Approaching ^{100}Sn in Decay Studies

The doubly magic region based on ^{100}Sn is an ideal testing ground for nuclear structure theory. Ernst Roeckl from GSI, Darmstadt, reviews progress in understanding the region and estimating whether or not ^{100}Sn can be synthesized in the near future.

An important part of today's nuclear structure physics is devoted to the study of "exotic" nuclei [1, 2] characterized by strong deviations of the proton number Z, the neutron number N, or the Z/N ratio from the corresponding values for stable nuclei occurring in Nature. This interest arises because exotic nuclei exhibit unusual properties such as new decay modes, extraordinarily large decay energies (Q values), "halo" structures of loosely bound nucleons, and new, magic nucleon numbers. The term "magic" indicates enhanced nuclear binding compared to the average value observed for neighbouring nuclei, this effect being explained by the nuclear-shell model.

The study of exotic nuclei allows one to gain new insights into both nuclear structure and astrophysical aspects. This is especially valid for very proton-rich heavy nuclei with $Z \approx N$ all the way to the doubly-magic nucleus ^{100}Sn ($Z = N = 50$) and beyond. For isotopes with odd atomic numbers A and $A \geq 70$, these nuclei lie at the "proton-drip line" beyond which they are no longer bound against prompt emission of protons. Furthermore, this region represents the termination of the astrophysical rp-process, and shows exceptionally interesting nuclear structure phenomena due to the fact that protons and neutrons occupy identical or energetically close-lying shell-model orbits. Such phenomena include, for example, the unexpected strong deformation of ^{76}Sr, ^{80}Zr and ^{84}Mo and the rapid $\pi g_{9/2}$ to $\nu g_{7/2}$ beta transitions near ^{100}Sn.

One of the most successful models used for comparing theoretical predictions with the measured properties of exotic nuclei is the *macroscopic-microscopic* approach. It starts from a liquid-drop type (macroscopic) description and includes a (microscopic) shell correction. The latter, calculated on the basis of such a model, is displayed on the front cover. Verifying predictions by determining the ground-state binding energy (or mass) of nuclei with Z, $N \approx 50$ is experimentally very challenging. For although this region of the chart of nuclides shown on the cover is a "well-known doubly magic region", its core at ^{100}Sn has not been reached so far in experiments; the few-nucleon excitation states around the core are also poorly known. It is clear, however, that the Z, $N = 50$ region represents an ideal testing ground for the spherical shell-model which allows one to interpret features such as decay properties and excited-state configurations.

The present experimental status for $Z \approx N$ nuclei in the strontium-to-tin region (see figure) is based almost exclusively on measurements performed using recoil separators or isotope separators on-line (ISOL). In most of the relevant ISOL experiments, the proton-rich isotopes were produced by fusion-evaporation reactions such as ^{50}Cr (^{58}Ni, *xpyn*) and mass-separated as singly-charged 60 keV beams for subsequent decay studies. Note in particular that beyond ^{100}Sn, both alpha-radioactive and proton-radioactive nuclei have been observed recently.

In considering progress in understanding the region near ^{100}Sn and estimating whether or not this doubly-magic nucleus can be synthesized in the near future, I shall review the status of charged-particle and β-decay studies, before outlining possibilities arising from applying alternative methods such as in-beam γ-ray spectroscopy and isotope identification of products from high-energy fragmentation reactions.

Emission of Charged Particles

The decay of nuclear ground states by the emission of alpha particles, protons or clusters plays an important rôle in studying nuclei far from stability. Alpha-decay data (Q_α; total half-life branching ratio of alpha emission) can be measured rather easily (high detection probability, good energy resolution, low background), allowing one to identify rare nuclei, to determine their mass by "linking" the measured Q_α values to known masses, and to deduce information about the alpha-emitting ground state and/or the daughter state from the measured alpha width [3].

