

# Experimental Guidance of ISB Corrections via Direct Nuclear Reactions

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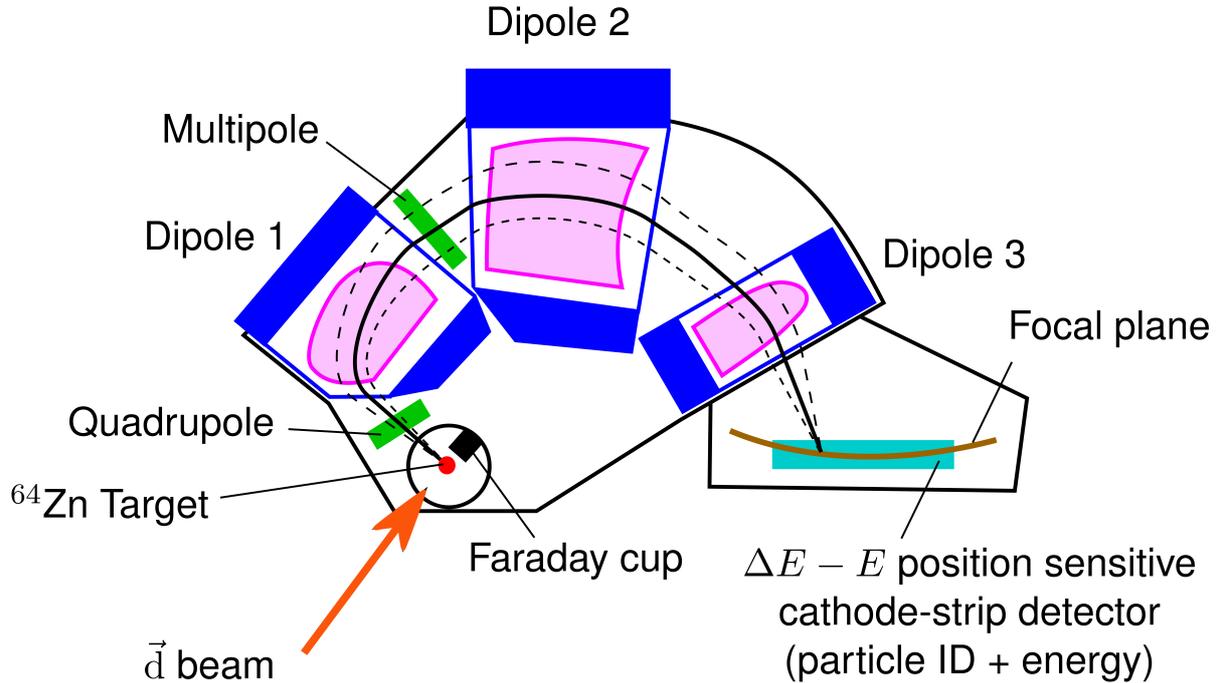
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**Abstract.** The most recent isospin-symmetry-breaking corrections,  $\delta_C$ , of Towner and Hardy for superallowed Fermi  $\beta$ -decay transitions, have included the opening of specific core orbitals. This change has resulted in significant deviations in some of the  $\delta_C$  factors from their previous calculations, and an improved agreement of the individual corrected  $\mathcal{F}t$  values with the overall world average of the 13 most precise cases. While this is consistent with the conserved-vector-current (CVC) hypothesis of the Standard Model, these new calculations must be thoroughly tested, and guidance must be given for the improvement of calculations for the upper- $pf$  shell nuclei. Using the (d,t) reaction mechanism to probe the single neutron wavefunction overlap, information regarding the relevant shell-model configurations needed in the calculation can be determined. An experiment was therefore performed with a 22 MeV polarized deuterium beam from the MP tandem Van de Graaff accelerator in Munich, Germany. Using the Q3D magnetic spectrograph, and a cathode-strip focal-plane detector, outgoing tritons were analyzed at 9 angles between  $10^\circ$  and  $60^\circ$ , up to an excitation energy of 4.8 MeV. This proceeding reports the motivational and experimental details for the  $^{64}\text{Zn}(\text{d,t})^{63}\text{Zn}$  transfer work presented.

