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BORDERS OF THE NUCLEAR WORLD — 100 YEARS AFTER DISCOVERY OF POLONIUM*

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Hundred years after the birth of nuclear physics almost 3000 bound nuclides are known. Most of them have been produced in nuclear laboratories. With help of new experimental tools, like beams of relativistic heavy ions and projectile fragment separators, still new territories on the chart of nuclei are being conquered. A few examples of experiments which have recently shifted the limits of known nuclei will be presented.

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1. Introduction

The first paper of M. Skłodowska-Curie on radioactivity was presented to the *Académie des Sciences* in April 1898 [1]. Already in this first work, a new fundamental idea was formulated that radioactivity may serve as diagnostic for the discovery of new chemical substances. This hypothesis was soon confirmed by Pierre and Marie Curie who announced the discovery of polonium in July 1898 [2]. The number of known radioactive substances was growing fast and already in 1904 E. Rutherford presented a list of the eighteen of them [3]. The next milestones in unveiling the subatomic world were the discoveries of the atomic nucleus (Rutherford, 1911) and of the neutron (Chadwick, 1932). With the first production of artificial radioactivity (F. Joliot and I. Curie, 1934) and the development of accelerators in the thirties, the modern nuclear physics began.

Since then our knowledge of nuclear world expanded enormously. Today we know about 3000 nuclides bound by the strong (nuclear) forces. Except for 273 stable ones, they are all radioactive, being subject to transformations

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like α- and β-decay or fission, see figure 1. However, according to our understanding of the nuclear forces, about 8000 bound nuclear systems could exist. It means that the territory of the all possible nuclides remains largely unknown.

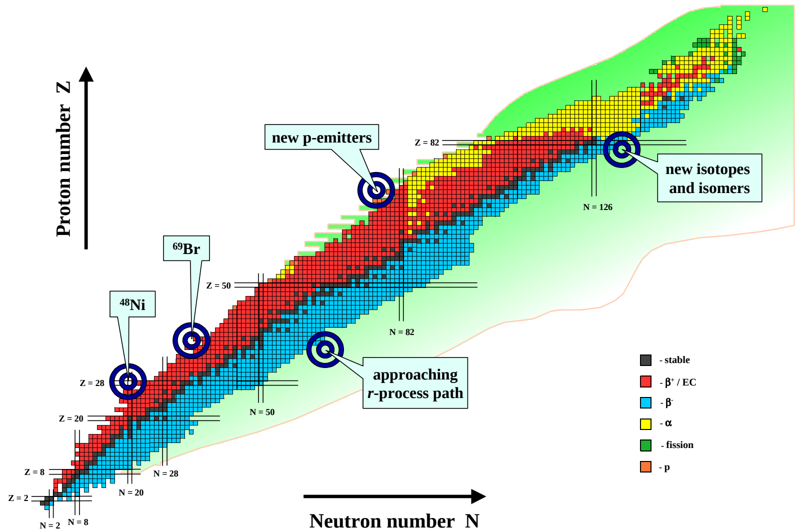

Fig. 1. The chart of nuclides. The lightly shaded area shows approximately the region, yet unexplored, where nuclei are predicted to be bound. The topics discussed in the paper are indicated.

In the present article, I will give some examples of the experimental work undertaken on the borders of the nuclear world and I will mention techniques applied to expand these borders.

2. Radioactive beams

The most promising experimental techniques used in the last years to produce and study exotic nuclei, lying far from the line of stability, utilize beams of radioactive ions. There are two basic methods of generating radioactive beams. The first one employs the fragmentation reaction of heavy ions accelerated to relativistic energies. The reaction products — projectile like fragments — emerging from the production target are separated by means of a magnetic spectrometer. Since the products are flying with approximately the velocity of projectiles, this method is very fast and allows studies of the very short-lived activities, down to about 100 ns. Another important advantage of this method is the lack of the chemical sensitivity. The projectile fragmentation method has been applied and is developed in several laboratories like MSU in East Lansing (USA), GANIL in Caen (France), RIKEN (Japan) or GSI in Darmstadt (Germany).

The second method is based on the classical isotope separator on-line (ISOL). A variety of reactions can be employed in this method, for example the spallation of a thick target induced by relativistic proton beam or ion-induced fission. While much higher intensities of secondary beams may be reached, compared with the fragmentation technique, this method suffers from relatively long extraction time from the ion source, limiting possible applications to longer activities. Also a drawback of chemical sensitivity is inherent in the construction of a majority of ion-sources. The low-energy, exotic beam provided by the isotope separator can be subsequently accelerated to be exploited in secondary reactions, opening a broad field of new reaction channels to be studied. Although the intensities of such beams will be much smaller than these of currently available stable beams, the expected increase of production cross sections will result in production of even more exotic nuclei. The ISOL method with the postacceleration technique is being developed for example at CERN (Isolde-Rex project) or at GANIL (Spiral project).