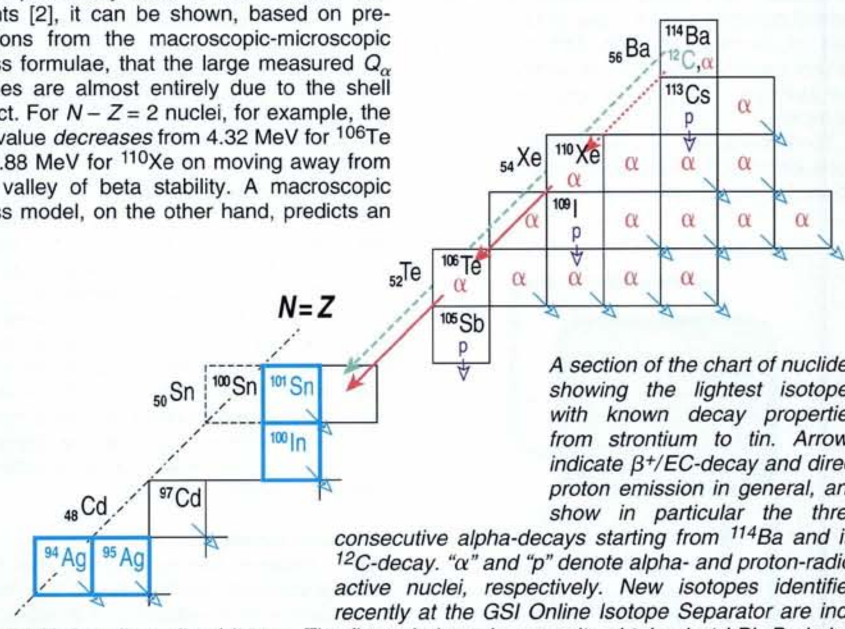
Alpha radioactivity

The region of neutron-deficient isotopes above tin is well suited for discussing the interplay between alpha, proton and cluster radioactivity (see figure). The occurrence of an island of alpha emission between ^{106}Te and ^{114}Cs is the most convincing experimental proof of a shell closure at $Z = 50$ and $N = 50$. In line with conclusions drawn from the alpha-decay data of the heaviest elements [2], it can be shown, based on predictions from the macroscopic-microscopic mass formulae, that the large measured Q_α values are almost entirely due to the shell effect. For $N - Z = 2$ nuclei, for example, the Q_α value *decreases* from 4.32 MeV for ^{106}Te to 3.88 MeV for ^{110}Xe on moving away from the valley of beta stability. A macroscopic mass model, on the other hand, predicts an *increase* from approximately 1.1 to 1.4 MeV. Another result of the alpha-decay studies in this region is that the alpha widths measured so far, namely those of ^{106}Te and ^{110}Xe, do not support the idea of so-called super-allowed alpha-decay of these nuclei — a speculation based on the assumption that protons and neutrons occupy identical shell-model states.

Proton and cluster radioactivity

The double shell-closure at ^{100}Sn also gives rise to two other ground-state decay modes. One of them is *proton radioactivity* [4], experimentally identified for ^{105}Sb, ^{109}I and ^{113}Cs. It is interesting to note that the spectroscopic factor determined for the proton decay of ^{109}I and ^{113}Cs is less than unity, which is interpreted as reflecting different deformations of mother and daughter states [4]. Another exotic decay mode in the region above ^{100}Sn is the ^{12}C decay *(cluster radioactivity)* of ^{114}Ba. This decay is predicted to occur with a branching ratio b_c between 10^{-3} and 10^{-10}. The predicted b_c value depends strongly on the assumed Q value for ^{12}C decay (this Q value could in principle be determined experimentally by detecting the alpha-decay of the so far unidentified isotope ^{114}Ba and combining the measured Q_α value with the values for ^{110}Xe and ^{106}Te). In a first experiment, an upper limit to b_c of 10^{-4} has been estimated. It would be interesting to further investigate ^{114}Ba situated on this "new island of cluster radioactivity", as all the data for the cluster mode of nuclear decay are restricted to nuclei above Pb.

