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 shells 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,γ) and (γ,n) reactions are in equilibrium (*r*-process) [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 ^{80}Zn and ^{130}Cd, all lie in the closest neighborhoods of the doubly-magic neutron-rich nuclei ^{78}Ni and ^{132}Sn. 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.

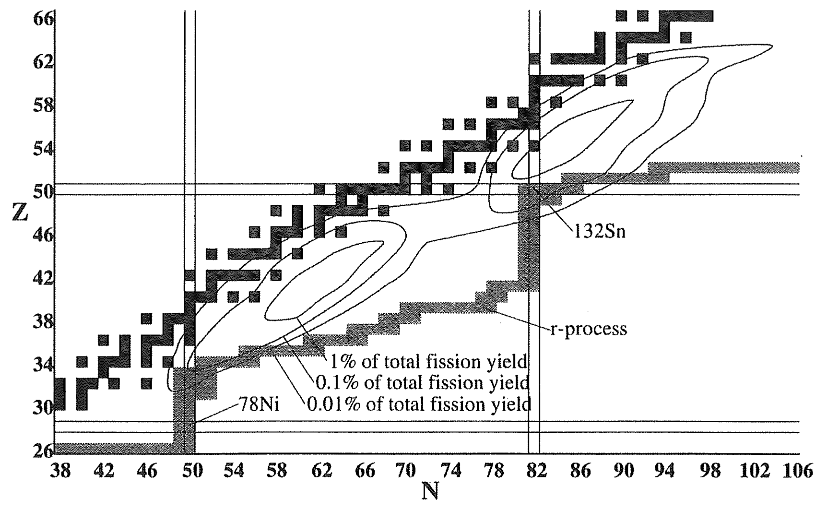

Figure 1. The intermediate mass region of the nuclear landscape. The strongest yield of nuclei produced by the neutron-induced fission of ^{245}Cm at LOHENGRIN are shown.

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 condensor field which deflect a fission product beam originating from a thin fissile target at an in-pile position, with a thermal flux of 5 x 10^{14} n/cm^2/s [4]. Fission rates at the source are at a level of 10^{11}/s.

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 field characteristics, and count rates in the detectors are of order of 3000/s for the most abundant isotopes produced by the fission reaction. In the last few years some considerable improvements have been achieved. Two additional fields have been added to the spectrometer. A focusing magnet enhances the particle density at the focal position by a factor of seven, and an electrostatic deflector field allows chopping of the particle beam down to 100 μs periods. Beam chopping is in particular needed for lifetime measurements and delayed neutron experiments. These improvements considerably enhance the possibility to perform experiments on γ-, conversion-electron- and neutron decay of nuclei on the *r*-process path and beyond.

Spectroscopic investigation along magic numbers

r-process physics deals mostly with the investigation of nuclei along magic numbers in the neutron-rich regions above ^{56}Fe, which is the seed nucleus for this process. The reason is that along magic proton numbers lifetimes are long, due to increased binding, which gives ample time to proceed with neutron capture before any β-decay may interrupt the chain. Whenever a chain with a magic neutron-number is reached, neutron capture is inhibited because neutron binding energies rapidly drop to a level where (γ,n) reactions in the hot *r*-process environment destroy the neutron-rich species.

Nickel isotopes with Z=28 are magic, and constitute the beginning of the *r*-process path. When the doubly magic ^{78}Ni is reached, the *r*-process has to climb up the N=50 magic line. Nuclei in this region were investigated at LOHENGRIN, and the experiment showed that, despite the very low fission yield for this mass region, the sensitivity of the spectrometer allows for β-spectroscopic investigations. Subsequently ground-state lifetimes have been measured by (f,β) delayed coincidences [5].

Climbing up the N=50 neutron shell, the intensities from fission strongly increase, and detailed γ- and β-spectroscopy is planned in the near future. Also the search for the doubly magic nucleus ^{78}Ni, which is important for our understanding of the shell model far outside stability, has begun.

