Shape-phase transition at ^{98}Zr - Measurement of the B(E2;$2^+ \rightarrow 0^+_{g.s.}$) value with the RDDS method

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^{98}Zr is the stepping stone between the doubly (semi-)magic ($N = 56$) and the strongly deformed ($N \leq 60$) Zr isotopes. The $E2$ excitation strength of the 2^+_1 state at present only has a limit, which does not allow to judge on the degree of its collectivity, important to characterize the shape transition in the Zr isotopic chain and the surrounding region of the nuclear chart. This proposal is following up the successful ^{18}O(^{96}Zr,^{98}Zr)^{16}O reaction test. Its aim is the measurement of electro-magnetic matrix elements, most importantly the B(E2) excitation strength of the first excited 2^+ state in the transitional nucleus ^{98}Zr using the recoil distance doppler-shift (RDDS) method.

I. SCIENTIFIC MOTIVATION

Zr nuclei are of particular interest for nuclear structure studies such as the emergence of collectivity due to the $Z = 40$ sub-shell closure. With the lack of valence protons, except for particle-hole excitations across $Z = 40$, the lowest states in Zr isotopes between $N = 50-56$ are dominated by neutrons, which mostly populate the $d_{5/2}$ orbital. As a consequence, the $d_{5/2}$ sub-shell closure at $N = 56$ is stabilized, leading to the well-known peak in the 2^+_1 energy in ^{96}Zr. Higher-lying structures have been identified as more collective excitations in ^{94}Zr [1], and more recently in ^{96}Zr [2], which coexist with the spherical ground state configuration. These excited structures involve protons and/or neutrons being promoted to the respective $\pi(g_{9/2})$ and $\nu(g_{7/2}, d_{3/2}, h_{11/2})$ orbitals, which strongly interact through the tensor force. Hence, low-lying excited states, especially the low-lying 0^+ states which do not fit into a typical spherical-collective pattern, have different shapes resulting from normal and particle-hole configurations. This phenomenon has recently been described as a type II shell evolution [10], where a change of shapes is not governed by nucleon number, but occurs within one nucleus by promoting particles among the orbitals of the active valence space. In addition, states of a given structure, i.e. deformed or spherical, may migrate in energy within the isotopic chain, leading to the occurrence of a shape (phase) transition. In ^{100}Zr a deformed structure is energetically favored and becomes the ground state at $N = 60$, as indicated by a dramatic drop of the 2_1^+ energy from $N = 58$ and an increase of the $B(E2)$ excitation strength by an order of magnitude from $N = 56$ to $N = 60$.

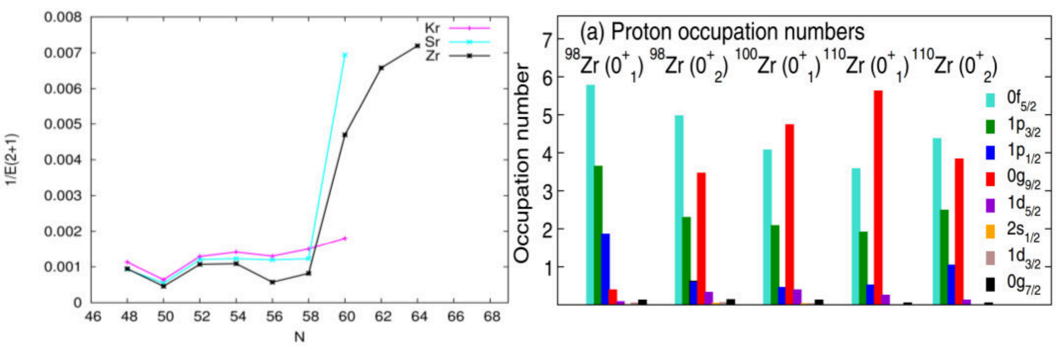

FIG. 1: Left: Inverse of the 2_1^+ excitation energies in Zr isotopes, compared to the known values in the lower-Z Sr and Kr chains. Right: Occupations of given orbitals in relevant states (from [10]).