## 1. Introduction

Superallowed Fermi  $\beta$  decay data currently provide the most precise determination of the vector coupling constant,  $G_V$ , which is vital in the extraction of the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix,  $V_{ud}$ . Since precision testing of the Standard Model through CKM matrix unitarity depends on the accuracy and precision of  $V_{ud}$ , the importance of accurate superallowed  $\mathcal{F}t$ -values is crucial. In order to extract  $V_{ud}$  from the high-precision experimental data, corrections to the almost nucleus-independent  $ft$ -values for superallowed  $\beta$  decays must be made for radiative effects as well as isospin symmetry breaking (ISB) by Coulomb and charge-dependent nuclear forces [1]. Although these corrections are small (on the order of a few percent), experimental measurements have provided such precise  $ft$ -values [2] ( $\pm 0.03\%$ ) that the uncertainty on  $G_V$  is dominated by the precision of these theoretical corrections.



**Figure 1.** A schematic diagram of the Q3D magnetic spectrograph.

The transition-independent  $\mathcal{F}t$ -value may be written as [1]:

$$\mathcal{F}t \equiv ft(1 + \delta_R)(1 - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_R)} \quad (1)$$

where  $\delta_R$  is the transition-dependent radiative correction,  $\Delta_R$  is the transition-independent radiative correction, and  $\delta_C$  is the nucleus-dependent ISB correction. A great deal of attention has recently been given to the  $\delta_C$  calculation, including revisions to the existing formalism [3, 4], as well as new approaches based on density functional theory [5] and relativistic RPA [6]. Although these recent papers have addressed some important concerns regarding the current calculations, there are few results which can currently be used to test the standard model. In fact, of these new methods, only one set of calculations [6] provides  $\delta_C$  values which can be used in the determination of  $\overline{\mathcal{F}t}$ . This fact, in addition to the current lack of uncertainties quoted for these values, suggests that work is still needed within these new approaches before the results should be combined with those of Ref. [1] in order to extract  $\overline{\mathcal{F}t}$ .

### 1.1. Towner and Hardy $\delta_C$ Calculation Method

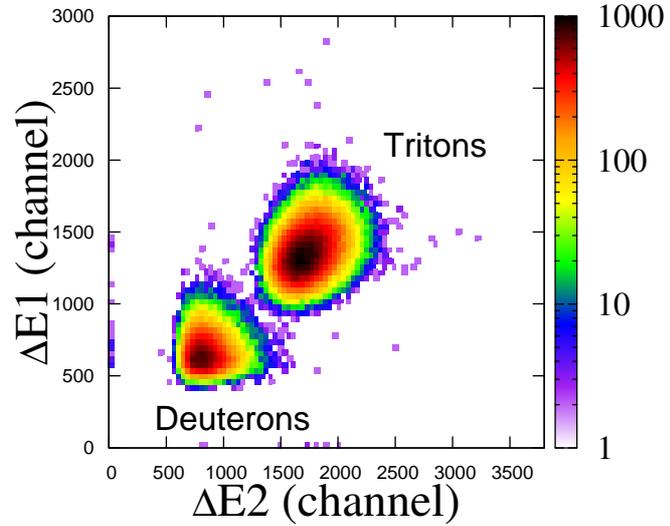
The ISB corrections of Towner and Hardy (TH) [1, 7], combined with the Hartree-Fock (HF) approach of Ormand and Brown (OB) [8], have been the standard set used over the last 20 years to determine  $G_V$ . Both groups used a separation of the  $\delta_C$  correction into a sum of two terms:

$$\delta_C \approx \delta_{C1} + \delta_{C2}, \quad (2)$$

where  $\delta_{C1}$  represents the ISB correction due to isospin mixing, and the  $\delta_{C2}$  correction results from imperfect radial overlap between the initial and final spatial nuclear wavefunctions. It is the latter of the two terms which has garnered most of the recent attention.



