Investigation of excited $0^+$ states in $^{160}$Er populated via the $(p, t)$ two-neutron transfer reaction

C. Burbadge$^1$, P.E. Garretti, G.C. Ball$^2$, V. Bildstein$^3$, A. Diaz Varela$^4$, M.R. Dunlop$^1$, R. Dunlop$^1$, T. Faesternann$^3$, R. Hertenberger$^4$, D.S. Jamieson$^1$, D. Kisliuk$^{1,5}$, K.G. Leach$^{1,3}$, J. Loranger$^1$, A.D. MacLean$^4$, A.J. Radich$^1$, E.T. Rand$^4$, C.E. Svensson$^3$, S. Triambak$^{3,5,6}$, and H.-F. Wirth$^4$

1Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada
2TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
3Technische Universität München, D-85748 Garching, Germany
4Fakultät für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany
5Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada
6Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA
7Department of Physics and Astronomy, University of the Western Cape, P.O. Box 722, Somerset West 7129, South Africa
8Thembalaboury for Accelerator Based Sciences, P.O. Box 722, Somerset West 7129, South Africa
9B X17, Bellville ZA-7535, South Africa

Abstract. Many efforts have been made in nuclear structure physics to interpret the nature of low-lying excited $0^+$ states in well-deformed rare-earth nuclei. However, one of the difficulties in resolving the nature of these states is that there is a paucity of data. In this work, excited $0^+$ states in the $N = 92$ nucleus $^{160}$Er were studied via the $^{162}$Er$(p, t)^{160}$Er two-neutron transfer reaction, which is ideal for probing $0^+ \rightarrow 0^+$ transitions, at the Maier-Leibnitz-Laboratorium (MLL) in Garching, Germany. Reaction products were momentum-analyzed with a Quadrupole-3-Dipole magnetic spectrograph. The $0_{1+}^+$ state was observed to be strongly populated with 18% of the ground state strength.

1 Introduction

The nature of excited $0^+$ states in well-deformed nuclei remains an open question in nuclear structure physics. Traditionally, deformed nuclei are suggested to have $\beta$-vibrational and $\gamma$-vibrational bands which result from collective low-lying surface vibrational excitations [1]. Recent data in nuclei near $N = 90$, such as Gd [2–4], Sm [5–8] and Dy [9–11], have put into question whether the nature of low-lying excited $0^+$ states should be re-examined [12, 13].

Two-neutron transfer reactions are excellent probes to study excited $0^+$ states as they are sensitive to pairing correlations in nuclei [14–17]. This has been demonstrated by the strongly-populated $0_{1+}^+$ states which emerged in both $(p, t)$ and $(t, p)$ reactions in the $N = 90$ region [7]. In particular, the cross sections of the first excited $L = 0$ excitations were comparable to that of their ground states in $N = 88 – 90$ nuclei, indicating a rapid onset of deformation [7, 13].

Evidence of collectivity in the $N = 90$ region is also demonstrated by the simultaneous increase of the $B(E2; 0_{1+}^+ \rightarrow 2_{1+}^+)$ value and the $E4/E2$ energy ratio, plotted in Figure 1, indicating that a rapid transition between the vibrational and rotational limits occurs near $N = 90$. \footnote{e-mail: cburbadg@uoguelph.ca}

![Figure 1. $B(E2; 0_{1+}^+ \rightarrow 2_{1+}^+)$ value and $E4/E2$ ratio systematics in the $N = 90$ region plotted as a function of neutron number. The dramatic increase in both quantities suggests that these isotopes lie in a transitional region of rapid shape change. The Er isotopic chain also possesses similar characteristics.]

2 Experimental Details

Excited states in $^{160}$Er have been studied via the $^{162}$Er$(p, t)$ reaction at the MLL in Garching, Germany. Proton beams up to 2 $\mu$A were accelerated to 22 MeV or 24 MeV using a 14 MV tandem...
Van de Graaff accelerator. The proton beam impinged on a highly-enriched $^{162}$Er target. Reaction products were momentum-analyzed with a Quadrupole-3-Dipole (Q3D) magnetic spectrometer. In the focal plane of the Q3D, two proportional counters produce two energy-loss signals, $\Delta E$ and $\Delta E_1$. A thick plastic scintillator located behind the proportional counters stop the particles to determine their energy. $\Delta E$ is placed on the outgoing tritons (left), to eliminate coincidence tagging of a deuteron contaminant (right).

An elastic scattering angular distribution was collected from $15^\circ$ to $115^\circ$ to determine the target thickness and select an appropriate global optical model potential (OMP) [18–22] to be used in the Distorted Wave Born Approximation (DWBA) calculation. The target thickness was determined to be 61(3)$\mu$g/cm$^2$ by normalizing the cross section at $15^\circ$ to the Becchetti and Greenlees OMP [18], which best reproduced the distribution minima. In this work, the DWBA calculations were performed using FRESCO, a coupled-channel reactions code [26]. The isotopic purity of 99% is remarkable given the 0.14(1)% natural abundance [24] of $^{162}$Er.

### 3 Results and Conclusions

Evaluated data for levels in $^{160}$Er [23] were used to calibrate the triton spectrum, plotted in Figure 3. Members up to $J^\pi = 4^+$ were assigned by comparison of angular distributions to DWBA calculations. It is worth noting that some of the members of the higher-lying $K^\pi = 0^+$ and $K^\pi = 2^+$ bands are speculative, motivated by the similarity of the $^{160}$Er band structures to those of $^{162}$Er and $^{152}$Sm, but are in agreement with those observed in unevaluated works [10, 25].

