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The 3D Nuclide Chart

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Abstract. We present an overview of *The 3D Nuclide Chart*, a new online nuclide chart designed for producing high quality 3D nuclide chart images for use in publications, presentations, education and outreach. An historical overview of the design of nuclide charts is given, followed by a description of *The 3D Nuclide Chart* itself.

1. Introduction

The nuclide chart depicts nuclear properties as a function of the numbers of protons and neutrons, and over the last eighty five years it has become an indispensible tool in nuclear science. In publications, talks, education and outreach, nuclide charts are frequently used to set the context of discussion, illustrate key nuclear phenomena and explore the connections between nuclides. To this end, we have created a new online nuclide chart, with the express purpose of producing high quality images, whilst also providing easy access to basic nuclear properties. Two versions are available: *The Colourful Nuclide Chart* [1] and *The 3D Nuclide Chart* [2], the latter of which will be discussed here.

We begin with a brief historical overview of the nuclide chart, focused on the evolution of its design and use, before discussing *The 3D Nuclide Chart*. We conclude with a brief overview of planned developments.

2. History of the Nuclide Chart

The essence of the nuclide chart is that it seeks to graphically convey nuclear properties as a function of the number of protons (Z) and neutrons (N). The first to organise nuclear properties in this way was probably Par K. Guggenheimer in 1934 [3, 4], just two years after the discovery of the neutron [5] and the realisation that nuclei were composed of protons and neutrons [6]. The charts shown in Refs. [3, 4] plot nuclides as a function of Z and N, with filled circles representing abundant nuclides, open circles representing rare nuclides, and crosses representing radioactive nuclides. Georgio Fea [7] further refined this scheme, adding more detail in the representation of abundances, and indicating radioactive decay chains for heavy elements by connecting lines. Though the design is simplistic, it is recognisably a nuclide chart in that it systematically represents the properties and connections of known nuclides.

Further development of the nuclide chart is widely attributed to Glenn Seaborg and Emilio Segrè. One early example can be found in a 1945 Los Alamos report [8], written by Elfrida Segrè. This version is recognisably modern: individual nuclides are represented by squares containing text denoting the nuclide and known information about half lives, decay modes, and fission

Figure 1. Glenn Seaborg standing in front of a nuclide chart, likely in his office at the University of Chicago in the first half of 1946. From Argonne National Laboratory, courtesy of AIP Emilio Segrè Visual Archives [10]. © Argonne National Laboratory.

characteristics. Details of the isomer of ^{234}Pa are also given. In subtle contrast to the charts of Guggenheimer and Fea, there is no abstraction of the data: Segrè's chart presents information textually rather than symbolically, primarily acting to organise and store the data. The report [8] focuses exclusively on the high atomic number end of the nuclide chart, $Z = 88 - 96$, but a more complete version would have certainly existed at the time. Indeed, the article refers to the "mural isotope chart"[1], suggesting that the high atomic number section presented can be pasted onto the mural chart "once security permits it". One point to note is that, in contrast to the modern arrangement, the proton number is on the horizontal axis, and neutron number on the vertical.

A more complete early nuclide chart can be seen in a photo from the Emilio Segrè Visual Archive [10], shown in Figure 1. In the picture, Glenn Seaborg stands in front of a wall-mounted nuclide chart. Remarkably, a nearly identical shot appeared in a 1946 edition of the general interest LIFE Magazine ("Plutonium Laboratory", 8th July issue [11])[2]. In Seaborg's 1946 version of the nuclide chart, the properties of nuclides appear to have been written by hand, with some nuclides pasted on to the chart, consistent with the practise suggested in the Los Alamos Report [8]. For many elements, isotopes with unknown mass can be found at the borders of the chart. Compared to the Los Alamos version, there is now a distinction between stable and radioactive nuclides, with the latter having a dark background, and the axes are reversed into the (now) conventional configuration. The LIFE version [11] also shows a key to indicate the changes induced by nuclear decays in the bottom right corner. These photos

[1] The title of the report [8] was "Isotope Chart", owning to the fact that the word "nuclide" did not exist until it was proposed by Truman Kohman in 1947 [9].

demonstrate that the modern design of the chart was well established by 1946 and, in printed form (e.g., Ref. [12]), it has changed remarkably little since.

Whilst the early nuclide charts were able to include essentially all known information about the nuclides depicted, the second half of the twentieth century saw an explosion in the volume of nuclear data. Printed nuclide charts, though still common in physics departments and nuclear laboratories across the globe, cannot possibly convey the vast catalogues of measured nuclear properties. Online nuclear databases can, however, and this data is made accessible through online nuclide charts, such as the US National Nuclear Data Center Interactive Nuclide Chart [13] and the IAEA LiveChart [14]. Rather than conveying a fixed, limited set of key data in textual form, the online charts typically allow plotting one of a set of properties, communicated via the background colour of each nuclide. They also link to additional nuclear data resources, providing access to much more detailed information.