**Figure 2.** Photographed image of the  $^{64}\text{Zn}$  target on the MLL target ladder shortly after the experimental run.



**Figure 3.** Particle energy loss through the detector at the focal plane of the Q3D for  $\theta_{\text{lab}} = 30^\circ$ . The characteristic localization of the particles as a function of energy allows for particle identification.

The radial-overlap component of the ISB correction is used to correct the exact-symmetry matrix element,  $M_0$ , to obtain the Fermi-transition matrix element,  $M_F$ .

$$|M_F|^2 = |M_0|^2(1 - \delta_{C2}). \quad (3)$$

The contributions to the radial-overlap correction term  $\delta_{C2}$  are related to the single-nucleon transfer spectroscopic factors via [1]:

$$\delta_{C2} \approx \sum_{\pi, \alpha} \frac{T_f(T_f + 1) + \frac{3}{4} - T_\pi(T_\pi + 1)}{T_f(T_f + 1)} S_{\alpha, T_f}^{T_\pi} \Omega_\alpha^\pi, \quad (4)$$

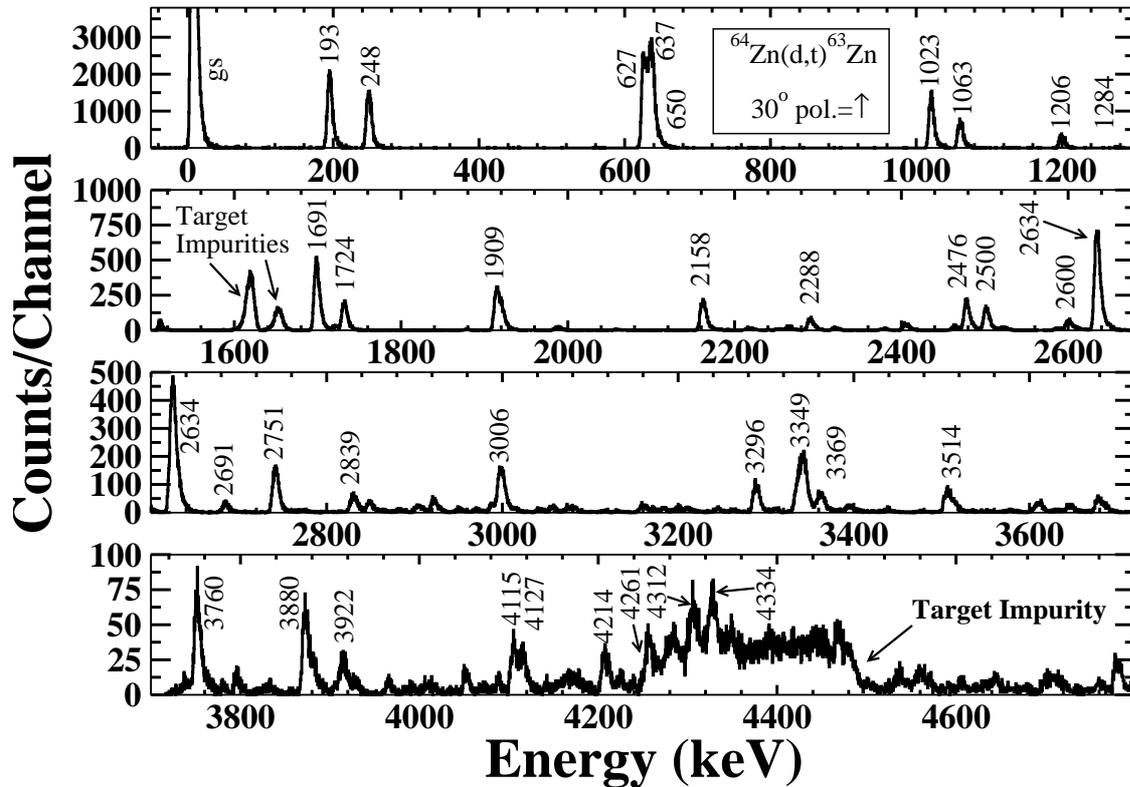
where  $S_{\alpha, T_f}^{T_\pi}$  is the spectroscopic factor for pickup of a neutron in quantum state  $\alpha$  from an  $A$ -particle state of isospin  $T_f$  to an  $(A - 1)$ -particle state of isospin  $T_\pi$ , and  $\Omega_\alpha^\pi$  is the radial mismatch factor.

