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Lifetime measurements in 50-52Ca , 46-48Ar, 43-45Cl

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Lifetimes in Ca isotopes: Large matter radii and halo-like neutron p-shells hypothesis in 50-52Ca: do we see evidence from spectroscopy?

Physics motivation

The large charge radii measured in 50-52Ca [Garcia] have proven a surprise from the experimental point of view, and a challenge for theoretical description. Not only laser spectroscopy has determined a large charge radius for 50-53Ca, but also the matter radii are very large compared to the standard R=1.2·A1/3 formula, and indeed the discrepancy is even more striking than for the charge radii [Tanaka]. Until now, two different hypotheses have been made to explain such a behavior [Nowacki]. A. Zuker and collaborators postulated the existence of large, halo-like neutron 1p3/2 and 1p1/2 orbitals in 50-54Ca which would in turn determine a large charge radius by isovector interaction [Bonnard]. In Ref. [Tanaka], the authors noted indeed that the orbitals should be as large as 6-7 fm (similar to the 11Li halo) to justify their measurement of matter radii. A second hypothesis is that the filling of the neutron 1p3/2 and 1p1/2 orbitals, which have a node and thus have a larger density of the center of the nucleus compared to 0f7/2 orbital, engenders a swelling of the 48Ca core when going from 48Ca to 54Ca [Horiuchi]. This would justify both the large charge and matter radii without the need of halo-like p-orbitals.

Discriminating between these two very different hypotheses is not easy, yet the difficulty in the description of the saturation properties of nuclei not so far from the stable doubly magic 48Ca demands prompt investigation. In particular, one may wonder if there are spectroscopic observables which could be sensitive to large neutron radii. We note here, that, at the first order, the electromagnetic transition in low lying 50-52Ca states involve the supposedly neutron-halo orbitals. The E2 operator connects (at leading order) different configurations:

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50Ca   B(E2; 2+->0+):  p3/2- p3/2

        50Ca   B(E2; 4+->2+):  p3/2- p1/2

        52Ca   B(E2; 2+->0+):  f5/2- p3/2
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Since B(E2) strengths scale with r4, a significant increase of the B(E2)s is expected. However, this effect is compensated for by opposite change in the E2 neutron change in effective charges. Nevertheless, the measurement of the 50,52Ca 4+ and 2+ half lives, respectively, will provide an essential benchmark for our understanding of the N=32 shell closure in terms of the shell model predictions.

While “neutron”E2 transition are not sensitive to nuclear radii, proton transitions are, as well as M1 transitions. For protons, their bare electric charge of 1e will preserve the r4 dependence of the B(E2): only the renormalization charge of 0.5e will scale as 1/ r4. For M1 transitions, a large orbital radius will mean M1 spin and orbital effective charges close to their bare value, and thus an increase of the B(M1) transition.

In 50Ca, the most interesting state is the second 2+, which is predicted to come from the p3/2-p1/2 coupling and it decays to the p3/2 first 2+ state. This is an allowed M1 p3/2->p1/2 transition which should be increased by 50% if the neutron spin effective charge has a value close to its bare one as a result of the large radius.

In 51Ca, the lifetimes of interest are those of the 1/2-, 5/2- and second 3/2- levels. Also the 7/2- ->5/2+ E1 transition is expected to be sensible to a large matter radius.

The physics case for the 46-47Ar nuclei : development of collectivity

The 46Ar isotope, located between the doubly magic 48Ca and the collective 44S nucleus, has challenged the existing shell-model description of nuclei in this region. While some observables related to the neutron contribution are well described by the theory, others, where the role of the proton is relevant, are not. In 46Ar, a shallow nuclear potential results in a moderate oblate ground-state deformation. The B(E2:2+ -> 0+) value was measured using intermediate Coulomb excitation [Gade] as well as extracted from the measured lifetime [Men], giving conflicting results, see Fig. 1 on the left part. The former smaller value is in agreement with time-dependent Hartree-Fock-Bogoliubov calculations that predict a strong N=28 shell gap in the 46Ar isotope. Conversely, shell-model calculations favor a larger B(E2), obtained from lifetime measurements, linking it to a quenching of the N=28 shell gap. Significantly, a Coulomb excitation measurement in 47Ar [Win] gives a B(E2:5/2+ -> 3/2+) value which is also not reproduced by shell model calculations, although the B(E2:2+ -> 0+) in 48Ar [Win] is well reproduced. The failure in predicting the B(E2) values is counterbalanced by the striking agreement with other obervables related to the neutron wave function, as detailed in Ref. [Mei]. In that work, the authors state that the neutron gap at N=28 is well reproduced by their shell-model calculations performed with SDPF interaction, since they predict Sn values in perfect agreement with mass measurements. In addition, the energy of the 2+ in 48Ar state is well reproduced and the state is interpreted to derive mainly from the valence neutrons and N=28-core breaking.