Given the utility of the nuclide chart in setting the context for discussions about the characteristics of any given nuclide, the chart is frequently used in publications, presentations, education and outreach. To this end, we developed *The Colourful Nuclide Chart* [1], with the express aim of producing high quality, highly configurable nuclide chart images. The chart is designed to be easy and fast to use and, as of September 2019, has nearly 600 unique users per month. More recently, we have developed *The 3D Nuclide Chart*, discussed next.

3. The 3D Nuclide Chart

Three dimensional nuclide charts are particularly suited to outreach and education, offering a much more intuitive understanding of concepts such as the valley of β-stability, fusion, and fission. Particularly effective physical 3D nuclide charts have been produced before, notably those made of LEGO at RIKEN [15] and through the Binding Blocks project [16, 17]. *The 3D Nuclide Chart* [2] is a new online 3D nuclide chart, accessible to anyone using a modern desktop web browser. *The 3D Nuclide Chart* builds on the earlier *Colourful Nuclide Chart* [1], and the two websites share much of the same underlying code. We first give an overview of the use and key features, before providing some technical detail on the implementation.

3.1. Use and Features

On loading the webpage, the user is presented with a view of the complete nuclide chart, coloured by the primary decay mode. The chart can be easily navigated using a mouse or trackpad. Left clicking allows one to pan the chart, right clicking allows for rotation, and scrolling zooms in and out. Double clicking on a nuclide brings up a panel with further information, and provides links to external nuclear data resources. Icons in the top left of the page give access to various tabs to choose the data to be plotted and precisely configure the appearance. Some examples are shown in Figure 2. The appearance of the chart has a large number of configurable options, including,

- Plotting of nearly all quantities from AME2016 [18] and NuBase2016 [19], with the option to hide any value flagged as estimated in the database;
- Plotting of raw data, uncertainty, or single and double differences (see Ref. [20] for an explanation);
- Linear or logarithmic plotting, with variable height scaling;
- Limit plotting to a specified range in N and Z, or plotting of only even-even nuclides;

[2] The LIFE article credits the photo to renowned science photographer Fritz Goro, and notes that it was taken in Seaborg's office at the University of Chicago. The issue of LIFE Magazine can be found at `https://books.google.com.au/books?id=JEoEAAAAMBAJ&lpg=PA69&dq=glenn%20seaborg&pg=PA70#v=onepage&q&f=true`.