In conclusion, one should note that the Q values measured for alpha and proton decay, together with those from β^+/EC-decay discussed below, can be used as "mass links". This method enables one to deduce the ground-state mass of very proton-rich nuclei near ^{100}Sn. These masses has been determined, for instance, for the proton-unbound nuclei ^{109}I and ^{113}Cs with an accuracy of ±140 keV [5]. Even though these



A section of the chart of nuclides showing the lightest isotopes with known decay properties from strontium to tin. Arrows indicate β+/EC-decay and direct proton emission in general, and show in particular the three consecutive alpha-decays starting from ^{114}Ba and its ^{12}C-decay. "α" and "p" denote alpha- and proton-radioactive nuclei, respectively. New isotopes identified recently at the GSI Online Isotope Separator are indicated with heavily outlined boxes. The figure is based on results obtained at LBL Berkeley, NSCL Daresbury, GSI Darmstadt, JINR Dubna, CERN Geneva, and TU Munich. It includes unpublished data on ^{94}Ag, the heaviest N = Z nucleus known to date, on ^{101}Sn, the closest experimental approach to ^{100}Sn achieved so far, and on the proton-radioactive nucleus ^{105}Sb [R.G. Tighe, preprint (1993)].

measurements have not quite reached ^{100}Sn, they represent already a firm basis for testing mass formulae far from stability.

Beta Decay Near ^{100}Sn

The region near ^{100}Sn has been discussed so far as a case of an interesting interplay between different charged-particle disintegration modes. However, it has also recently been the subject of an intense programme of β-decay studies [6]. The conceptually interesting feature of this region is that β-decay of nuclei is dominated by a $\pi g_{9/2}$ to $\nu g_{7/2}$ Gamow-Teller (GT) transition. Correspondingly, such experiments allow one to compare the GT strength distribution, even with low source strengths, with model predictions. I shall consider some recent results of β-decay studies using the ISOL systems at CERN and at GSI.

Even-even nuclei

The decay of even-even nuclei such as ^{98}Cd [7] is characterized by the feeding of several 1^+ levels in the odd-odd daughter nuclei instead of one $1^+\{\pi g_{9/2}^{-1}, \nu g_{7/2}\}$ state as expected from the extreme single-particle shell model. The excitation energy of the observed 1^+ states ranges from 1.7 to 2.5 MeV, in rough agreement with what is expected from shell-model considerations for the two-quasiparticle state. The splitting of the GT strength has been interpreted as being due to residual $\pi g_{9/2} - \nu g_{7/2}$ interactions. Part of the GT strength is missed by the experiment because of the decay energy window combined with the limited experimental sensitivity. An additional reduction is caused by core polarization effects in the parent nuclei. However, even when all calculated hindrance factors are taken into account, part of the GT strength still seems to be missing when comparing theoretical values to the experimental data for N = 50 isotones. The question is whether the nuclear structure and the experimental limitations are understood well enough to assign at least part of this missing strength to subnucleonic effects.

Even-odd nuclei

The decay of even-odd nuclei such as ^{105}Sn is governed by a resonance-like beta-strength function whose maximum, at an excitation energy of approximately 3.3 MeV in the odd-even daughter nuclei, might be ascribed to the coupling of an odd $d_{5/2}$ neutron to the GT pair $1^+\{\pi g_{9/2}^{-1}, \nu g_{7/2}\}$.

