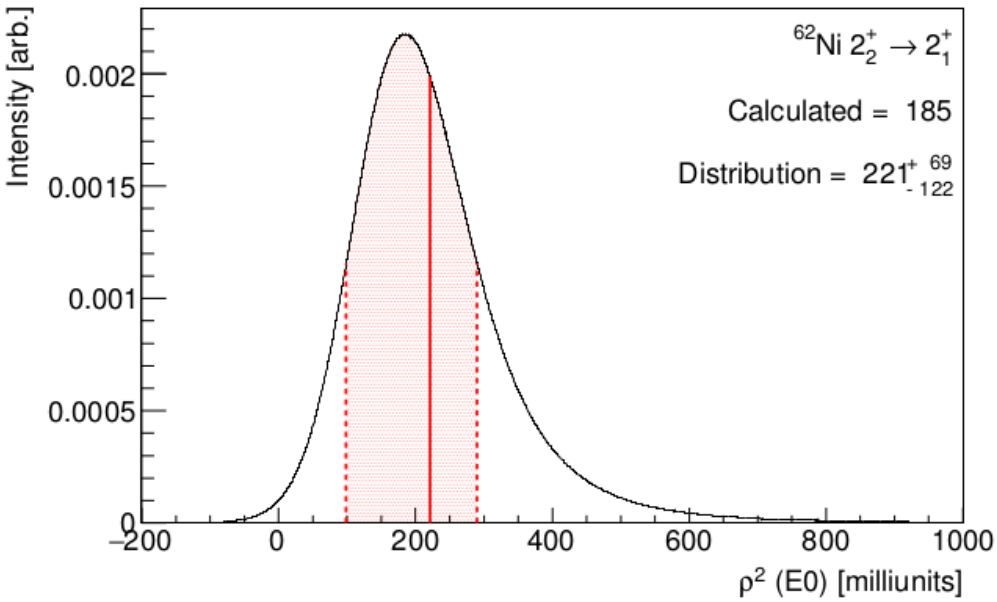

Figure 4.1: An example distribution of $\rho^2(E0)$for the $2_2^+ \rightarrow 2_1^+$ transition in ^{110}Pd, produced by the Monte Carlo method. The solid red line is the mean of the distribution and the shaded error is the 68% confidence limit, or 1σ.

Chapter 5

Results and Discussion

5.1 Measured Internal Conversion Coefficients

The ratio of measured internal conversion coefficients (for the K shell) to the theoretical values from BrIcc are shown in Figures ?

5.2 Measured $E0$ Transition Strengths

Chapter 6

Conclusion

Bibliography