Although the spectroscopic factors here are calculated, the core-orbitals which are important to include in the calculation model space are determined from an examination of measured spectroscopic strengths from single-nucleon pickup reactions [1].

It should also be noted that although the above formalism is used in the current shell-model treatments of the  $\delta_C$  calculations, for the lightest superallowed case used in the evaluation of  $\overline{\mathcal{F}t}$  ( $^{10}\text{C}$ ), *ab initio* no-core shell-model (NCSM) calculations which do not require this separation of terms have already been conducted [9]. At the current limit of these calculations,  $^{14}\text{O}$  may be available in the near future as well.

## 2. $^{62}\text{Ga}$ Superallowed $\beta$ -Decay $\mathcal{F}t$ Value

The difficulties with using a shell-model approach are the truncations necessary in order to calculate the eigenvalues for each  $\pi$ - $\nu$  particle-hole configuration, the truncations become more severe towards the mid- $pf$  shell. Due to these truncations, the ISB calculations are the limiting

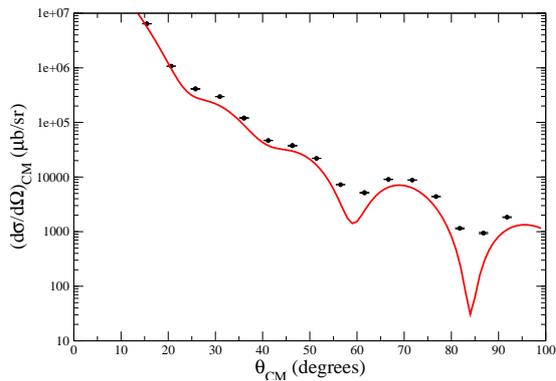


**Figure 4.** Complete spectrum observed in the population of  $^{63}\text{Zn}$  levels at  $\theta_{\text{lab}} = 30^\circ$  resulting from 22 MeV deuterons on  $^{64}\text{Zn}$ . The values shown are the level excitation energies in keV.

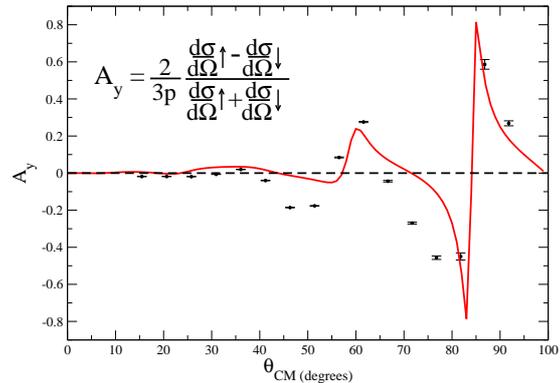
factor on the overall precision of the individual  $\mathcal{F}t$  values. This is most evident in the upper- $pf$  shell, an example is the case of  $^{62}\text{Ga}$ .

