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Studies of exotic nuclei with advanced radiation detectors

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HIGHLIGHTS

- Contemporary nuclear physics questions explained.
- State of the art radiation detectors developed for the use in basic nuclear physics studies are introduced.
- Examples of detectors used by the NuSTAR collaboration for electromagnetic radiation and charge particles are explained.

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ABSTRACT

Contemporary key nuclear physics questions are introduced. The role of radiation detection in the study of exotic nuclei is illustrated with examples related to NuSTAR at the FAIR facility. The discussed detection systems include: Si-tracker for light charged particle detection, the AGATA gamma-ray tracking detector, diamond detectors for heavy ion measurements, the AIDA implantation and decay detector, and the $LaBr_3$(Ce) fast-timing array. Due to technology transfer, applications related to radiation physics are expected to benefit from these developments.

1. Introduction

The vast majority, over 99.9%, of the mass in the visible universe is concentrated in atomic nuclei. Currently, out of the around 7000 possible bound nuclei, some experimental information is known on less than 4000 nuclear species. In particular we have information mainly on stable nuclei and those on the proton rich side of the valley of stability (see Fig. 1). Although various models of nuclear matter can adequately describe some of the properties of many of these known nuclei, they have little in the way of predictive power. For example the mass of the nucleus is one of its simplest gross properties, but we are unable to predict its value accurately for an unknown nucleus. Similarly, the neutron emission limit, or drip-line, cannot be predicted (for the case of the tin isotopes see Patra et al., 2005). Different mass models and mass parameterisations are working well for nuclei for which the mass was actually measured. However they differ hugely for nuclei where no experimental information is available (see Fig. 2). The reason for this is that a number of parameters used in the theories, which come from known nuclei, have to be extrapolated in a poorly defined manner.

Experimentally, information about nuclei are obtained by detecting and analysing the properties of the radiation leaving the system. Gamma-ray and conversion electron detection give information about excited states. In addition to the energy measurements, angular distributions, polarisations, lifetimes, etc., can be determined and used to infer the properties/wave-functions of the nuclear states. Some excited states and the majority of the ground-states (with the exception of the stable nuclei) will decay via alpha decay, beta decay, proton decay, two-proton decay, or possibly neutron decay. In addition, different reactions can be used to produce exotic nuclei and by measuring the properties of incoming and outgoing particles information about the nucleus of interest can be obtained.

Currently nuclear physics is being revolutionised by the new radioactive ion beam accelerator facilities. The biggest European Facility, the GSI-FAIR complex is being built in Darmstadt, Germany (Krücken, 2005). The aim of the Nuclear Structure, Astrophysics and Reaction (NuSTAR) collaboration at FAIR is to study exotic nuclei, mainly on the neutron-rich side (see Fig. 1). NuSTAR (Rubio and Nilsson, 2006) will be able to study the properties of nuclei which previously could not be produced.

The present paper will discuss the use of radiation detectors in fundamental nuclear physics. The status of the exotic nuclei studies will be illustrated via examples related to NuSTAR. State-of-the-art radiation detector systems developed for charged particles and electromagnetic radiation will be discussed.

2. Key physics questions in nuclear physics

Key physics questions in nuclear physics are: (i) what is the nature of nuclear matter? and (ii) how were the heavy elements synthesised?

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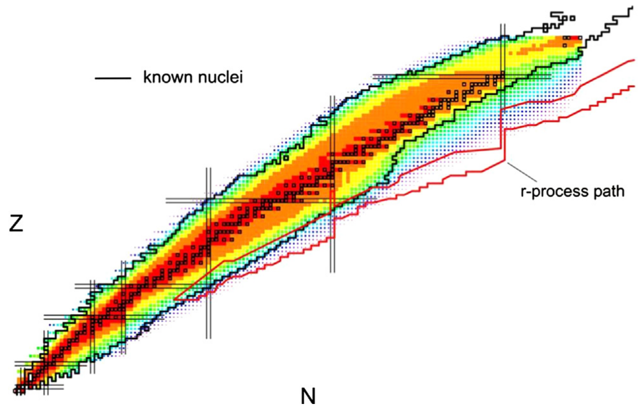

Fig. 1. Nuclide chart showing the nuclei already studied (solid line). The dotted area shows the nuclei which will be produced by the future radioactive beam facility at FAIR; several of them are on the r-process path.

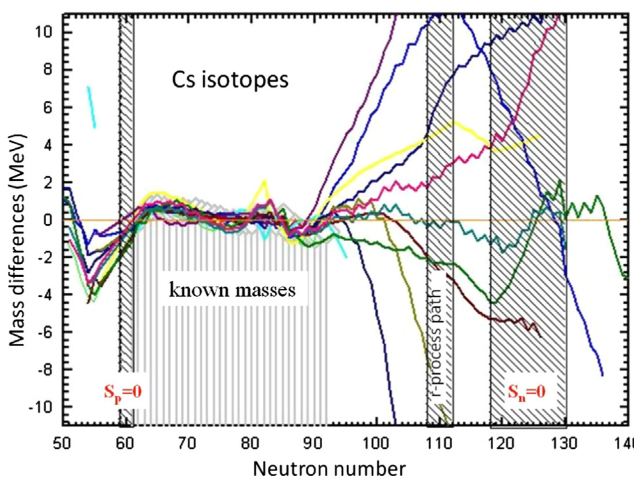

Fig. 2. Mass differences predicted by different mass models and parameterisations for Cs isotopes ($Z=55$). The predicted positions of the proton drip-line, r-process path and the neutron drip-line are indicated.