^{98}Zr at $N = 58$ plays a pivotal role in this region. At $N = 58$, the neutron $s_{1/2}$ orbital is filled, which separates the $d_{5/2}$ and $(g_{7/2}, d_{3/2}, h_{11/2})$ neutron orbits, while blocking $j = 2$ neutron configurations to be formed at low energies. As such, the 2_1^+ energy in ^{98}Zr is still rather high at 1223 keV, while significantly lowered with respect to the 2_1^+ state in ^{96}Zr at 1750 keV. At the onset of deformation in ^{100}Zr the 2_1^+ state energy drops to 213 keV. Figure 1 shows the inverse of the 2_1^+ energies as a function of N for the Zr and neighboring even-even isotopes. ^{98}Zr is located in between the two limiting cases, and the degree of mixing between the different configurations depends largely on the details of the respective interactions. Coexistence of different structures is already obvious from the first excited state in ^{98}Zr being a 0^+ state. To predict the correct degree of mixing between the configurations, however, is a challenge to nuclear models (see, e.g., Ref. [3]). The wave functions of the low-lying states can be comprised of several major constituents. An example from

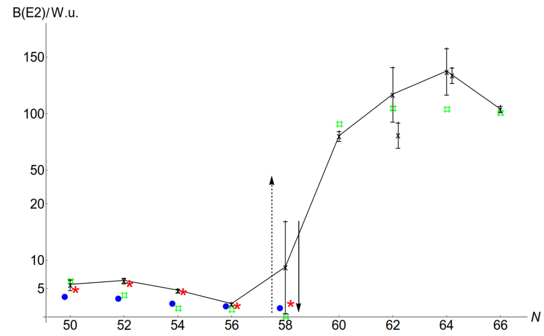

FIG. 2: Experimental (in black) and theoretical B(E2;$2_1^+ \rightarrow 0_{g.s.}^+$) values for Zr isotopes. Shell-model calculations with different effective charges (blue circles, red stars) [3] and recent Monte-Carlo SM calculations [10] (green squares) are shown. The value at N=58 is not known but limited from both sides by previous experiments [4][9]. Note the logarithmic scale.

Ref. [10] is shown on the right-hand side of Fig. 1, which shows the dramatic increase of protons occupying the $g_{9/2}$ orbital in the excited 0^+ state of ^{98}Zr, whereas the ground state is dominated by a closed-pf shell configuration. This prediction needs direct tests by experiment. As such, electro-magnetic matrix elements are important in order to constrain interactions. This is most important for the first excited 2^+ state of ^{98}Zr, in order to see whether, akin to ^{96}Zr, it is a rather pure spherical configuration, or whether it is mixed with the low-lying deformed configuration that becomes the ground state in ^{100}Zr. The measured and theoretically predicted B(E2) excitation strengths in the Zr isotopic chain are shown in Fig. 2.

In ^{98}Zr the excitation strength of the first excited 2^+ state is unknown to date; only a lower limit on its $B(E2; 2_1^+ \rightarrow 0_1^+)$ reduced transition strength has been measured [4], which does not yet allow to conclude on its structure. Although Coulomb excitation of the radioactive ^{98}Zr would be a suitable method to obtain the desired value, a previous experiment at Argonne National Laboratory showed difficulties producing the desired beam and only an upper limit on the B(E2) value was obtained [9]. The now available limiting values constrain the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value to 0.7-17 W.u., pointing to little deformation. A higher precision is highly desirable in order to quantify the collectivity of the ground state structure. The most recent shell model calculations by the Tokyo group [10] indicate a near-zero B(E2) value, so experimental precision needs to be improved to few percent.
We aim to measure the corresponding $E2$ matrix element using the Bucharest Plunger device,

and employing the 2-neutron transfer reaction ^{96}Zr(^{18}O,^{16}O)^{98}Zr. This reaction mechanism was tested in a previous experiment with ROSPHERE at IFIN-HH and proved to be efficient to produce ^{98}Zr. An excitation function measurement for this reaction was carried out and the beam energy of 51.5 MeV found to yield the highest cross-section for the production of ^{98}Zr, cp. Figs. 3, 4.

