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

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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 $0^+ \to 0^+$ transitions, at the Maier-Leibnitz-Laboratorium in Garching, Germany. Reaction products were momentum-analyzed with a Quadrupole-3-Dipole magnetic spectrograph. The 0_2^+ 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 β-vibrational and γ-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 is demonstrated by the strongly-populated 0_2^+ 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 $B(E2; 0_1^+ \to 2_1^+)$ value and the $E_{4_1^+}/E_{2_1^+}$ energy ratio, plotted in Figure 1, indicating that a rapid transition between the vibrational and rotational limits occurs near $N = 90$.

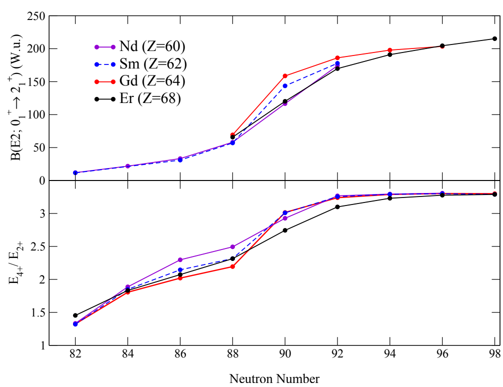

Figure 1. $B(E2; 0_1^+ \to 2_1^+)$ value and $E_{4_1^+}/E_{2_1^+}$ ratio systematics in the $N = 90$ region plotted as a function of neutron number. The dramatic increase in both quantities suggests that these isotopes lie in a transitional region of rapid shape change. The Er isotopic chain also possesses similar characteristics.

2 Experimental Details

Excited states in ^{160}Er have been studied via the ^{162}Er(p,t) reaction at the Maier-Leibnitz-Laboratorium (MLL) in Garching, Germany. Proton beams up to 2 μA were accelerated to 22 MeV or 24 MeV using a 14 MV tandem

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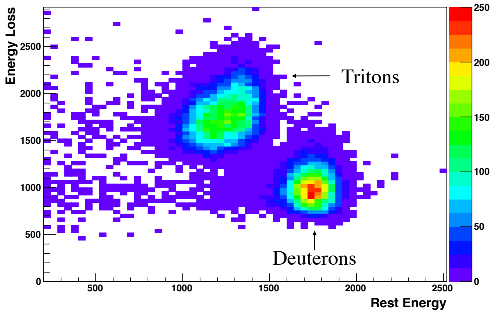

Figure 2. ΔE- E histogram for the ^{162}Er(p, t) reaction at 30°. A gate is placed on the outgoing tritons (left), to eliminate coincidence tagging of a deuteron contaminant (right).

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 spectrograph. In the focal plane of the Q3D, two proportional counters produce two energy-loss signals, ΔE and ΔE_1. A thick plastic scintillator located behind the proportional counters stop the particles to determine their energy, E. An example of a ΔE- E histogram used to identify and gate on reaction ejectiles is shown in Figure 2.

An elastic scattering angular distribution was collected from 15° to 115° 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) µg/cm^2 by normalizing the cross section at 15° 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

$$S = \frac{\frac{d\sigma}{d\Omega}^{LAB}_{0^+_{ex}}}{\frac{d\sigma}{d\Omega}^{DWBA}_{0^+_{ex}}} \cdot \left(\frac{\frac{d\sigma}{d\Omega}^{LAB}_{0^+_{gs}}}{\frac{d\sigma}{d\Omega}^{DWBA}_{0^+_{gs}}} \right)^{-1}$$

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

E_{exp} (keV)	$S(0^+_{ex}/0^+_1)$(%)
0	100
894	18(1)
1279	1.0(1)
1528	1.0(1)
1864	1.4(5)
1930	0.10(3)
2032	1.7(1)
2129	0.7(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.

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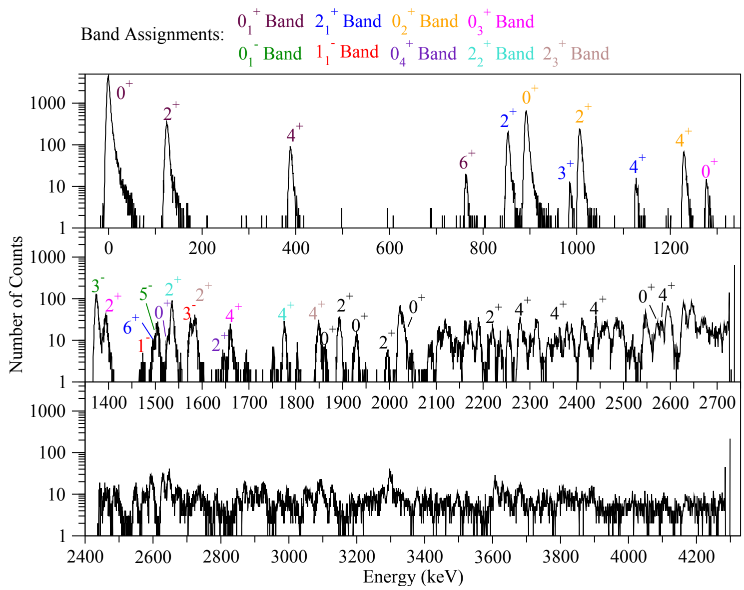

Figure 3. Energy-calibrated spectrum from the ^{162}Er(p, t) reaction at a beam energy of 24 MeV and Q3D angle of 30°. The angular momentum of some of the more prominent peaks are labelled.

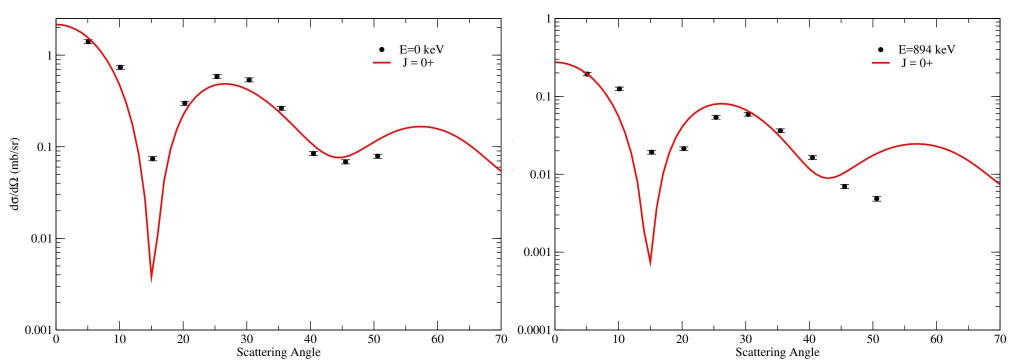

Figure 4. Comparison of the angular distributions of the 0_1^+ state (left) and 0_2^+ state (right) to their DWBA calculations at a beam energy of 24 MeV, demonstrating the level of certainty in assigning J=0^+ states due to the unique shape of its angular distribution.

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