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Proposal for the TANDEM accelerator for the period

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Investigation of $E3$ transition strength and particle-octupole phonon coupling in ^{91}Zr using the in-beam fast timing technique

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We propose the measurement of the half-life of the yrast $\frac{11}{2}^-$ level in ^{91}Zr, a key observable for the investigation of the octupole collectivity and particle-phonon coupling around the quasi-magic nucleus ^{88}Sr. The measured $B(E3)$=47(10) W.u. for the transition of the yrast $\frac{11}{2}^-$ level in ^{89}Sr to the ground state is among the largest from the table of isotopes and suggests an enhancement of octupole collectivity by coupling one neutron with the $N = 50$ core. This effect might be present also in ^{91}Zr, which is much simpler to be produced using the ^{82}Se(^{13}C,4n) reaction at 42 MeV, and can be observed using the in-beam fast timing technique with the ROSPHERE array.

I. Scientific motivation

In his lecture delivered on the occasion of the presentation of the 1975 Nobel Prizes in Physics, Ben Mottelson said reminding the pioneering times of the nuclear theory : *I remember vividly the many lively discussions in these years reflecting the feeling of unease, not to say total disbelief, of many of our colleagues concerning the simultaneous use of both collective and single-particle coordinates to describe a system that we all agreed was ultimately built out of the neutrons and protons themselves.* Even today, the complex phenomena of interplay of the single-particle and collective features is a key topic in understanding the structure of the atomic nucleus. A tremendous amount of experimental data accumulated in the meantime and, for instance, the role of particle-phonon couplings as catalyzer for the mixing of pure single-particle and vibrational states is now well established. The region around the doubly-magic ^{208}Pb is extremely rich in examples of states resulting from particle-quadrupole and particle-octupole phonon coupling and a lot of experimental and theoretical effort in the field was focused on that region of the isotopic chart.

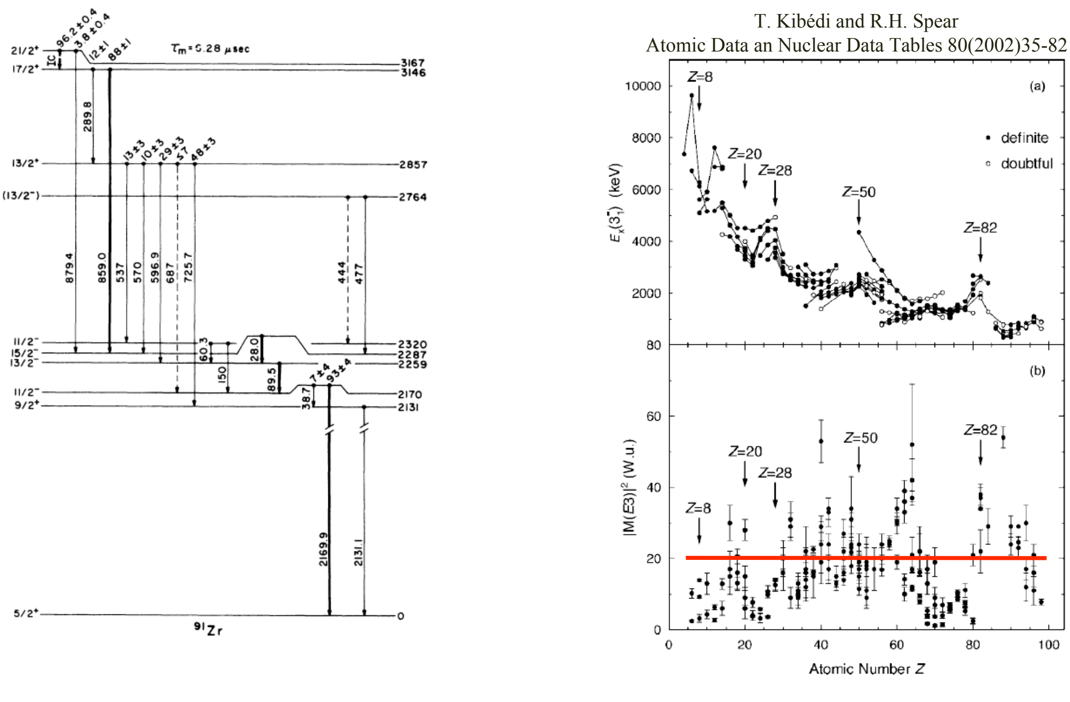

FIG. 1: Relevant level scheme of ^{91}Zr (figure taken from ref. [1]) and the systematic of the $E3$ matrix elements in even-even nuclei.

Concerning the particle-octupole phonon coupling, if we look at the systematic of $B(E3)$ values one notice that the region around Z=38-40, though less investigated on this aspect, it might be very interesting as well as the Z=82 region. The $B(E3)$ values for the even-even Z=38-40, N$\sim$50 even-even nuclei are around the average value of 20 W.u. corresponding to octupole vibration, with a peak value for ^{96}Zr where the $B(E3)$ is around 50 W.u. The finest example of particle-octupole coupled state in the region is encountered in ^{89}Sr, where the measured $B(E3)$=47(10) W.u. for the transition of the yrast $\frac{11}{2}^-$ level to the $\frac{5}{2}^+$ ground state is among the largest from the table of isotopes. Compared with the $B(E3)$ value of the ^{88}Sr core of 23(2) W.u. it suggests an enhancement of octupole collectivity by coupling one neutron with the $N = 50$ core. The possible nature of this enhancement was discussed by Arnell et al. in Ref. [2], where is stated that if one consider almost equal proportions of pure single-neutron $h_{\frac{11}{2}}$ and $(3^- \times d_{\frac{5}{2}})$ components on the wave function of the $\frac{11}{2}^-$ state as suggested by the spectroscopic factors, one obtain an unusually large effective octupole charge of the $h_{\frac{11}{2}}$ neutron, $e_{eff} = (1.9 \pm 0.5)e$ respect to a much smaller value, $e_{eff} = (0.6 \pm 0.3)e$ for an analog state $\frac{15}{2}^-$ in ^{209}Pb. Nevertheless, we should consider that the $B(E3)$ value in ^{89}Sr was measured in a very difficult DSAM experiment with gaseous Kr target[2].

