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SYNOPSIS
Single particle versus collectivity, shapes of exotic nuclei

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Abstract. In this article I will discuss some selected topics of nuclear structure research as illustration of the progress reached in this field during the last thirty years. These examples evidence the improvement of our understanding of the atomic nucleus reached on the basis of countless experiments, performed to study both exotic nuclei (nuclei far-off the valley of stability) as well as nuclei under exotic conditions (high excitation energy/temperature or large angular momentum/rotational frequency), using stable and radioactive ion beams.

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1 Introduction

During the last ten to fifteen years, nuclear structure physics has experienced a worldwide renaissance and our understanding of the atomic nucleus has not only improved, but very often we have found ourselfs confronted with real surprises which demanded changes in our view of this fundamental system. As is often the case in the history of science, the very dynamic evolution of this field of research has been closely related to the development of new experimental tools. As we will see in the course of this article, the probably most important new tools were on one hand side the first generation radioactive ion beams and on the other hand highly efficient 4π γ-ray spectrometer in conjunction with sophisticated ancillary detectors. In this article I will not try to provide an all-embracing view of nuclear physics research but instead illustrate the accomplished progress by means of some selected topics (evidently chosen according to personal taste). The focus will be on the "simple physics behind" and the qualitative understanding rather then detailed technical or theoretical aspects - assuming that these are presented in other contributions to this conference.

Fig. 1 shows the chart of nuclides, the orientation map for nuclear physicists. The black squares mark the about 300 stable nuclei existing in nature and forming the valley of stability. The nuclei on the left side of this valley decay via β^+-decay, the ones on the right hand side via β^--decay. Since the pioneering work by Maria Goeppert-Mayer and Hans Jensen in 1949, we know that due to the shell structure of the atomic nucleus, it is particularly stable (has a large binding energy) for certain numbers of protons and neutrons, the so-called magic numbers. Nuclei in the vicinity of closed shells are spherical and their excitation spectrum is dominated by single-particle excitations, whereas nuclei with many protons and neutrons outside the closed shells are very often deformed and here collective excitations such as rotations or vibrations, to which many nucleons contribute, become energetically favoured. The basic predictions of both the spherical shell model

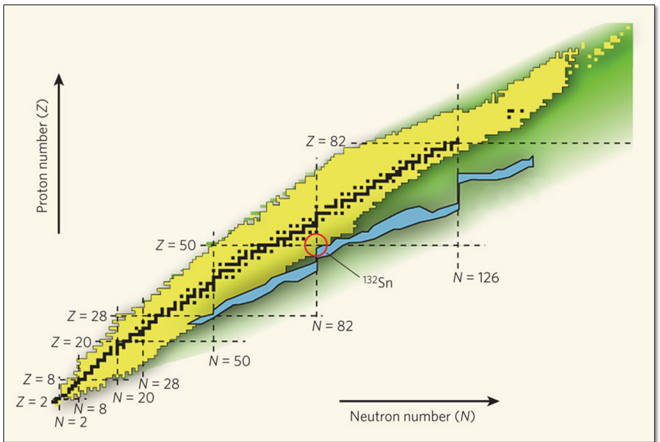

Fig. 1. Chart of nuclei with the black squares marking the about 300 stable nuclei existing in nature. The yellow area indicates the region of nuclei which already have been experimentally studied while the green region consists of thousands of nuclei which are expected to be bound (stable against particle emission) but have not yet been produced in terrestrial laboratories. Note that many of these nuclei are however continuously produced in the Universe during nucleosynthesis processes. The path of the astrophysical r process in indicated in blue. Finally, the magic numbers of the nuclear shell model are included as black dashed lines.

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and the collective models have been confirmed in numerous studies during the last decades and it seemed that the atomic nucleus is - at least at not too high excitation energy and angular momentum and not too far off stability - very well understood.

In the last decades, however, it became possible to experimentally explore both *exotic nuclei* as well as *nuclei under exotic conditions*. By exotic nuclei, we mean nuclei far off stability, which includes i) nuclei with large isospin (T_3=N-Z) close to the driplines and ii) superheavy nuclei, i.e. nuclei with large mass number A (=N+Z). The driplines mark the limits of nuclear stability, i.e. outside these borders the nuclei are unstable against the emission of nucleons. Complementary to the investigation of these exotic nuclei is the study of nuclei closer to stability but under exotic conditions.