The experimental  $ft$ -value for  $^{62}\text{Ga}$ , with a fractional uncertainty of  $< 0.05\%$ , has a precision approximately matching those of the best cases in the  $sd$  or  $f_{7/2}$  shells. However, once the theoretical corrections are applied, the fractional uncertainty on the  $^{62}\text{Ga}$  transition-independent  $\mathcal{F}t$  value increases to  $0.2\%$ , making it one of the least-precise  $\mathcal{F}t$  values of the 13 cases. For the cases in the  $sd$  and  $f_{7/2}$  shells, guidance for the most important orbitals to include in the calculations was taken from the results of single-neutron pickup reactions. However, since such reactions on  $^{62}\text{Zn}$  involve a radioactive beam, these have not yet been performed. In the absence of this guidance, the calculations of Ref. [1] adopted the  $(p_{3/2}, f_{5/2}, p_{1/2})^n$  model space for the initial state ( $^{62}\text{Zn}$  or  $^{64}\text{Zn}$ ), using  $^{56}\text{Ni}$  as a closed core, while for the final state ( $^{61}\text{Zn}$  or  $^{63}\text{Zn}$ ) all configurations obtained from picking up a neutron from the  $pf$ -shell are retained, namely  $(p_{3/2}, f_{5/2}, p_{1/2})^{n-1}$  and  $f_{7/2}^{-1}(p_{3/2}, f_{5/2}, p_{1/2})^n$ .

The ultimate goal of this experimental campaign is the extraction of single-neutron pickup spectroscopic factors into superallowed daughter nuclei, for the case of  $^{62}\text{Ga} \rightarrow ^{62}\text{Zn}$ , this requires a radioactive  $^{62}\text{Zn}$  beam. Since access to stable beam facilities is a more feasible solution, a single neutron transfer probe can be used on the stable Zinc isotope  $^{64}\text{Zn}$ , and compared to calculated spectroscopic factors for  $^{63}\text{Zn}$  using the same method adopted for  $^{61}\text{Zn}$  in Ref. [1]. The results gained from this technique will help determine whether or not the relevant orbitals are included within the calculation model space for  $^{62}\text{Zn}$ .



**Figure 5.** Angular distribution for deuteron elastic scattering from  $^{64}\text{Zn}$ . The calculated DWBA curve was done so using deuteron parameters given in Ref. [12].



**Figure 6.** Vector analyzing powers for  $^{64}\text{Zn}$  deuteron elastic scattering at 22 MeV. The calculated curve uses deuteron parameters given in Ref. [12].

### 3. Experiment

The experiment was performed at the Maier-Leibnitz-Laboratorium (MLL) of Ludwig-Maximilians-Universität (LMU) and Technische Universität München (TUM) in Munich, Germany. Using a 22 MeV polarized deuterium beam from the MP tandem Van de Graaff accelerator and the Stern-Gerlach polarized ion source, polarized deuterons were incident on  $^{64}\text{Zn}$  and the reaction products were momentum analyzed using the Q3D magnetic spectrograph (Fig. 1). The target consisted of 99.3(1)% isotopically pure,  $172 \mu\text{g}/\text{cm}^2$  of  $^{64}\text{Zn}$  with a  $13 \mu\text{g}/\text{cm}^2$  carbon backing (Fig. 2). The resulting particles were detected at the focal plane with a position-sensitive proportional counter and a thick plastic scintillator which provides particle identification via  $\Delta E - E$  information [10]. At 9 angles between  $10^\circ$  and  $60^\circ$ , five momentum settings of the spectrograph were taken to cover excitation energies of up to  $\sim 5$  MeV, with both polarizations. A  $0^\circ$  Faraday cup inside the target chamber was used to determine the number of beam particles incident on the  $^{64}\text{Zn}$  target, by integrating the total current. This information, along with the data-acquisition system (DAQ) dead-time was read into the data stream using scalers. Dead-time associated with the detection system was also tracked, where all events gathered during this time were binned in channel zero of each respective particle-position spectrum. These dead-time values were typically  $\leq 0.5\%$  and  $\sim 1\% - 20\%$  for the detector and DAQ, respectively. A sample spectrum of the detected  $\Delta E - \Delta E$  particle identification spectrum is displayed in Fig. 3. After providing a triton particle gate, the observed levels in  $^{63}\text{Zn}$  at  $30^\circ$  are displayed in Fig. 4, values shown correspond to peak energies in keV. The typical resolution obtained for the particle energy spectra was 8 keV full-width at half-maximum (FWHM). Due to target impurities, the momentum settings were varied slightly as a function of angle within each range window. Further identification of all impurities in the spectra will be necessary to separate the  $^{63}\text{Zn}$  levels from all observed peaks.