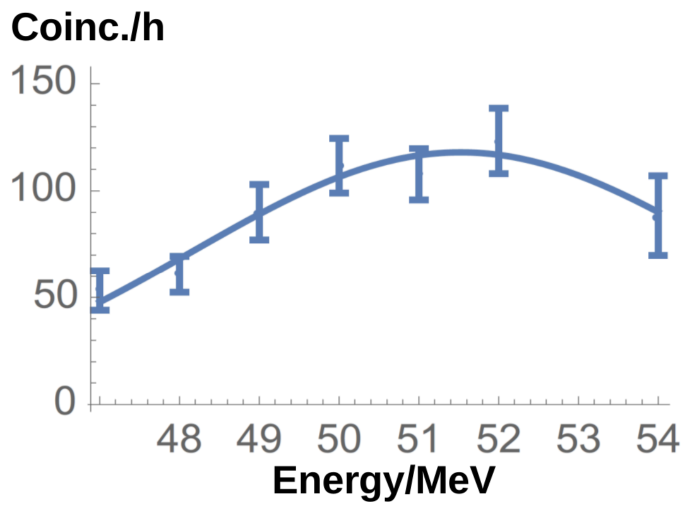

FIG. 3: Excitation function of the employed ^{18}O(^{96}Zr,^{98}Zr)^{16}O reaction showing the rate of observed coincidences between the $2^+_1 \to 0^+_{g.s.}$ and $3^-_1 \to 2^+_1$ transitions as a function of beam energy.

It should be noted that the correct theoretical treatment of competing deformations in this region is important also in the context of neutrino-less double-beta decay. Candidates for this rare decay mode, which is actively being searched for by several collaborations, exist in the vicinity of ^{98}Zr, and predictions for double-beta decays depend strongly on the wavefunctions of mother and daughter states, configuration mixing, as well as proton-neutron symmetry.

II. EXPERIMENTAL DETAILS

In the preceding test experiment a ^{96}Zr target with 1.29 mg/cm^2 thickness on a 6 mg/cm^2 Pb backing was used. However, the high oxidation (^{16}O) caused unwanted γ transitions in fusion-evaoration products (mainly ^{28,29}Si, ^{25}Mg and ^{31}P) in the energy range of interest. To improve the peak-to-background ratio a new (less oxidized) target will be used. The energy of the ^{98}Zr ions after reaction was calculated to be around 20 MeV which results in a

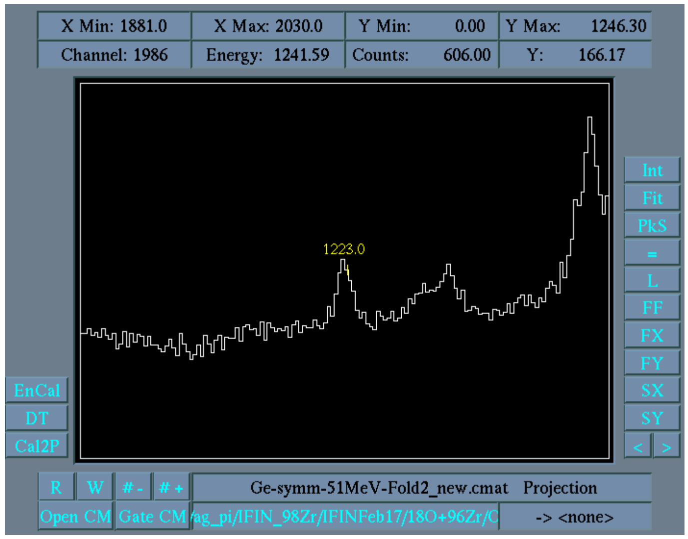

FIG. 4: Energy spectrum measured with the total ROSPHERE array after 9h including the ^{98}Zr $2_1^+ \rightarrow 0_{g.s.}^+$ transition of interest at 1223keV following the ^{18}O(^{96}Zr,^{98}Zr)^{16}O reaction at 51 MeV beam energy.