Odd-odd nuclei

Whereas high-resolution germanium detectors were used to obtain the β-decay data described so far, a total-absorption γ-ray spectrometer was recently employed to study the decay of odd-odd nuclei, namely ^{100}Ag and ^{104}In. Here one expects the dominant population of the four-quasiparticle structure to be at an excitation energy of the order of 5 MeV in the final even-even nuclei, consisting of a GT pair $1^+\{\pi g_{9/2}^{-1}, \nu g_{7/2}\}$ from the respective core decay coupled to the spectator particles, *i.e.*, the odd $d_{5/2}$ neutron and the odd $g_{9/2}$ proton. Indeed, the results obtained for the decay of ^{100}Ag and ^{104}In indicate such a dominant four-quasiparticle component of the strength distribution.

One should note that, besides these studies of beta-delayed γ-rays, progress in the ^{100}Sn region has also been made by investigating beta-delayed protons. The case of ^{101}Sn has already been mentioned. Beta-delayed protons have also been measured for the decays of $^{100,102}In$ and $^{103,105}Sn$, which may help, together with high-resolution γ-ray information and total-absorption γ-ray data, to clarify GT decay in the ^{100}Sn region.

In summary [8]: "Studies of GT beta decay, particularly near the exotic (and elusive) ^{100}Sn..., are challenging current dogma on the renormalization of the weak axialvector coupling constant in nuclei and, as always, are pushing our need for comprehensive calculations that will enable us to distinguish renormalization effects from inadequacies in model calculations of nuclear wavefunctions".

A Positive Future

The study of alpha-, proton- and beta-decay near ^{100}Sn, which has made considerable progress recently, is a continuing programme. Its success depends crucially upon the development of experimental methods that include, in the case of ISOL experiments, the development of rapid, efficient and chemically selective ion sources, the application of total-absorption γ-ray spectroscopy, and the search for cluster decay. The results summarised above form a solid basis for continuing these experiments.

Radioactive beams

One may ask whether reactions induced by radioactive beams represent an interesting alternative for decay investigations, *i.e.*, whether, for example, a fusion-evaporation reaction such as $^{58}Ni(^{46}Cr, 2p2n)^{100}Sn$ would yield higher ^{100}Sn rates. However, both the intensity of a hypothetical 5 MeV/u beam of ^{46}Cr (half-life of 0.26 s) and the (2p,2n) production cross-section are not known well enough to give reasonable estimates of rates. Furthermore, what counts is not only the intensity of the ^{100}Sn beam after separation (that is, the product of primary beam intensity, effective target thickness, production cross-section, and separation efficiency), but also the atomic number A- and Z-selectivity of the ISOL or recoil separation method which is adopted. Since post-acceleration or deceleration methods for 5 MeV/u radioactive beams, as well as the related experimental techniques, are in their infancy, the suitability of the radioactive beam method for approaching ^{100}Sn remains open.

In-beam γ-ray spectroscopy

In-beam γ-ray spectroscopy, which uses fusion-evaporation reactions such as ^{58}Ni + ^{50}Cr and is thus on similar experimental grounds to most of the work discussed here, represents a competitive option for nuclear structure studies near ^{100}Sn. The most proton-rich nuclei in this region which have been investigated [9] are ^{96}Pd, ^{97}Ag, ^{100}Cd, ^{102}In, and ^{104}Sn. Briefly, one can say that the similarity to decay studies concerns the importance of technical developments; in other words, the application of advanced detector arrays such OSIRIS, NORDBALL and maybe EUROGAM and EUROBALL in the future, as well as the possible use of radioactive beams.

Heavy-ion beams

With regard to the wealth of interesting nuclear physics phenomena encountered "on the way" to ^{100}Sn, one may conclude that it is better to journey than to arrive. For it is interesting to note that intermediate-energy or relativistic heavy-ion beams seem to be promising new tools for approaching ^{100}Sn. Experiments using fragmentation reactions of ^{112}Sn and ^{124}Xe beams are underway at GANIL and GSI, respectively. Sufficiently high production rates of ^{100}Sn are expected to allow an unambiguous in-flight isotope identification and maybe even a half-life measurement. The long-sought for doubly-magic nucleus ^{100}Sn may thus soon be reached.

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