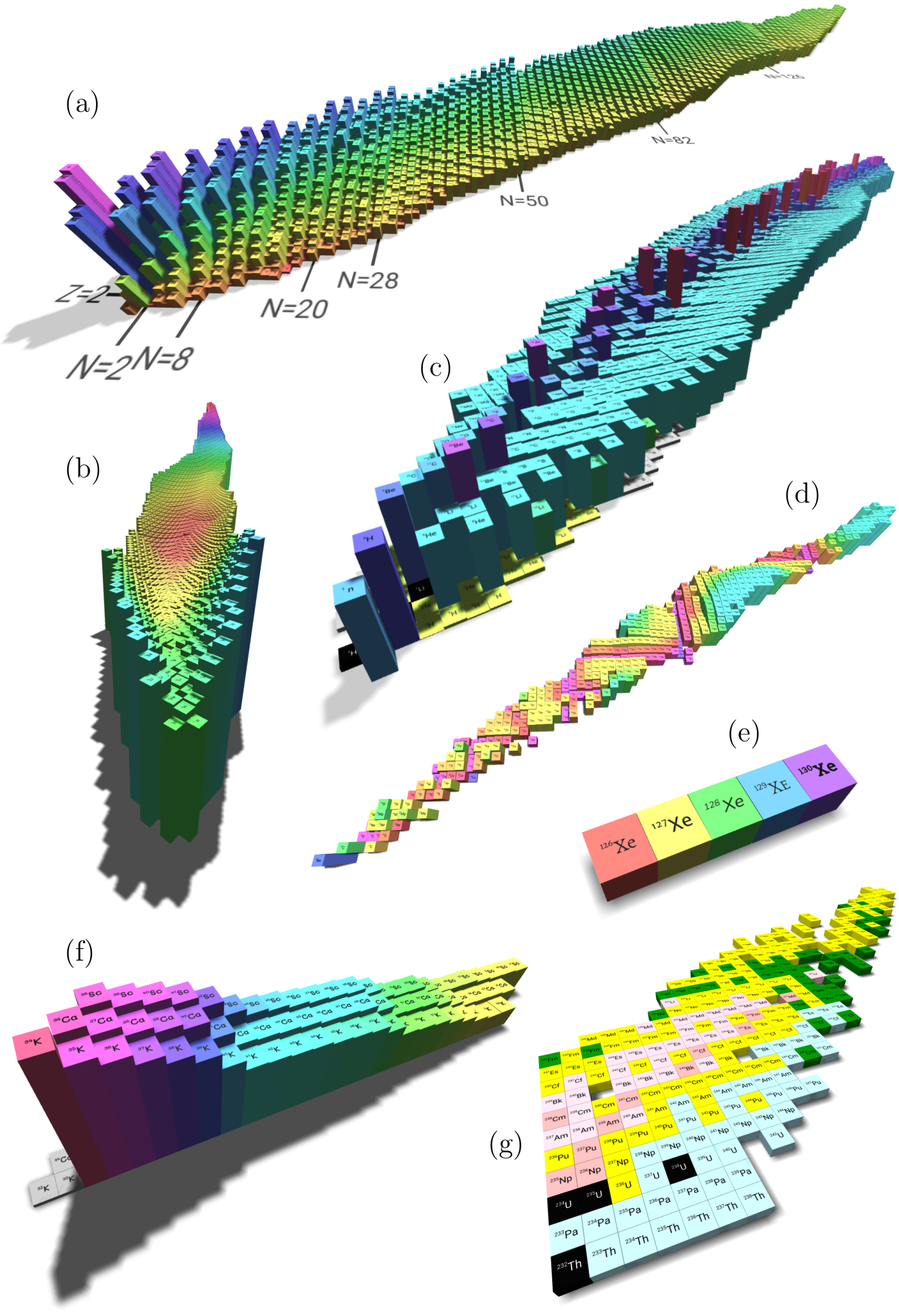

Figure 2. A collage of examples from *The 3D Nuclide Chart* showing (a) single neutron separation energies with magic numbers indicated on the base, (b) mass excesses, (c) half-lives, (d) $4^+/2^+$ energy ratios, (e) xenon isotopes illustrating different fonts, (f) two-neutron separation energies for calcium isotopes, and (g) decay modes for the heaviest nuclides.

- Configurable HSV colours, including the hue range, lightness, saturation, and hue offset (hue of the minimum value);
- Option to colour stable nuclides in black and highlight magic numbers on the base;
- Plotting with or without shadows, and rotation of the light source to alter shadow direction;
- Choice of 12 fonts, taken from Google Fonts, available in bold, italic and small caps.

These options are stored in a cookie, so that on returning to the site the chart appearance, including the position and zoom of the view, is retained. One can also generate a link to share exactly the current state of the chart, again including the position and zoom of the current view. This feature could be particularly useful in teaching and outreach. For example, you could share a view of the half-lives of heavy nuclides[3]. Saving images of the chart is as simple as clicking the export button. This produces a png file of the current view, and opens a dialogue box so that the file can be saved. In addition, a text file corresponding to the currently plotted data can saved.

3.2. Technical Implementation

The 3D Nuclide Chart is built using PHP, HTML, CSS, and JavaScript, and uses the JQuery [21] library. CSS media conditions are used to scale and rotate the user interface based on the aspect ratio and size of the screen. Data is stored in a MySQL database, retrieved using PHP, and sent to the client as JSON objects. Currently, most of the properties from the Atomic Mass Evaluation 2016 [18] and NuBASE 2016 [19] data sets are available to plot. Select properties from the Evaluated Nuclear Structure Data File [22] are also available, notably the lowest 2^+ and 4^+ energies for even-even nuclides. The format of the database is relatively simple, and, provided with data in machine readable form, additional properties can be added relatively easily.

In order to ensure consistency across different browsers, fonts are loaded dynamically from Google Fonts [23]. The default font for the chart is Roboto, though a number of others are available. The 3D chart itself is drawn using the JavaScript library Three.js [24], which provides a convenient interface to WebGL. The three main components of the 3D scene are (a) the chart itself, made of a series rectangular cuboids to represent each nuclide, (b) two small rectangular planes for each nuclide, which use a texture to show the mass number and element symbol, and (c) a large flat plane to act as a base, textured with illustrations of magic numbers and the chart title.

In making the chart tactile and responsive for users, efficient rendering is key. A key factor in improving performance of the website comes from minimising the number of draw calls. A draw call is a command to the GPU to render a particular part of the scene. Making a draw call itself is computationally expensive, and if the work that the GPU must do to render the scene is packaged into many small draw calls, performance can be significantly affected. The geometries for all nuclides are therefore merged into a single large object, which can be rendered with a single draw call.

Another performance barrier comes from the labels for the nuclide symbol and mass number. Rendering text is computationally costly. As around 12000 characters are required for the labels, rendering them every frame would lead to very low frame rates. To counter this, a 2048×2048 pixel spritesheet is rendered to an html canvas element, which contains the numbers 0-319 and all 118 element symbols. This is done for both black and white text. Each nuclide symbol or mass number on the chart then uses these textures, with appropriate texture offsets and scaling.

[3] To view this example, go to `https://people.physics.anu.edu.au/~ecs103/chart3d/?ShowStable=true&HideEstimated=true&CurrentDataMode=logx&InitialPropertyCode=hl&TargetX=45.3&TargetY=-3.7e-17&TargetZ=-30.2&PositionX=38.4&PositionY=15.8&PositionZ=-16.7`

This technique, in addition to avoiding rendering the text every frame, reduces the number of draw calls to just two for all ∼6000 labels.

4. Summary

We have given an overview of a new online nuclide chart, *The 3D Nuclide Chart*. Planned new features include the plotting of user data, plotting of time-series data (e.g., for astrophysical process simulations), exporting to video, and improved support for touchscreen devices. Bug reports, corrections and feature suggestions from users are strongly welcomed.

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