Symmetries in proton-rich nuclei seen through ground-state properties

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Light proton-rich nuclei are valuable objects to investigate various symmetries in atomic nuclei. Recent investigations of nuclear ground-state properties using laser spectroscopy and Penning-trap mass spectrometry performed at ISOLDE/CERN addressed the symmetries in multiple ways: Magnetic moments of ^{21}Mg and ^{17}Ne allowed studying the isospin symmetry. Charge radii of both isotopic chains revealed a wealth of geometrical phenomena, from proton halos to alpha-clustering, when adding only a few neutrons. The mass of ^{35}K gave evidence for a breakdown of the isobaric multiplet mass equation, related also to the isospin symmetry. Finally, the precise mass of ^{22}Mg contributed to the determination of the V_{ud} element of the CKM matrix.

SYMMETRIES PROBED VIA GROUND-STATE PROPERTIES

The ground-state properties of atomic nuclei, such as mass, charge radius, spin and electromagnetic moments are extremely valuable to investigate the nuclear structure when going away from the valley of beta stability. Among others, they can be used to probe various symmetries present in nuclei: geometrical symmetries (i.e. shapes) and, relevant especially for proton-rich and Z=N nuclei: isospin (proton-neutron) symmetries, as well as fundamental symmetries (e.g. in superallowed decays).

The geometrical symmetries are revealed in quadrupole moments or changes in charge radii. The isospin symmetry can be probed with masses by using the Isobaric-Mass-Multiplet Equation (IMME) [1,2] which connects the binding energies of the analog states within a given isospin multiplet. One can use this equation to predict the position of analog states and attribute configurations to observed states, or conversely to test IMME by searching for terms beyond the quadratic term. Isospin symmetry can be also investigated via the magnetic moments of mirror nuclei by representing the moments in the isospin space [3,4]. If the average of the two moments is used, only the iso-scalar moment of the mirror pair remains, based on which it is possible to determine the so called “spin expectation value”. This allows probing the isospin symmetry, comparing configurations of mirror nuclei, and testing terms which break isospin. Mass measurements, on the other hand, give also Q-beta values of the superallowed 0^+->0^+ β-decays, which lead to the corrected comparative half-lives Ft [5]. These in turn can be used to test the conserved-vector-current (CVC) hypothesis and the unitarity of the CKM quark mixing matrix via the V_{ud} matrix element. Inversely, when assuming that the CKM matrix is unitary, tests of nuclear-structure corrections in the determination of Ft are possible [5].

EXPERIMENTAL TECHNIQUES

The main experimental methods devoted to studies of nuclear ground-state properties make use of atomic physics. They use Penning traps to measure atomic masses and laser spectroscopy to determine the nuclear electromagnetic properties.

The results discussed below were obtained at the ISOLDE facility at CERN [6]. Here, proton bunches of 1.4GeV energy impinge on thick targets to produce a large variety of radionuclides via spallation, fragmentation, and fission reactions. The produced atoms are then ionized, extracted and accelerated to 30-60keV and mass separated, before they reach the given experimental setup.

In the collinear laser spectroscopy (used at ISOLDE within the COLLAPS setup [7]) the ion beam is overlapped with a narrow-band cw laser which allows scanning across atomic resonances. The resulting precise measurements of hyperfine structures and isotope shifts give then access to the nuclear spin, magnetic and quadrupole moment, and differences in charge radii. The usual detection method is by fluorescence, but to optimize the signal to noise ratio, element- or isotope-specific methods are employed.

The other atomic method relies on Penning traps which give access to atomic masses of exotic nuclei, with ISOLTRAP [8] at ISOLDE being the pioneer in this field. Inside the trap, the ions are manipulated by rf fields which can purify isobaric, and even isomeric contamination. Finally, by determining the ion's cyclotron frequency, the atomic mass can be measured with up to (or even beyond) 10^{-8} relative precision.

