EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

# Tracking quantum phase transition by means of neutron pair transfer

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## Abstract


Scientific goal of the present letter of intent is the evaluation of the feasibility of the $^{98}$Zr (t, p) reaction for the study of shape transitions in heavy Zr isotopes. The study of the production and transport of the reaccelerated $^{98}$Zr beam is required to this purpose.


**Beamline:** [MINIBALL + T-REX]

Nucleon-pair-transfer reactions have long since been an important experimental tool for studying nuclear structure. In particular, they have been crucial in obtaining evidence of collective features due to pairing interaction [1,2] or in unraveling the single-particle nature of excited bands in nuclei that feature shape-coexistence phenomena, near to the closed shells, over the entire nuclear chart [3]. Pair-transfer reactions are also useful in the study of nuclear shape-phase transitions, i.e., the rapid evolution of nuclear structure with mass number, such as from sphericity to axial-symmetric deformed or from sphericity to deformed γ-unstable nuclei.

Observables that are often used to follow the evolution of shape transitions are, e.g., ratios of excitation energies such as $R=E_{4^+_1}/E_{2^+_1}$, electromagnetic transitions such as B(E2; $2^+_1 \rightarrow 0^+_1$),B(E0; $0^+_2 \rightarrow 0^+_1$), and B(E2; $2^+_2 \rightarrow 0^+_1$)/B(E2; $2^+_2 \rightarrow 2^+_1$), two-neutron separation energies, isomer shifts, and isotope shifts.

The two neutron transfer reaction provides a unique key to establish systematics in shape evolution and transition. The usual dominance of the ground-to-ground L=0 pair transfer connecting neighbor even-even isotopes fails in correspondence to the phase transition, with a characteristic distribution of the L=0 pair strength that depends on the nature of the transition [5].

The stable Zr isotopes has been a pivotal example for how the (t, p) and (p, t) reactions can be used to strictly constrain the structure of the involved initial and final states. It is now natural to extend such study to the unstable isotopes to address the changes in structure that have been proposed.

Zirconium isotopes show a quick shape phase transition from spherical ground states for $^{90-98}$Zr to deformed ground states in $^{100}$Zr and heavier isotopes [5]. The nucleus $^{96}$Zr has a low-lying excited $0^+$ state, which could be deformed, and is suggested as an example for exhibiting type II shell evolution driven by the tensor force. In fact, shape coexistence has been suggested in the heavier isotope $^{98}$Zr [6,7]] and has recently been reported for the lighter isotope $^{94}$Zr [8], albeit a considerable mixing of the coexisting structures was deduced from the sizable interstructure E2 transition strengths. Recently an electron scattering experiment suggested the coexistence in $^{96}$Zr of prolate and triaxial shapes without mixing [9].

Figure 1 shows the properties of $0^+_{1,2}$ states. The ground state remains spherical up to N = 58, and becomes prolate at N = 60. A spherical state appears as the $0^+_4$ state at N = 60. An abrupt change seems to occur in the structure of the ground state as a function of N, which can be viewed as an example of the quantum phase transition (QPT), satisfying its general definition to be discussed [10]. This is quite remarkable, as the shape transition is, in general, rather gradual. The parameter here is nothing but the neutron number N, and the transition occurs from a "spherical phase" to a "deformed phase."

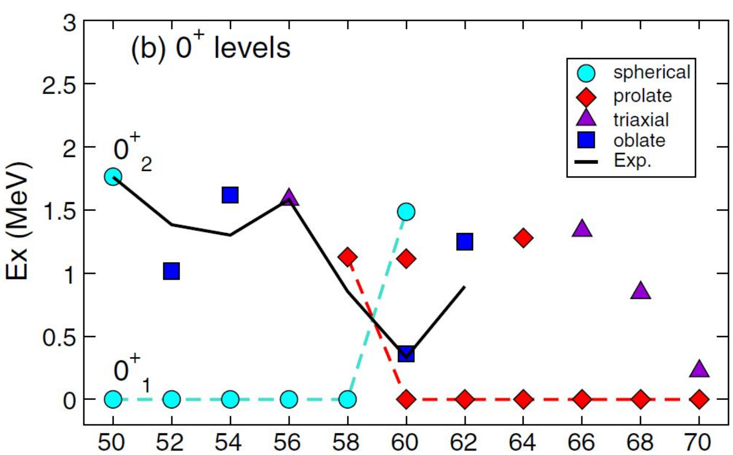


*Figure 1 Systematics of the $0^+$ states described with different shapes. Taken from [11].*

Such reorganization of the shell structure involves substantial reconfiguration of protons and neutrons (or type II shell evolution), leading to more different configurations between the normal states and the states with this deformation-optimized shell structure. This property results in a suppressed mixing of two such states even around their crossing point. The abrupt change, thus, appears with almost no mixing, leading to a QPT.

A clear signature for such description of shape evolution and quantum phase transition could be obtained from two neutron transfer (t, p) reaction on $^{98}$Zr. In particular, guided by the predictions shown in Figure 1, we expect weak L=0 pair transitions to the ground and the two first excited states in $^{100}$Zr (all characterized by a deformed shape at variance with the starting spherical $^{98}$Zr ground state), with a strong transition to the third excited $0^+$ state, which is expected to display a spherical behavior. The goal of the present letter of intent is the evaluation of its feasibility.

## Beam time request

In order to evaluate the feasibility of the study of the two-neutron transfer (t, p) reaction on $^{98}$Zr we request the measurement of the characteristics of the beam obtainable for this refractory element. The $^{98}$Zr isotope can be produced from the decay of rubidium, strontium or yttrium. Using 0.6 GeV protons, a 13 g/cm$^2$ UCx target and W surface ionization, $^{98}$Rb has been produced with a yield of $3.2 \cdot 10^6$ ions/μCi. The yields of $^{98}$Sr and $^{98}$Y have never been measured.

Two shifts of beam time are required in order to explore the production technique exploiting ionization of $^{98}$Rb, $^{98}$Sr or $^{98}$Y and to measure the rate and purity obtainable for their reaccelerated beta-daughter $^{98}$Zr.


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