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Exploring New Neutron-rich Nuclei with the Facility for Rare Isotope Beams

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About 3000 different isotopes of 118 elements are presently known. The discovery of these isotopes is closely linked to the development of new production and detection techniques and more powerful accelerators. A brief overview of the history of isotope discovery and our present knowledge of the nuclear chart are given. The status of the Facility for Rare Isotope Beams (FRIB) is described, and the potential for discovery is discussed especially for neutron-rich nuclides.

I. INTRODUCTION

More than 100 years after Rutherford discovered the atomic nucleus the limits of what combinations of protons and neutrons can make up a nucleus are still only known for the lightest elements. Exploring the nuclear landscape and pushing towards the limits of nuclear existence is important for our understanding of the strong force and element formation in the universe. The discovery of new isotopes is the first step in the study of the properties of the most exotic nuclei.

The quest to create new types of nuclides has led to the discovery of over 3000 different isotopes of the 118 known elements. These discoveries were made possible with continuous developments of more and more powerful accelerators and increasingly sophisticated techniques and detectors. While almost all of the neutron-deficient nuclides have been discovered, the neutron-rich region above magnesium is for the most part still unknown. Next generation radioactive beam facilities like FRIB, the Facility for Rare Isotope Beams, will be necessary in order to explore the formation and properties of these nuclei.

II. HISTORY OF NUCLIDE DISCOVERIES

Fig. 1 shows the number of nuclides discovered per year (black histogram) and the five-year running average (red solid line). These data show that new nuclides were not discovered at a constant rate. Periods of intense progress were followed by years in which very few new nuclides were discovered. The various peaks can be attributed to specific technological advances.

During the 1920s and 1930s most of the stable nuclides were discovered. The first peak in the mid-1920s is solely due to experiments by Aston using his mass spectrograph. A second peak in the mid- to late-1930s is not only due to the development of the next generation mass spectrographs, but also to the invention of particle accelerators and the creation of unstable nuclides by means of nuclear reactions.

The next peak following the second world war includes the discovery of nuclides generated as a consequence of fission (mostly from reactors) and fusion-evaporation reactions, made possible by the development of heavy-ion accelerators. Continuous increases in the beam energy of accelerators then enabled the use of target and projectile fragmentation reactions to produce many more neutron-deficient and neutron-rich nuclides leading to very productive years around 1970 and 1980. Construction of dedicated projectile fragment separators in several laboratories in the early 1990s resulted in another boost in the discovery of nuclides.

In contrast to most of the earlier discoveries of radioactive nuclides which were predominantly identified by their β-decay, nuclides studied with fragment separators are identified directly event-by-event by their mass and charge. These experiments are capable of covering large fractions of the nuclear chart within one setting of the magnetic field, and thus many nuclides can be discovered in a single experiment.

The large fluctuations in the number of discoveries during the last few years are directly related to the publications of the fragment separator groups. More than 100 nuclides were discovered in the single year of 2010 for the first time, mostly arising from two experiments. Alvarez-Pol *et al.* reported the discovery of 47 new nuclides using the FRS separator at GSI [1], and Ohnishi *et al.* discovered 30 new nuclides with the new BigRIPS separator at RIKEN [2]. Oganessian *et al.* also measured 11 new superheavy nuclides at Dubna [3]. No new major results

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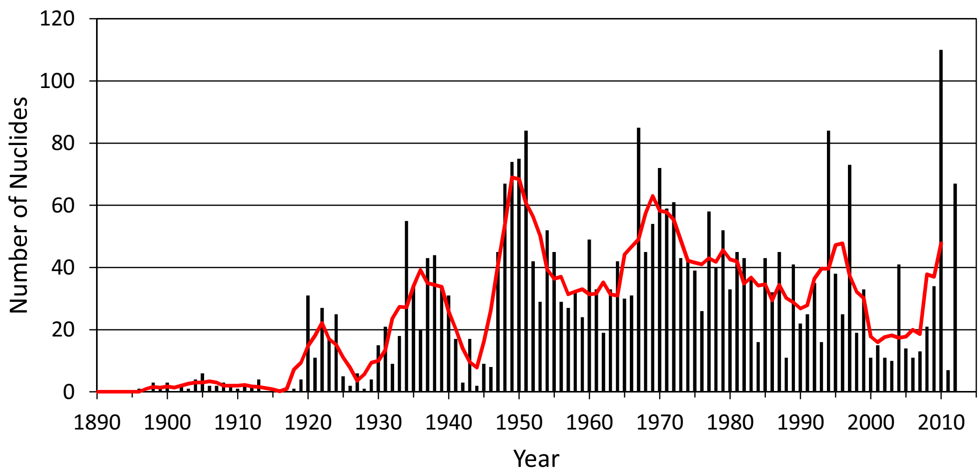