To report the strength of the excited $0^+$ states relative to the ground state, the relative cross section strength, $S$, is defined by

$$S = \frac{\frac{d\sigma}{d\Omega_{\text{LAB}}}}{\frac{d\sigma}{d\Omega_{\text{LAB}}}} \left( \frac{d\sigma_{\text{LAB}}}{d\Omega_{\text{LAB}}} \right)^{-1}$$

where the differential cross sections are stated in the centre-of-mass frame. Normalizing both the excited and ground states to the DWBA calculation applies a Q-value correction to account for the dependence of the reaction cross section on excitation energy. Figure 4 shows the agreement between the $0^+_1$ and $0^+_2$ state cross sections and their DWBA calculations.

The relative cross section strength of excited $0^+$ states in this work are listed in Table 1. The low-lying $K^\pi = 0^+$ band head is strongly populated with 18% of the ground state strength, while higher excited $0^+$ states have a relative strength of less than 2%. The strong population of the $0^+_2$ in $(p, t)$ reactions in the $N = 92$ region, reminiscent of the strong $(p, t)$ strength in the $N = 90$ region [7], may suggest that the same mechanism is responsible for the strength of $0^+$ states in both $N = 90$ and $N = 92$ nuclei.

![Figure 2. $\Delta E - E$ histogram for the $^{162}$Er($p, t$) reaction at $30^\circ$. A gate is placed on the outgoing tritons (left), to eliminate coincidence tagging of a deuteron contaminant (right).](https://doi.org/10.1051/epjconf/201817802025)

### Table 1. Energy and relative strengths of excited $0^+$ states, normalized at $5^\circ$ to the DWBA calculation.

| $E_{\text{exp}}$ (keV) | $S(0^+_N/0^+_N)$ (%) |
|------------------------|------------------------|
| 0                      | 100                    |
| 894                    | 18(1)                  |
| 1279                   | 1.0(1)                 |
| 1528                   | 1.0(1)                 |
| 1664                   | 1.4(5)                 |
| 1939                   | 0.10(3)                |
| 2032                   | 1.7(1)                 |
| 2129                   | 0.7(1)                 |

References

[1] A. Bohr, B.R. Mottelson, *Nuclear Structure Volume II: Nuclear Deformations* (W.A. Benjamin, Inc. Advanced Book Program Reading, 1975)
[2] J.F. Sharpey-Schafer et al., *Eur. Phys. J. A* 47, 5 (2011)
[3] J.F. Sharpey-Schafer et al., *Eur. Phys. J. A* 47, 6 (2011)
[4] W.D. Kulp et al., *Phys. Rev. Lett.* 91, 102501 (2003)
[5] P.E. Garrett et al., *Phys. Rev. Lett.* 103, 062501 (2009)
[6] W.D. Kulp et al., *Phys. Rev. C* 77, 061301(R) (2008)
[7] W.D. Kulp et al., *Phys. Rev. C* 71, 041303(R) (2005)
[8] W.D. Kulp et al., *Phys. Rev. C* 76, 034319 (2007)
[9] S.N.T. Majola et al., *Phys. Rev. C* 91, 034330 (2015)
[10] N. Blasi et al., *Phys. Rev. C* 90, 044317 (2014)
[11] M.A. Caprio et al., *Phys. Rev. C* 66, 054310 (2002)
[12] P.E. Garrett, *J. Phys. G* 27, R1 (2001)
[13] K. Heyde, J.L. Wood, *Rev. Mod. Phys.* 83, 1467 (2011)
[14] C.Y. Wu et al., *Annu. Rev. Nucl. Part. Sci.* 40, 285 (1990)
[15] D. Bès, R. Broglia, *Nucl. Phys.* 80, 289 (1966)
[16] S. Yoshida, *Nucl. Phys.* 33, 685 (1962)
[17] A.A. Shihab-Eldin et al., *Int. J. of Mod. Phys. E* 04, 411 (1995)
Band Assignments: $0^+_1$ Band $2^+_1$ Band $0^+_2$ Band $0^+_3$ Band $0^+_4$ Band $1^+_1$ Band $0^+_5$ Band $2^+_2$ Band $2^+_3$ Band $0^+_6$ Band

**Figure 3.** Energy-calibrated spectrum from the $^{162}$Er($p$, $t$) reaction at a beam energy of 24 MeV and Q3D angle of 30°. The angular momentum of some of the more prominent peaks are labelled.

**Figure 4.** Comparison of the angular distributions of the $0^+_1$ state (left) and $0^+_2$ state (right) to their DWBA calculations at a beam energy of 24 MeV, demonstrating the level of certainty in assigning $J=0^+$ states due to the unique shape of its angular distribution.

[18] F.D. Becchetti, G.W. Greenlees, Phys. Rev. 182, 1190 (1969)
[19] R.L. Varner et al., Phys. Rep. 201, 57 (1991)
[20] B. Morillon, P. Romain, Phys. Rev. C 76, 044601 (2007)
[21] R.L. Walter, P.P. Guss, Rad. Effects 95, 73 (1986)
[22] A.J. Koning, J.P. Delaroche, Nucl. Phys. A 713, 231 (2003)
[23] C.W. Reich, Nuclear Data Sheets 105, 557 (2005)
[24] P. Holliger, C. Devillers, Earth Planet. Sci. Lett. 52, 76 (1981)
[25] K. Dusling et al., Phys. Rev. C 73, 014317 (2006)
[26] I.J. Thompson, *Fresco coupled reaction channels calculation*, http://www.fresco.org.uk/, version 2.9