3. Towards the neutron drip-line

The neutron drip line has been reached only for the very light elements, up to $Z = 10$. For heavier elements the drip line lies far beyond reach of present experimental possibilities. Since the structure of the extremely neutron-rich nuclei is predicted to differ from what is known closer to stability, and the properties of these nuclei are key to the detailed understanding of the astrophysical r-process, the extension of the limit of known nuclei towards neutron-drip line counts to the most important challenges of nuclear physics.

Considerable progress in this matter has bean reached recently in the region of medium mass nuclei at the projectile fragment separator FRS at GSI. A unique feature of the heavy ion facility at GSI is the availability of relativistic ^{238}U beam. In two experiments the beam of ^{238}U at 750 MeV/nucleon was used to study fission in inverse kinematics induced by peripheral collisions with the nuclei in beryllium and lead targets [4,5]. The fission products, separated by the FRS could be identified in mass (A) and atomic number (Z) event by event at the final focus of the spectrometer by means of measuring their time-of-flight, magnetic rigidity and energy loss (TOF–$B\rho$–ΔE). More than 100 neutron-rich isotopes of elements between titanium and neodymium, including the doubly magic ^{78}Ni, were observed for the first time [5]. It was demonstrated that this method provides an access to nuclei lying on the r-process path up to bromine and between tin and cesium. The increase of uranium beam intensity, expected in GSI in the near future, will allow decay spectroscopy studies and mass measurements in this important and still unexplored region.

In the region of heavier nuclei the neutron drip line is so far from the known isotopes that it probably will never be reached experimentally. However, there might be a chance that properties of loosely bound isomeric states in neutron-rich nuclei that can be studied, reflect phenomena characteristic for the ground states of much more exotic systems. Search for μs-isomers in the region of the ^{208}Pb and the test of the production rates of neutron-rich nuclei in the lead region were the goals of another experiment performed with the uranium beam at GSI [6]. In this case a 1 GeV/nucleon ^{238}U beam on a beryllium target was used. Projectile-like fragments were selected by the FRS, identified in flight event by event and stopped in the catcher surrounded by germanium detectors. A number of known μs-isomers around ^{208}Pb was observed demonstrating for the first time that in the high-energy fragmentation reaction isomeric states are populated with a considerable probability (from about 50% for spin $I = 7$ to about 20% for $I = 12$). Decays of four new isomers were observed adding information on the shell structure in the region. Scanning of the production rates resulted in observation of seven new isotopes : ^{209}Hg, ^{210}Hg, ^{211}Tl, ^{212}Tl, ^{218}Bi, ^{219}Po and ^{220}Po. The identification plots for polonium and thallium isotopes are shown in figure 2.

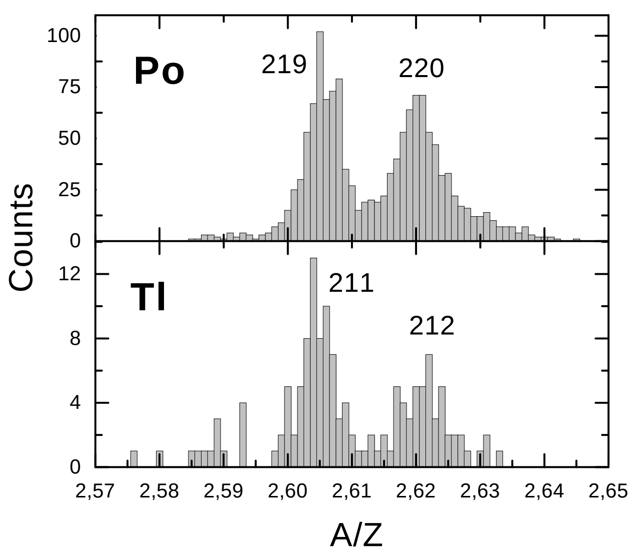

Fig. 2. Mass-to-charge spectra of polonium and thallium isotopes identified at the final focus of the FRS spectrometer. Numbers indicate masses of the new isotopes.

The systematics of the measured production cross sections suggests that with the planned intensity increase of the uranium beam at GSI, the study of still more neutron-rich nuclei in the lead region will become feasible. It is striking that until recently this part of the nuclear chart was very difficult to reach experimentally. For example, the heaviest polonium isotope known before, ^{218}Po, was studied already by E. Rutherford in 1904. At that time, still before atomic nucleus was discovered, this substance, known as RaA, was listed together with the properly measured half-life in the summary paper of Rutherford [3]. Similarly, ^{210}Tl (RaC$''$) was studied by Hahn and Meitner [7] in 1909.

