Spectroscopy Far from Regions of Nuclear Stability—a Made-to-Order Challenge for the LOHENGRIN Spectrometer

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Introduction
The main task in future low-energy nuclear science is now clearly visible. In recent years experiments have revealed that present nuclear models, which turned out to be so successful near the stability line, can probably not be directly transposed to regions of very neutron-rich isotopes. In particular in lighter nuclei strong deviations from the "standard" nuclear physics view appeared; lighter neutron-rich species have been shown to possess neutron halos and neutron skins, features which are not known near the valley of stability [1]. The accumulation of neutrons on the nuclear surface is in turn thought to be responsible for the alteration of standard parameters used to calculate the properties of nuclei, depths of the central potential, spin-orbit force, pairing [2]. These parameters are crucial for the calculation of the nucleus. They determine where magic numbers are located and how strongly the nucleus is bound. Recent measurements have shown evidence for the disappearance of shell structure in the N=20 magic nuclei, and the reason is very likely the change of shell-model parameters, due to strong neutron excess.

To understand the nuclear structure of neutron-rich isotopes is not only an intellectual challenge restraint to the nucleus itself, but to a large extent determines our understanding of the macroscopic world. About half of the heavy elements found in the solar system were created by a process where in a stellar explosion neutrons are rapidly captured onto a seed nucleus up to a point, where (n,T) and (n,2n) reactions are in equilibrium [3]. Here the process is brought to a halt, and the neutron-rich specimen has to wait for β-decay, before neutron capture can start again. Famous waiting point nuclei, such as 82Zn and 135Cd, all lie in the closest neighborhoods of the doubly-magic neutron-rich nuclei 78Ni and 132Sn. The r-process proceeds along this path, where nuclei are located in the far neutron-rich side of the nuclear chart, Figure 1.

Few reactions are available to probe the r-process line in the laboratory. The most promising way to produce the nuclei is by neutron-induced fission. Here, by chance, fission products have appreciable yield on the r-process path. In order to understand the phenomenon of r-process burning, the following questions have to be addressed:

a) Where is the exact location of the r-process path?
b) At the end of the r-process path the nuclei fission: what is the contribution of fission to the solar abundance curve above mass A=80?
c) What are the stellar conditions ensuring r-process burning, in terms of neutron densities, temperatures and timescales?

The last question is answered by astrophysics, and depends largely on how well cosmological and astrophysical models work. Questions a and b are addressed by nuclear structure investigation and by our understanding of the fission process. Knowledge on these items is obtained from ground-state and excited-state properties of nuclei far outside stability, their electromagnetic decay characteristics, and hadronic decay modes, e.g. delayed neutron emission. The LOHENGRIN spectrometer at the ILL is an ideal instrument to investigate questions a and b. It is possible to sample the fission process in detail and to try to describe this process correctly. Of equal importance, the instrument delivers the right species along the magic numbers where the r-process path operates. This gives the possibility for experiments addressing question b.

The LOHENGRIN spectrometer
LOHENGRIN occupies the beam tube H9 of the ILL high flux reactor, Figure 2. The main components of the instrument are a magnetic dipole field and an electric condenser field which deflect a fission product beam originating from a thin fissile target at its in-pile position, with a thermal flux of 5 x 10^14 neutrons/cm^2/s [4]. Fission rates at the source are at a level of 10^15 s^-1.

The separating fields of the spectrometer act as a velocity filter. Neutron-rich isotopes with the same mass and kinetic energy are selected by the proper field setting. A double focusing of the particles is achieved by the fringing fields have been added to the spectrometer: A focusing magnetic dipole field and an electric condenser field which deflect a fission product beam originating from a thin fissile target at its in-pile position, with a thermal flux of 5 x 10^14 neutrons/cm^2/s [4]. Fission rates at the source are at a level of 10^15 s^-1.

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first time in these experiments to measure the mass and charge of fission fragments up to the symmetry point, which for this compound system is \( \{A=125, Z=48\} \) \([6]\). The experiment enabled us, with assumptions about excitation energy and spin distribution of the fission fragments, to reconstruct the mass and charge spectrum for the heavy wing. It was shown that with this target the region around \( ^{132}\text{Sn} \) is well populated. The location of single particle states near magic numbers constitute the key input for shell-model calculations. It determines, together with the \( \beta \)-decay half-lives which nuclei, aside of the main path, are contributing to the \( \gamma \)-process network. To proceed towards this line of research a neutron detector was designed and constructed. First measurements showed an efficiency of about 15 percent.

**Figure 2.** The LOHENGRIN electromagnetic fission-fragment spectrometer.

In passing the \( \beta \)-process line, neutron-binding energies drop significantly and allow for delayed neutron emission. Data on this process are equally important for \( \gamma \)-process calculations. It determines, together with the \( \beta \)-decay half-lives which nuclei, aside of the main path, are contributing to the \( \gamma \)-process network. To proceed towards this line of research a neutron detector was designed and constructed. First measurements showed an efficiency of about 15 percent.

**Figure 3.** \( \gamma \)-ray- and conversion-electron spectra of the isomeric decays in \( ^{132}\text{Sb} \).

The quest for a multidetector set up \( \gamma \)-ray spectroscopy of neutron-rich isotopes is quite straightforward at LOHENGRIN, and a couple of experiments have been performed with relevance to the \( \gamma \)-process phenomenon. Further spectroscopic work in the nickel and Ni=50 region, as well as in the Ni=82 region demands a higher sensitivity than presently available. Therefore a collaboration has started with the European Miniball Consortium to obtain more germanium detectors for experiments. This will not only increase the sensitivity of the measurements, but will enable us to specify better the states by determining the electromagnetic radiation via angular correlation work. Furthermore the lifetime of the states accessible with LOHENGRIN directly allows the application of a magnetic dipole field to precess the spin vector of the nuclear state and to determine the wavefunction of the \( \gamma \)-states in terms of neutron or proton excitations. Hints of disappearing shell gaps have already been seen by magnetic moment measurements in the neutron-rich mass 150 region \([10]\).

**References**