Decay Studies of Exotic Nuclei using RISING and the GSI Fragment Separator

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This proposal forms part of the 'Stopped Beam' RISING experimental campaign at GSI.

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Abstract: *We will investigate new structures in exotic, heavy neutron-rich and N~Z nuclei formed following projectile fragmentation reactions using the Fragment Separator. The specific physics focus aims are:*

- *Investigating fundamental nuclear shell model interactions by identifying proton-hole states in the ^{208}Pb double-magic closed shell;*
- *The evolution of nuclear dynamical symmetries (and related nuclear shapes) from the extreme 'single-particle region' around ^{208}Pb towards the 'valence maximum' nucleus, ^{170}Dy;*
- *The identification of isomeric states in proton-hole configurations in the ^{132}Sn doubly-closed core; and*
- *The study of isospin symmetry across the N=Z line.*

The experimental technique involves the use of the FRagment Separator (FRS) at GSI to identify some of the most exotic, heavy nuclei synthesised to date. We will study the internal structure of these systems using γ-ray spectroscopy following: (i) the decay of metastable states (nuclear isomers) with lifetimes in the nano-to-millisecond time scale; and (ii) the β^--decay of highly neutron-rich nuclei with ground state lifetimes in the seconds range. In both types of measurement, events will be time correlated with respect to the detection of individually identified nuclei at the final focus of the FRS. The capability for such experiments with fragments heavier than A~100 is unique to the FRS. The proposed experiments will use the high-efficiency RISING γ-ray array of CLUSTER germanium detectors, complemented by BaF_2 detectors (which provide the opportunity for fast timing measurements in specific cases) and a segmented silicon 'active stopper' for β^--decay measurements.

BACKGROUND

A major thrust of nuclear structure research is to determine and understand how the shell structure of nuclei changes for systems with highly asymmetric proton-to-neutron ratios. The proposed research for this portion of the *Stopped Beam RISING Experimental Campaign* will exploit radioactive beams, produced using projectile-fragmentation reactions to enable the first study of a range of highly exotic, heavy, neutron-rich nuclei. These will take advantage of the existence of nano-to-millisecond isomers in these nuclei to enable the first spectroscopic information to be obtained (more details on this technique from GSI-FRS-based work can be found in references [1-6]). The relatively low intensities of the secondary radioactive beams in such experiments (typically less than 1 ion per second) can often preclude the use of γ-ray coincidence measurements that are needed to confirm the nuclear decay schemes. However, isomeric decays and measurements of decays following β-emission can provide the vital γ-ray 'fingerprints' which give the first glimpses of excited states and the internal structure of such nuclei. A systematic study of key experimental signatures, such as the energy of the first excited state and/or of the ratio of the excitation energies of the lowest-lying levels in even-even nuclei, can vividly demonstrate the erosion of the established magic numbers. This reveals both new regions of nuclear shell structure and the development of nuclear collective excitations. The current proposal aims to identify such fingerprints following radioactive-beam studies in selected exotic nuclei using isomer and β^{-}-delayed γ-ray detection.

Figure 1 shows the predicted ground state nuclear decay modes as predicted by the Moller-Nix mass model [8]. While a very wide range of exotic nuclei can be populated in projectile fragmentation, in-beam spectroscopy of such systems (as performed in the 'fast beam' part of the RISING Campaign) is limited by the total germanium singles counting rate at the production target for the secondary radioactive ions. For very weakly produced secondary nuclei, this limitation makes their spectroscopy impossible at the current time, using the in-beam technique. However, by using the Fragment Separator to select and transport the specific nuclei of interest to the final focal plane of the FRS, decays from both isomeric states [1-6] and following the radioactive decay of the daughter nuclei can be performed [7], allowing the first spectroscopic information on these highly exotic systems.