RECENT RESULTS IN SYMMETRY STUDIES

The first example of symmetries accessible with proton-rich nuclei concerns geometrical symmetries seen in the charge radii and quadrupole moments. Using the COLLAPS setup, charge of Ne and Mg isotopes were recently investigated (Fig. 1). These reveal a wealth of phenomena. In the Ne chain one sees the onset of proton-halo formation in ^{17}Ne, the closed neutron shell in ^{18}Ne, clustering in $^{19-22}$Ne, and appearance of a new shell closure at N=14 [9]. For Mg isotopes, with two more protons than Ne, similar structures can be observed: clustering around ^{24}Mg, new shell closure N=14 or 16 and no closure at N=20 in the region of the island of inversion [10].

The isospin symmetry was tested at COLLAPS with the magnetic moment of ^{17}Ne and ^{21}Mg. In both cases the resulting isoscalar moments were compared to the extreme single-particle prediction and to the nuclear shell-model calculations (Fig 1). For ^{17}Ne-^{17}N, the determined isoscalar spin expectation value was within the empirical limit of unity given by the Schmidt values of the magnetic moments [11]. For ^{21}Mg-^{21}F it was significantly outside, but shell-model calculations taking into account isospin non-conserving effects were still in agreement with experimental results [12].

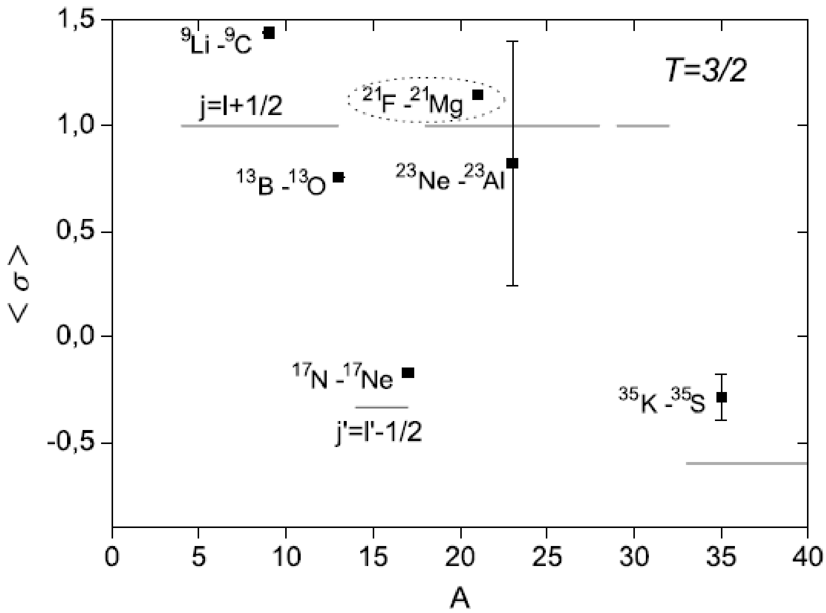

Fig. 1 Isoscalar moments for mirror pairs of the isospin 3/2 multiplet

The isospin symmetry has been also tested with mass measurements at ISOLTRAP. The measurement of ^{35}K gave evidence for a breakdown of the isobaric multiplet mass equation for the T = 3/2 isospin quartet. The non-zero cubic term in IMME showed the need of 2nd-order Coulomb effects, charge-dependent nucleon-nucleon interaction or many-body forces [13].

The last example was the mass of ^{22}Mg superallowed beta emitter, which led to the determination of the comparative half-life Ft, which agrees very well with other known cases [14]. ^{22}Mg belongs to superallowed beta emitters which require quite large nuclear-structure-dependent corrections and it is presently one of four best studied cases. Presently all measured cases are consistent with unitarity of the CKM matrix [15].

SUMMARY AND OUTLOOK

Ground-state properties on proton-rich nuclei are relevant (among others) for several symmetry questions, concerning isospin, shapes, or fundamental symmetries. The experimental studies in this area are lead by employing atomic physics methods, laser spectroscopy and Penning trap mass spectrometry, which give access to several properties at the same time (spins, radii, moments). Recent results from ISOLDE show how the symmetries were studied on relatively light systems, in Ne, Mg, and K chains.

In the future even more exotic proton-rich systems should be available, thanks to technical developments on the target and ion source side (more efficient ionization; new ISOL beams – B, C, O; new facilities) and due to increased sensitivity (thanks to bunched beams, ion-photon coincidence, new ion purifiers). This will give us access to ground-state properties of nuclei as ^{8}B, ^{9}C, ^{13}O, or ^{20}Mg.

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