Spectroscopy of Very Heavy Elements

The heaviest elements provide a unique laboratory to study nuclear structure and nuclear dynamics under the influence of large Coulomb forces and large mass (A).
The spectroscopy of VHE elements has made great progress in recent years thanks to the use of efficient detector arrays around the target position and at the focal plane of recoil separators. The data, although scarce, have shed light on some theoretical weaknesses. For e.g. there exists now a rather clear disagreement between the predictions of shell positioning obtained from all existing effective interactions/energy density functionals and experiment.
Hence, the systematic study of the stability and decay properties of deformed transfermium elements is essential, and probably for many years, the only available way to reach an understanding of the structure at the upper end of the nuclear chart.

This lecture will be organized in 6 parts.

<u>I Introduction</u>

In the first part, I will set the scene and give the theoretical and experimental motivations for performing spectroscopic studies of very heavy elements.

<u>II Experimental Methods</u>

The experimental methods used to produce and study the nuclei of interest will be presented in the 2nd part of the lecture. Studies involving transfer reactions on relatively long-lived heavy species are hindered by a lack of suitable targets. Another more widely spread method to populate the nuclei of interest is via heavy–ion fusion evaporation (HI,xn) reactions with gas–jet transport systems or in-flight recoil separators.
Spectroscopic studies of very heavy elements have recently seen intense activity in two distinct directions, which will be presented in detail:

1. Isomeric, and, or, decay spectroscopy at the focal plane of the recoil separator and,
2. Prompt in–beam spectroscopy at the target position exploiting the recoil decay tagging (RDT) method

<u>III Existing Facilities</u>

The 3rd part of the course will be dedicated to a virtual tour of the world's facilities, visiting the FLNR laboratory in Dubna (Russia), the University of Jyväskylä (Finland), GSI (Germany), JAEA and RIKEN laboratories (Japan), Argonne National Laboratory (USA), GANIL (France) and the Lawrence Berkeley National Laboratory (USA).

<u>IV Fine Structure Alpha Spectroscopy</u>

Historically the first, this technique, combined with the coincident detection of photons and conversion electrons, is an experimentally clean and powerful tool to determine the low-lying structure of odd-even or even-odd nuclei. Here, the decay mechanism favours decays between states with similar single-particle structure, and assignments can be made on the basis of the observed hindrance factors along alpha-decay chains. The complex example of ^{255}Lr will be presented as well as the cases of ^{253,255,257}No and ^{257,261}Rf, with special emphasis on systematic trends and the greater significance of the nuclear structure results. The decay of ^{255}No will serve to illustrate the experimental problem of summing whereas the story of ^{257}Rf will illustrate the tricky business of isomers.

V Isomer Decay spectroscopy

The 5th part of this course will start off with an introduction to calorimetric technique of isomer tagging. This technique will then be applied to study of the decay of K=8- states in N=150, which are well understood in terms of 2 quasi-neutron excitations. The controversial situation of K=8- states in N=152 isotones will also be presented and its repercussions on the interpretation of the ^{255}Lr data. Finally, the mystery of the missing long-lived K-isomer in ^{256}Rf will be discussed.
The decay of high-K isomers is also very interesting in that it populates non-yrast structures, which suddenly become accessible and which can therefore be systematically studied.

VI Prompt Spectroscopy Results

The 6th part of the lecture deals with prompt in-beam spectroscopy. This part will be articulated around 4 main themes:

1- Rotational properties of even-even nuclei starting with the first and most striking example, ^{254}No, and going on to present the accumulated knowledge in the region in terms of moments of inertia and 2+ energies and comparing the experimental results to theoretical calculations ,
2- Studies of strongly coupled bands in odd-even or even-odd nuclei with the textbook example of ^{251}Md and the heaviest example of ^{255}Lr. The “problematic case” of ^{253}No will be discussed in the light of combined photon and electron data.
3- Rotational structures built on multi-particle states of the nucleus and in particular high-K isomers, whose intensity patterns can be revealing of the underlying quasi-particle structure of the isomer and can provide crucial complementary information to the one obtained from isomer decay spectroscopy.
4- Calorimetric studies, solely performed at GAMMASPHERE, in which the total energy and the total number of photons emitted by the nucleus are measured and which give an experimental measure of the saddle point energy as a function of spin. So far, only ^{254}No has been studied in such a way.

VII Perspectives

The last part of the course will focus on the perspectives lying ahead with the development of new instrumentation and the advent of new accelerators.