4. On the proton drip-line

Due to the Coulomb interaction between nucleons the proton drip line lies much closer to the line of stability then the neutron drip line. Therefore, it was possible to study experimentally the proton drip line nuclei up to bismuth. Moreover, a number of nuclei unbound to the emission of a proton is known — they are located, of course, beyond the proton drip line. Observation of protons emitted from these isotopes provides the information on the mass and structure of the parent nucleus.

Recently, a progress in studying ground-state proton emitters has been reported from the Recoil Mass Spectrometer at the Oak Ridge Holifield Radioactive Beam Facility [8]. Using the fusion-evaporation reactions with ^{92}Mo and ^{96}Ru beams at about 5 MeV/nucleon on ^{58}Ni and ^{54}Fe targets the five new proton emitters were discovered: ^{140}Ho, ^{141m}Ho, ^{145}Tm, ^{150m}Lu and ^{151m}Lu. The remarkable fact is that ^{145}Tm is already the third thulium isotope for which proton emission was observed and presumably the fifth beyond the proton drip line. Analysis of the protons emitted from the isomer of ^{151}Lu and from the ground state of ^{151}Lu by means of a spherical WKB model yielded relative energies and spectroscopic factors of two single particle orbitals $d_{3/2}$ and $h_{11/2}$, respectively. The same holds for the pair ^{150m}Lu and ^{150}Lu. In case of holmium isotopes, the spherical model does not explain the observed half-lives which is consistent with the predicted strong deformation of these nuclei. The need for a legitimate interpretation of the experimental data in these cases triggered a development of theoretical models of proton emission from the deformed nuclei [9, 10].

Observation of new isotopes produced by the projectile fragmentation method is based, as already mentioned, on the in-flight measurements of the time-of-flight, energy loss and magnetic rigidity, allowing for the unambiguous identification of a single ion. Although this method is very sensitive — observation of new isotopes was reported on the basis of 3 counts only [11,12] — it brings no information on the properties of the discovered nucleus. For the determination of the half-life, mass, decay modes and other characteristics, larger statistics are needed and the detailed studies of most exotic isotopes have to be postponed until higher beam intensities will be available and/or more sensitive spectroscopy methods will be developed. However, in some cases the mere observation (or unobservation) of the ion at the final focus of the projectile fragment separator allows to draw important conclusions. One of such cases is ^{69}Br. When bound, this nucleus would play a crucial role in the flow of the rp-process occurring at high temperature and density present possibly in explosive stellar environments (like supernovae or X-ray bursts), allowing it to pass to the region of heavier elements. The proton drip line nuclei around krypton were investigated at the LISE spectrometer at GANIL [13]. The $T_z = -1/2$ nuclei from ^{51}Fe to ^{71}Kr were identified except for ^{69}Br, indicating that its half-life is much shorter than the time of flight through the separator. The deduced limit was $T_{1/2} < 100$ ns. Later, in another experiment performed at MSU, the more stringent limit of $T_{1/2} < 24$ ns was established [14]. The consequence of such a short half-life of ^{69}Br is that the rp-process has to slow down considerably or even terminate at ^{68}Se, because its half-life, 35 s, is longer than the predicted time scale of the rp-process itself.

Another case where the identification of the isotope would be extremely interesting is ^{48}Ni. This nucleus is one of the most favourite candidates for the two-proton ground-state radioactivity. The half-life of this, yet unobserved, phenomenon depends drastically on the 2p separation energy and according to a recent prediction ranges from 10 μs to 3 s [15]. In an attempt to produce neutron-deficient nuclei in the region of nickel, undertaken at the FRS at GSI, the ^{49}Ni was reached [12]. Five events of this most proton-rich nucleus ever observed ($T_z = -7/2$) were identified among projectile-like fragments of the ^{58}Ni beam impinging on a beryllium target at 600 MeV/nucleon. Identification of the next isotope, ^{48}Ni, will be hopefully feasible after the intensity upgrade of the SIS/FRS facility at GSI. Observation of this nucleus at the final focus of the separator would indicate the half-life longer than 100 ns, opening possibility for further, detailed spectroscopy studies.

5. Summary

Hundred years after the discovery of polonium and radium a few thousand nuclides constitute the recognized and studied nuclear world. We know, however, that equally large number of radioactive nuclides, not discovered yet, may exist. Further expansion, especially to the neutron rich side on the nuclidic chart, is extremely difficult and calls for new ideas and new experimental techniques.

In the present paper I gave a few examples of experiments aiming at crossing the present borders of the nuclear world. Most of them illustrate a progress reached, and perspectives opened, by the method of the radioactive beams produced by projectile fragmentation of relativistic heavy ions. This and other methods utilizing beams of radioactive ions are expected to provide a wealth of information about new exotic nuclei, lying far from the stability line. We believe that the second hundred years of research on radioactive substances will be equally fascinating and fruitful as the first, started by works of Bequerel, Curies and Rutherford.

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