FIG. 1. Number of nuclides discovered - the histogram shows the number of nuclides discovered per year, while the (red) solid line corresponds to the five-year running average. A first version of this graph including publications of discoveries up to 2010 was published in Ref. [7].

from these collaborations were reported in 2011 resulting in the discovery of only 7 nuclides. This was followed by a large increase in 2012 when the observation of 67 new nuclides was reported. Again, most of these nuclides were discovered in a single FRS experiment at GSI by Kurcewicz *et al.* who were credited with the discovery of 59 new nuclides [4].

A more detailed description of the history of the discovery of nuclides including the relevant bibliography can be found in Ref. [5].

III. PRESENT KNOWLEDGE

A recent initiative entitled the "Isotope Discovery Project" furnished an appropriate visual summary of nuclide discovery (Fig. 1). Discovery of a nuclide required the clear identification by decay-curves and relationships to other known nuclides, particle or γ-ray spectra, or unique mass and element identification, as reported in a refereed journal. Particle unbound nuclides were also included, whereas isomers were not considered as separate nuclides.

A first detailed compilation of the project has recently been completed and published in a series of papers in Atomic Data and Nuclear Data Tables, beginning in 2009 with the article on cerium isotopes [6]. The detailed references, further aspects, and most recent update of the project can be found at http://www.nscl.msu.edu/∼thoennes/isotopes.

The latest update includes the published literature until the end of 2012, and summarizes the discovery of 3172 different nuclides. The element with the most isotopes presently known is mercury (46), followed by platinum and osmium with 43 each. Element 118 with only one isotope (A = 294) has the fewest at the present time. While the heaviest nuclides are ^{294}117 and ^{294}118, However, their discovery has not yet been officially accepted. Also of interest is that the first isotone with N = 164 (^{271}Bh) was only discovered this year [10], and presently remains the only nuclide discovered in 2013.

The discoveries were achieved in over 100 different laboratories in 25 different countries. Overall, most of the nuclides were discovered at Berkeley (>600) and within the USA (>1300). However, most recently GSI in Germany and RIKEN in Japan have been the most productive laboratories [8, 9]. Although the majority of nuclides have recently been discovered at the major projectile fragmentation facilities, a relative large number of diverse facilities still contribute. Nine different laboratories have been involved in these discoveries since 2009: as well as the projectile fragmentation facilities at GSI, RIKEN, and MSU, and the laboratories studying superheavy elements at GSI, Berkeley and Dubna, nuclides were also discovered at Texas A&M University (^{14}F [11]) , Legnaro (^{170}Dy [12]), Jyväskylä (^{157}W [13]), Argonne (^{157}Nd and ^{155}Pr [14]), and CERN (^{229}Rn [15]). Overall the discoveries were reported by more than 3400 different authors in over 1500 papers with almost 900 different first authors.

IV. FUTURE POTENTIAL FOR DISCOVERY

The approximately 3000 presently known nuclides do not represent even half of the nuclides predicted to be particle bound. Recently, Erler *et al.* estimated that about 7000 nuclides could exist [16]. Fig. 2 shows the chart of nuclides in which the stable nuclides are indicated by black squares, presently known nuclides are shown in green, and additional nuclides predicted to be particle bound by Erler *et al.* are shown in yellow. 2000 of the predicted nuclides are in the region above N > 184 and will