Recently, the first excited 0+ state has been measured in 46Ar using a (t,p) reaction [Now]. The observed state, as with other states involving a proton-neutron interaction, cannot be reproduced by shell model and there is a large difference among the predictions of the different interactions. The authors relate this problem to the monopole part of the tensor interaction nf7/2-πd3/2, which is the strongest among the T=0 cross-shell monopole terms. Indeed, the tensor part of the nuclear interaction, by causing a change in shell splitting, also plays a fundamental role for the quadrupole correlation of the protons in the sd shell and the neutrons in the pf shell. Subsequently, quadrupole correlations, together with the large fraction of neutron excitation across the N=28 gap, trigger the rapid transition from spherical to deformed shapes in 42Si, as pointed out in Ref. [Bha]. It is apparent that there is a need for measurements to clarify the role of protons in the excitation spectra and in the evolution of the shell below N=28.

The physics case for the 43-45Cl nuclei: towards 44S

The overestimation of the measured B(E2) by the SDPF-U Hamiltonian is not only present in 46Ar, but also in its lighter isotone 44S [Long]. In this regard, a measurement lifetime of excite states in 43-45Cl, particularly the 1/2+, 3/2+ first excited states as well se the 2+ core-coupled state, can provide a useful benchmark on the evolution of collectivity approaching the N=28 island of inversion.

Proposed Measurement

Ca isotopes

We propose to measure the lifetimes of the 50Ca 4+ , second 2+ states (and remeasure the 2+ as a cross-check) , the 52Ca 2+ state. In 51Ca, we propose to measure the lifetimes of the 1/2-, 5/2- and second 3/2- states. Also the 7/2- ->5/2+ transition will be measured. Nuclei will be populated by multi-nucleon transfer reproducing the same experimental conditions as in Ref. [Rejmund]. A 208Pb beam at 1.31 GeV will impinge on a 1 mg/cm2 48Ca target, mounted on a plunger device. PRISMA will be placed at the grazing angle for the inverse kinematics, i.e. 35 degrees as in the GANIL run. The 48Ca target will be sandwiched between two Au layers of 2 mg/cm2 each to prevent oxidation and enable stretchability for the plunger device. The differential plunger degrader will be made of 22Mg (93Nb is also a possibility).

Fig. 1: 50-52Ca populated in a multi-nucleon transfer reaction from Ref. [Rejmund]

Figure 1 show the level populated in the GANIL experiment. The 50Ca 4+ state is predicted to have lifetime of 0.3 ps, while the 52Ca 2+ state should have a lifetime of 0.9 ps (according to KB3G predictions with harmonic-oscillator wave functions). Since these lifetimes are at the limit of lunger capabilities, and they could turn out shorter if the p1/2 orbital has a large radius, we will add a thicker Au backing on the back of the 48Ca target in order to be able to perform DSAM measurements together with the differential plunger. Feeding to the 50Ca 4+ state is via a 595 keV E1: if one takes a similar 5- state in 48Ca (B(E1)=0.00012 Wu), a feeding lifetime of 0.3 ps is predicted. This will be measured and dealt with Bateman equations. A similar situation holds for the 52Ca lifetimes measurement, where the 3- state can feed the 2+ with a lifetime of 1.4 ps (rescaling from 48Ca 3-): also in this case the lifetime of the 3- state will be measured and a Bateman equation decay sequence reconstructed.

Concerning the expected statistics, AGATA will have an efficiency larger than that of EXOGAM in Ref. [Rejmund] at large gamma-ray energies (2-4 MeV), and similar at energies of 1 MeV and below. The P/T ratio will be very superior to EXOGAM thanks to the better Doppler reconstruction.

Considering the expected 50-52Ca production yield, obtained from the GANIL experiment, we propose to measure 14 days to have about 500 events in the 52Ca 2+ gamma-ray peak, and a thousand in the feeding transition. A similar estimate holds for the gamma-ray depopulating the 50Ca 4+ , second 2+ states: 800-1000 events should be collected for each level. This should allow one to measure the B(E2) of the states of interest with a 20% error at the maximum. Finally, the 51Ca lifetimes measurements will have on the order of few hundred counts per gamma-ray line, enabling the measurement of their lifetime.

46-48Ar

We plan to (re)measure the lifetime of the 2+ states in 46,48Ar, and of the single-particle and core-coupled states in 47Ar.

Cross sections from GRAZING are of the order of 1.4 mb and 0.25 mb for 46,48Ar, respectively. A hundred of gamma-ray events should be collected per day, allowing one to measure the lifetimes of the 2+ states and the 47Ar states within 14 days with the plunger technique.

44-45Cl

We plan to measure the 1/2+, 3/2+ first excited states as well se the 2+ core-coupled states 5/2+, 7/2+. Those states are typically well populated by multi nucleon transfer reactions.

Cross sections from GRAZING are of the order of 0.03 mb and 0.06 mb for 4,45Cl, respectively.

Several tens gamma-ray events shpuld be collected per day, allowing one to measure the lifetimes of the 2+ states and the 47Ar states within 14 days with the plunger technique.

Direct kinematics

Owing to the difficulty of producing a plunger 48Ca target, a direct kinematics is also considered. In this case, several different Brho setting of PRIMSA will be needed, since past measurement s at LNL show that the charge states of 52Ca and 50Ca cannot be accepted at the same time into PRISMA without suppressing important components of the charge state distribution of either of the two isotopes.

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