(i) *The nature of nuclear matter*: Nuclei are formed by protons and neutrons. Even if the interaction between the nucleons within the nucleus were known, such a many-body problem cannot be solved. The problem is even more difficult, as the form of the nucleus–nucleus interaction is not known exactly. Additional complication is brought in by the non-elementary nature of the nucleons. In order to deal with this problem, three-body forces are also introduced. Considering all interactions between the constituents of the nucleus, the problem cannot be solved mathematically. Therefore, simplifications are made, and different models are used. Some models describe some properties of some nuclei. However single unified model of nuclei does not exist so far. Questions as how many neutrons can be added to an element before it falls apart (where the neutron drip-line is) or how the simplicity of collective states arise from the complexity of many individual nuclei cannot be satisfactory answered at the moment.

One crucial question in nuclear physics is how the quantum orbitals evolve as the number of protons and neutrons change in the system. The nuclear potential (the potential energy experienced by a nucleon, generated from its interactions with the other nucleons in the nucleus) is expected to take the form of the nuclear density. Close to stability, this has relatively well defined edge (surface), as shown in Fig. 3. For neutron-rich nuclei, with high neutron/proton ratio, the neutron matter radius is larger than the proton radius, therefore the nuclear potential has a more diffused surface. As a consequence, the ordering of the nuclear orbitals can change drastically in neutron-rich nuclei (see Fig. 3). In extreme cases, traditional magic numbers can disappear and new ones can emerge. Such changes were already observed for light nuclei, and are predicted for heavy ones. The evolution of orbitals and shell gap have obvious consequences on nucleosynthesis, as discussed below.

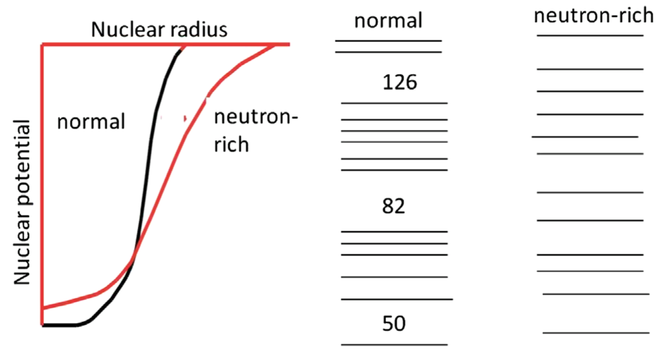

Fig. 3. The nuclear potential for normal matter as well as for neutron-rich matter is shown on the left. The corresponding change in the ordering of nuclear orbitals is illustrated on the right hand side. The traditional magic numbers are indicated.

(ii) *Production of heavy elements*: Half of the nuclei heavier than iron are believed to be synthesised in the rapid neutron-capture process, the so-called r-process (Arnould et al., 2007). No comprehensive model for the r-process exists. The understanding of the observed abundance pattern in the solar system and other stars requires detailed knowledge of the r-process waiting point nuclei (Nishimura et al., 2011). These are far from stability and at the moment very few of them can be studied experimentally. The NuSTAR facility will be unique in producing heavy r-process path nuclei (e.g. the heaviest of the $N=126$ r-process waiting point nuclei), related to the increased abundances in the $A\sim195$ mass region (see Fig. 1). The nuclear physics information is one of the main ingredients in nucleosynthesis, and its knowledge is needed to constrain the stellar evolution models (such as constraints on astrophysical conditions governing the neutron density, its time dependence, and the amount of ejected material) (Cowan, 2003).

Another open nucleosynthesis question is related to elements around Sr–Y–Zr. The abundances of these elements are poorly understood, both in the solar system and in old stars. It was postulated that they are partly synthesised in the so-called light-element primary process (LEPP). The nature of this process as well as the possible sites for it are debated (νp-process, additional r-process or s-process component) (Montes et al., 2007). The study of nuclei in this region, from the proton drip-line up to extremely neutron-rich isotopes, might help to shed more light on this mysterious process.

There is no single experiment which can answer the above physics questions. Rather, a number of nuclei have to be studied, using different techniques.

3. Detector systems and collaborations at NuSTAR

NuSTAR (nuclear structure, astrophysics and reactions) is an umbrella collaboration. It comprises nine different collaborations based around state-of-the-art detector systems. Here we discuss some examples of equipments used in three of them: R^3B (reactions with relativistic radioactive beams), HISPEC (high-resolution in-flight spectroscopy) and DESPEC (decay spectroscopy). Examples of detector systems are presented: for proton detection (silicon tracker for R^3B), next generation γ-ray detector (the AGATA γ-ray tracking array used at HISPEC), large area diamond detectors (LYCCA for HISPEC), implantation and decay