Fission yield and spectroscopy around doubly-magic ^{132}Sn

As well as ^{78}Ni at the beginning of the light fission product region, ^{132}Sn at the start of the heavy fragment region is a central point for both *r*-process calculations and our understanding of neutron-rich nuclei. The *r*-process here climbs up the N=82 shell to ^{132}Sn before proceeding to heavier elements. Besides ^{78}Ni, the doubly-magic tin is the second very neutron-rich isotope which enables us to test model parameters for these species.

^{132}Sn is near to the symmetric fission valley and here the use of heavier compound systems is preferable to produce fission fragments in this region. Yield measurements from a ^{245}Cm target were done, and it was possible for the

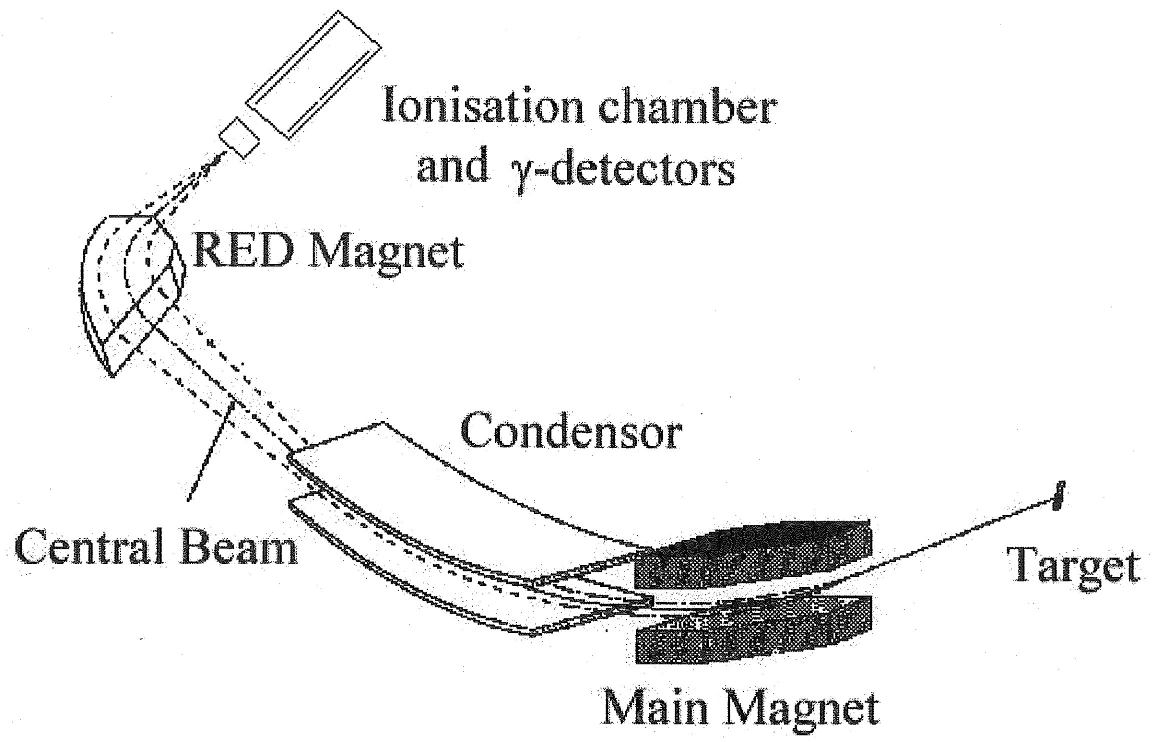

Figure 2. The LOHENGRIN electromagnetic fission-fragment spectrometer.

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=123, Z=48) [6]. The experiment enabled us, with assumptions about excitation energy and spin distribution of the fission fragments, to reconstitute the mass and charge spectrum for the heavy wing. It was shown that with this target the region around ^{132}Sn is well populated.

The location of single particle states near magic numbers constitute the key input for shell-model calculations. It is important to perform detailed spectroscopy around doubly-magic nuclei to sample shell-model states across the gaps. A complete set of *sp*-states leads directly to the value of the spin-orbit term and the residual interactions. Due to the presence of high orbital angular momentum single particle states near closed shells, many nuclei show spin isomers with level lifetimes above 1 μs. These states are directly populated in the fission reaction and can, due to short transition times in the spectrometer, be directly investigated at the LOHENGRIN instrument.