The situation in the isotone ^{91}Zr seems quite similar (see Fig. 1). The yrast $\frac{11}{2}^-$ state decays with the main branch through an $E3$ transition to the $\frac{5}{2}^+$ ground state. Even the excitation energies are similar, 2170 keV for the $\frac{11}{2}^-$ state in ^{91}Zr versus 2748 keV for the 3^- state in ^{90}Zr, compared with 2079 keV versus 2734 keV in the corresponding Sr isotones. However, the structure of the negative parity states in the ^{90}Zr core is more complicated. The first two negative parity states in the level scheme are the 5^- and 4^- states with dominant $\pi(p_{\frac{1}{2}} g_{\frac{9}{2}})$ two quasiparticle structure at 2319 and 2739 keV excitation energy, the 3^- state being only the third in sequence at 2748 keV. The measured $B(E3; 3^- \rightarrow 0^+)$ value is unclear, several references giving quite different values. Light particle scattering experiments[3] put this value in the 0.051-0.091 e^2b^3 range, similar with ^{88}Sr, while from scattering of high-energy ^{17}O a value of 0.027(5) e^2b^3 was proposed[4]. Experimentally is very difficult to measure directly the lifetime of the 3^- level in ^{90}Zr due to the weak population of this state in all reactions performed until now. In this conditions, the lifetime of the yrast $\frac{11}{2}^-$ state in ^{91}Zr becomes a key quantity. A sub-nanosecond value implies a large $B(E3)$, it may indicate particle-octupole phonon coupling character and quantify the octupole collectivity also for the core. A large value around 10 ns would correspond to a $B(E3)$ strenght of $\sim$1 W.u. and would indicate that this state is simply a member of the multiplet arising from the coupling of a neutron in $d_{\frac{5}{2}}$ with the low-lying, negative-parity two quasiparticle states of the core.

To define the expected limits for the half-life of the yrast $\frac{11}{2}^-$ level in ^{91}Zr we have to consider that a value below 100 ps would exceed the $B(E3)$ Recommended Upper Limit of 100 W.u., while a value above 10 ns would have been noticed in the previous experiments with delayed coincidences using Germanium detectors. Thus one should expect something between 100 ps and 10 ns, the ideal range for in-beam fast timing technique using the ROSPHERE array in mixed HPGe-$LaBr_3$(Ce) configuration.

II. Experiment

The excited states in ^{91}Zr will be populated using the ^{82}Se(^{13}C,$4n$)^{91}Zr fusion-evaporation reaction. The cross sections for different exit channels were calculated using the CASCADE code, indicating about 400 mb for the $4n$ evaporation channel at 42 MeV beam energy, which represents ~80% from the total fusion cross-section. The target will be 5 mg/cm^2 ^{82}Se on 5 mg/cm^2 gold backing, dimensioned to integrate over the optimum energy range for producing the ^{91}Zr nucleus, from 34 to 42 MeV.

The gamma rays will be detected with the ROSPHERE array configured for in-beam fast timing, consisting in this case of 14 HPGe detectors and 11 $LaBr_3$(Ce) detectors. The high-resolution Ge detectors will be used to gate on the 859 keV transition (Fig. 1), and thus select in the scintillator detectors the decay γ-ray of 2170 keV from the $\frac{11}{2}^-$ state as STOP, and the 89.5 keV gamma-rays feeding this level as START.

As shown in our recent work [5], by using a special technique for the processing of the timing information from the $LaBr_3$(Ce) detectors, and thus fully use the detection efficiency by adding up the contribution from all the pairs of such detectors, we can measure precisely in this way half-lives down to 30–40 ps. In this particular case, special care must be taken with the $LaBr_3$(Ce) detectors to keep the amplitude linearity and to correct for CFD walk over a wide energy range, from ~80 keV up to 2.2 MeV.

III. Beamtime request.

Considering the following conditions:

- 42 MeV ^{13}C beam with intensity of 2 particle-nA to reduce the counting rate per crystal and the dead time of the DAQ;
- 5 mg/cm^2 ^{82}Se on 5 mg/cm^2 gold backing;
- an average ^{91}Zr production cross section of 250 mb inside the ^{82}Se layer;
- that 80% of the total gamma flux is passing through the yrast $\frac{21}{2}^+$ state and follows the cascade 859–89.5–2170 keV;

- efficiency of 0.012 for gamma-ray energies of about 900 keV of the HPGe array, and with the $LaBr_3$:Ce array 0.02 at 90 keV and 0.001 at 2.2 MeV;

we get a rate of about 80 triple Ge-LaBr-LaBr coincidences/hour (total full-energy peak coincidences), therefore in 8 days of beamtime we will get around 15000 events in the triple-gated time spectrum for the $\frac{11}{2}^- \rightarrow \frac{5}{2}^+$ transition. This level of statistics should be enough to obtain the desired lifetime with precision better than 10%.

We ask therefore 8 days of beam time to measure with accuracy better then 10% the lifetime of the yrast $\frac{11}{2}^-$ state in ^{91}Zr.

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