velocity of 0.5-1% c after leaving the target (thickness 1-1.5mg/cm^2). This will be sufficient for a clear Doppler-shift in the energy spectrum.

While the beam energy for the highest reaction cross section is 51.5 MeV it will be lowered slightly to 50 MeV. The reduction in reaction cross section will be offset with the shift of the ^{16}O angular distribution toward more backward angles (cp. Fig. 5) and result in more forward focused ^{98}Zr, hence, in a larger Doppler shift of in-flight γ rays.

For this beam energy we measured a yield of 100 $\gamma\gamma$ coincidences/h in the whole ROSPHERE array. For the relevant resulting coincidence-detector-pairs (forward-forward, forward-backward, backward-forward and backward-backward angles) we estimate 20 coincidences/h each.

The use of particle detectors for recoiling ^{16}O ions is not possible due to the main recoil direction being occupied by the plunger device. However, energy conditions alone proved to be sufficient for reaction channel selection so the additional use of particle detectors will not be needed.

With the lifetime of the 2_1^+ state between 0.65 ps and 15 ps (from previous B(E2) limits [4, 9]) a Plunger lifetime measurement will be performed. In the rather unlikely case that the B(E2) value is on the high end of the known range, i.e., the lifetime is at the

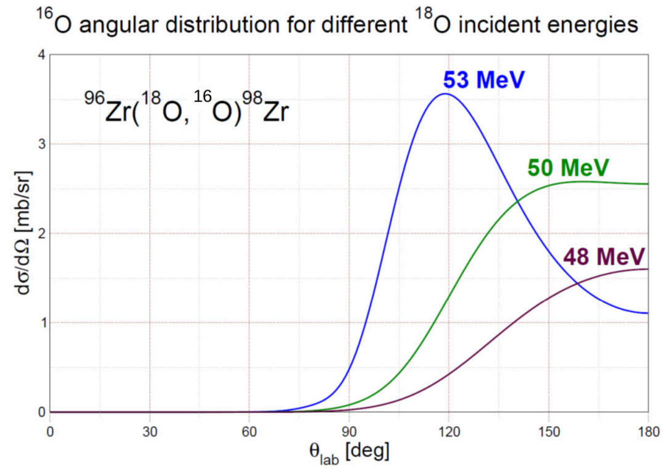

FIG. 5: Angular distribution calculation for the ^{18}O(^{96}Zr,^{98}Zr)^{16}O direct reaction for different beam energies. Calculations were done in DWBA with the code PTOLEMY.

low end, the experiment can quickly switch to a backed target and the lifetime can be determined through the Doppler-shift attenuation method (DSAM). More likely is a lifetime considerably larger than 1 ps, and we intend to use 10 different target-stopper distances, to obtain an uncertainty of the resulting lifetime <5%. The distances will include the shortest achievable plunger distance, as well as a large one (≈1 mm or more), in order to fix the lifetime curve at the extremes. For sufficient statistics we propose a measurement time of 2 days in average per distance, which is based on ≈1000 counts in the energy spectrum. The exact required beamtime will vary from smaller to larger distances (depending on the amount of the Doppler shifted $3^- \rightarrow 2^+$ transition to gate on) and on the actual lifetime of the state of interest. More measurements will be taken in the sensitive range.

In total we request 21 days (10 times 2 days per plunger distance and 1 day for beam tuning and calibrations) of beam time for this experiment to precisely determine the 2_1^+ level lifetime and the corresponding $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of ^{98}Zr.

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