A typical spectrum for a direct neighbor of ^{132}Sn, namely ^{131}Sb is shown in Figure 3. The measurement of conversion-electron- and β-decay here allowed the construction of the nuclear level scheme. Three isomers have been identified in this nucleus, and the levels could be well reproduced with a standard shell model calculation [7]. Subsequent experiments in this region have allowed a complete systematic of microsecond spin isomers along the tin chain to be made [8] and have investigated ^{130,132}Te and ^{134}Xe [9].

The quest for a multidetector set up

γ-ray spectroscopy of neutron-rich isotopes is quite straightforward at LOHENGRIN, and a couple of experiments have been performed with relevance to the *r*-process phenomenon. Further spectroscopic work in the nickel and N=50 region, as well as in the N=82 region demands a higher sensitivity than presently available. Therefore a collaboration has been 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 *sp*-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].

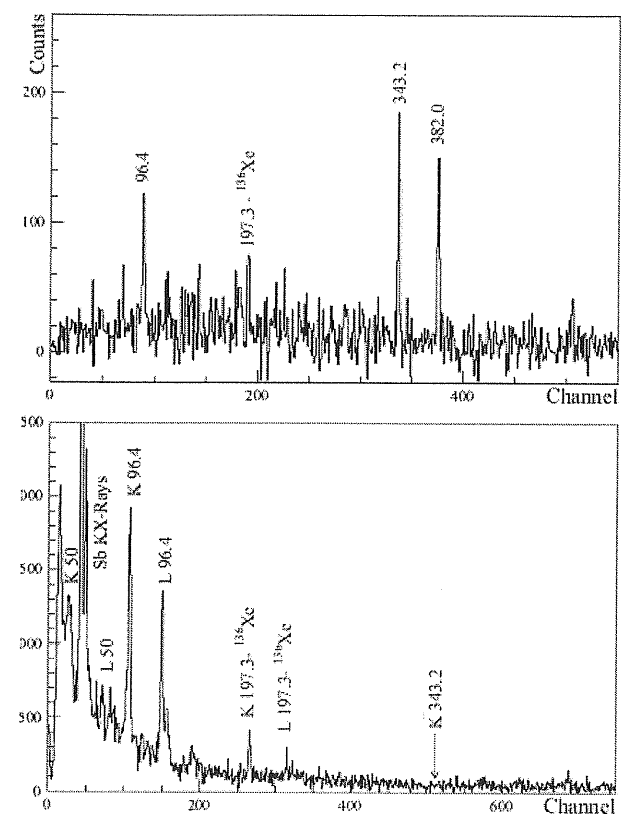

Figure 3. γ-ray- and conversion-electron spectra of the isomeric decays in ^{131}Sb.

In passing the *r*-process line, neutron-binding energies drop significantly and allow for delayed neutron emission. Data on this process are equally important for *r*-process calculations. It determines, together with the β-decay half-lives which nuclei, aside of the main path, are contributing to the *r*-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.

Conclusion

It has been shown in previous years that LOHENGRIN is highly competitive with other existing radioactive beam facilities for investigating nuclei on the far neutron-rich side of the nuclear map. Here intriguing features such as the existence of neutron-rich nuclear surfaces and the disappearance of shell gaps point to mechanisms that are not present near to the stability region. The consequences of these phenomena for our understanding of how elements are created in the solar system are considerable and need to be understood.

Quite low intensities for most nuclear species along the *r*-process line demand increased sensitivity of the experimental set up, so that nuclear properties can be well investigated.

The modernization program on the LOHENGRIN spectrometer to enable sensitive experiments in the neutron-rich region has already begun. Additional deflecting and focusing fields are installed, new detector systems including ionization chambers, γ-ray- and conversion-electron detectors and neutron counters enveloping the focal plane have been built. The main task consists now to assemble a high-efficiency γ-detector array to push experiments further in the neutron-rich region. This will be achieved by a network of European collaborations, and by an effort of the Institute to provide the necessary modifications and the infrastructure in order to ensure that the multidetector system can be efficiently used.

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