The energy calibration was determined using well-known low-lying levels in  $^{63}\text{Zn}$  [11]. However, as the excitation energy increased, many new, previously unidentified levels were observed and it becomes impossible to match these levels with those listed in Ref. [11]. Therefore, the  $^{54}\text{Fe}(d,t)$  reaction was also employed for energy calibration by taking advantage of the larger negative reaction  $Q$ -value for  $^{54}\text{Fe}(d,t)$  (7121.2(16)keV) as compared with  $^{64}\text{Zn}(d,t)$  (6724(56) keV). Using the same magnetic field settings of the Q3D and accounting for the differences in the energy losses of the particles in the  $^{54}\text{Fe}$  and  $^{64}\text{Zn}$  targets, energies of the  $^{64}\text{Zn}(d,t)$  reaction peaks up to 4.8 MeV excitation energy could be accurately determined. The calibrated energy spectrum for  $^{63}\text{Zn}$  is displayed in Fig. 4.

#### 4. Summary and Progress

Due to the recent revisions in superallowed Fermi  $\beta$ -decay isospin symmetry breaking corrections, experimental guidance is needed to help constrain the shell-model calculation space. The work presented above is part of an experimental campaign which attempts to address this concern via single-nucleon pickup reactions, and ultimately experimental spectroscopic factors. One of the most important cases for guidance in these model space truncations is in the calculation of the  $^{62}\text{Ga} \rightarrow ^{62}\text{Zn}$  ISB correction.

The investigation into a suitable deuteron optical model parameter set and their ability to reproduce the deuteron elastic scattering data is ongoing. This scattering data is shown in Fig. 5 along with the calculated DWBA curve using deuteron optical model parameters presented in Ref. [12]. The tuning of these parameters requires further work, as can be seen by the discrepancies in the analyzing powers shown in Fig. 6. Future work includes the comparison of the extracted spectroscopic factors from the  $^{64}\text{Zn}(d,t)$  reaction with those calculated for  $^{63}\text{Zn}$  using the shell model space previously outlined, to determine if further refinements to the ISB calculations are necessary.

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#### 5. References

- [1] I.S. Towner and J.C. Hardy, Phys. Rev. C **77**, 025501 (2008).
- [2] J.C. Hardy and I.S. Towner, Phys. Rev. C **79**, 055502 (2009).
- [3] G.A. Miller and A. Schwenk, Phys. Rev. C **78**, 035501 (2008).
- [4] G.A. Miller and A. Schwenk, arXiv:0910.2790v1 [nucl-th], (2009).
- [5] W. Satula, J. Dobaczewski, W. Nazarewicz, and M. Rafalski, Phys. Rev. Lett. **103**, 012502 (2009).
- [6] Haozhao Liang, Nguyen Van Giai, and Jie Meng, Phys. Rev. C **79**, 064316 (2009).
- [7] I.S. Towner and J.C. Hardy, Phys. Rev. C **66**, 035501 (2002).
- [8] W.E. Ormand and B.A. Brown, Phys. Rev. C **52**, 2455 (1995); Phys. Rev. Lett. **62**, 866 (1989); Nucl. Phys. **A440** 274 (1985).
- [9] E. Caurier, P. Navrátil, W.E. Ormand, J.P. Vary, Phys. Rev. C **66**, 024314 (2002).
- [10] H.-F. Wirth, H. Angerer, T. von Egidy, Y. Eisermann, G. Graw, and R. Hertenberger, Maier-Leibnitz-Laboratorium Jahresbericht, p.71 (2000).
- [11] Bai Erjun and Huo Junde, Nuclear Data Sheets **92**, 147 (2001).
- [12] Haixia An and Chonghai Cai, Phys. Rev. C **73**, 054605 (2006).