2 The neutron-rich side of the nuclear chart

2.1 Halos, skins and clusters in light nuclei

We will briefly discuss the surprising features exhibited by light nuclei such as halos, neutron skins and cluster structures. The development of the field from the pioneering work by Tanihata et al. thirty years ago to the present status will be summarized.

2.2 Mapping of the neutron dripline

We will discuss how and up to which mass region the neutron dripline is experimentally established today. Furthermore it will be shown that the mere existence of certain radioactive isotopes, i.e. the exact position of the dripline, can bear important information.

2.3 Shell evolution close to the neutron dripline

The evolution of the nuclear shell structure when leaving the valley of stability towards the driplines is one of the major topics in nuclear structure research today. The experimentally established modifications of the $N = 8$, 20, and 28 shell gaps close to the neutron dripline and the occurrence of new "magic" numbers such as $N = 16$ (making ^{24}O a new doubly-magic nucleus) and their possible origins are discussed. The evidence for (sub)shell closures for neutron numbers $N = 32$ and $N = 34$ is critically examined.

2.4 The region around doubly-magic ^{132}Sn and its relevance for the r process of nucleosynthesis

Unfortunately, the heavier neutron shell closures $N = 50$, 82, and 126 cannot be studied experimentally in the regions close to the neutron dripline. Nevertheless, supposed evidence for modifications, in particular of the $N = 82$ shell closure, has been discussed in the literature some time ago. The evolution of the $N = 82$ shell gap below douby-magic ^{132}Sn is of particular relevance for the r process of nucleosynthesis. We will discuss the current experimental status in this region and illustrate the importance of new experimental information for the description of the solar system abundance distribution.

3 The neutron-deficient side of the nuclear chart

3.1 Isospin symmetry studies in N=Z nuclei and the isoscalar T=0 pairing phase

The attractive strong nucleon-nucleon interaction is known to be nearly charge-independent and charge-symmetric leading to the concept of isospin in nuclear physics. The symmetry is most evident when considering mirror nuclei along the $N = Z$ line, i.e. nuclei with exchanged numbers of neutrons and protons. However, with increasing mass of the nuclei isospin non-conserving effects become more and more important. While the Coulomb interaction, the most important of the isospin non-conserving effects, is well understood, an additional non-Coulomb isospin-breaking term has to be introduced in order to reproduce experimentally determined energy differences, for example in the case of the $A = 54$ mirror pair ^{54}Ni and ^{54}Fe.

Furthermore, we will briefly discuss recent experimental evidence for the contribution of isoscalar $T = 0$ neutron-pairing to the energy spectrum of the heavy $N = Z$ nucleus ^{92}Pd.

3.2 The phenomenon of shape coexistence

It is well known that one of the unique features of the atomic nucleus is that at a given proton and neutron number it can exhibit eigenstates with different shapes. This shape coexistence is governed by the interplay between the stabilizing effects of closed shells or subshells which causes the nucleus to retain a spherical shape on one hand side and residual interactions between protons and neutrons, which drive the nucleus into deformation, on the other. Here we will discuss a few illustrative examples of this phenomenon.

4 The heavy end of the nuclear chart

4.1 The synthesis of super-heavy elements

During the last three decades the knowledge about the upper end of the nuclear chart has been extended considerably. Both cold and hot fusion reactions were employed to synthesize super-heavy elements up to proton number $Z = 118$. In this section we will briefly summarize the status of the field of super-heavy element research.

4.2 The spectroscopy of transfermium nuclei

Since the first observation of a rotational band in the nucleus ^{254}No in 1999, the field of in-beam γ-ray spectroscopy of transfermium nuclei has developed at a stunning speed. Today nuclei produced in fusion-evaporation reaction with cross sections as low as a few nano barns are accessible for spectroscopic studies. We will discuss selected examples to illustrate how these studies provide valuable information on the evolution of shell structure towards the island of stability.

5 Atomic nuclei under extreme conditions

In this section we will try to answer questions such as: How does a nucleus behave at high angular momentum and/or high excitation energies ? Can we under these circumstances observe the collapse of pairing correlations ? How does the shape of the nucleus changes with angular momentum ? What is the limit of deformation a nucleus can sustain ?

6 Summary and outlook