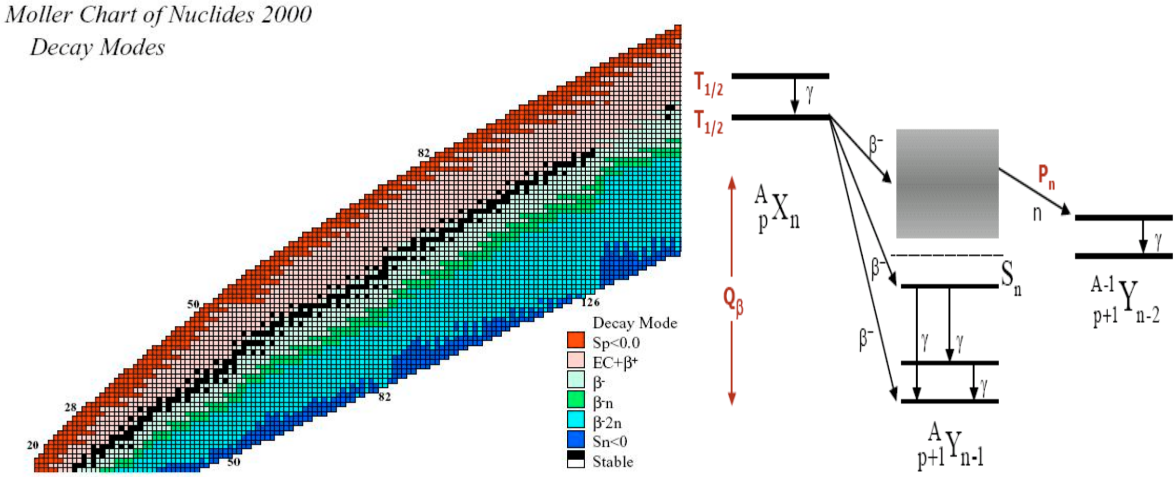

Figure 1: ***Left:*** Radioactive decay modes as predicted by the 2000 mass evaluation. ***Right:*** Schematic beta-decay and isomer modes of decay to populate excited states in specific daughter nuclei.

The specific stopped beam proposal are presented following a meeting to discuss the specific physics aims of the Stopped Beam RISING campaign, which took place at the University of Surrey in March 2004 (see http://www.ph.surrey.ac.uk/~phs1pr/rising/stopped_workshop_04). Note that the proposals submitted in this, 'active stopper' phase of the stopped beam RISING campaign are complemented by the a series of proposals aimed at measuring gyromagnetic ratios of isomeric states using a similar, but not identical, set-up (see proposals by G.Neyens et al.,).

The RISING project

RISING (<u>*R*are *IS*otope *IN*vestigations at *G*SI</u>) is a major new, pan-European collaboration. Its physics aims are the studies of exotic nuclear matter with abnormal proton-to-neutron ratios compared with naturally occurring isotopes. RISING consists of fifteen high-efficiency CLUSTER germanium detectors to measure the γ-ray fingerprints that reveal the internal structure of these exotic nuclei. The RISING project is supported by an International *Memorandum of Understanding* between centres in the UK, Germany, France, Sweden, Denmark, Poland, Belgium and Italy. It is managed by an International Steering Committee, currently chaired by Prof. J. Jolie of the University of Cologne. The RISING project has three components which use (i) fast, (ii) stopped, and (iii) slowed-down radioactive ion beams produced following projectile-fragmentation reactions. The proposals presented in this campaign deal with the 'stopped-beam' aspect of the RISING project with particular focus on those experiments which aim to perform β-delayed spectroscopy using a pixellated silicon 'active' stopper.

These experiments require that fifteen high-efficiency CLUSTER germanium detectors are placed at the focal plane of the FRS where they will be used to measure γ rays following (i) β decay to excited states and also from (ii) the direct electromagnetic decay of metastable excited nuclear states in the particular nucleus of interest (see schematic in figure 1). In order to study the structure of the daughter nuclei following β^- decay, a position sensitive, silicon *active stopper* detector will be used. Both the exotic mother nuclei produced in fragmentation and the subsequent β particles following the decay to populate the daughter species, will be measured in a position sensitive single silicon detector. This will allow a temporal correlation with the incoming (mother) heavy-ion fragment and its subsequent β-delayed gamma-ray emssion (measured following the β-decay to a specific daughter nucleus). The use of microsecond isomeric states in specific nuclei will also be used to calibrate and check the fragment particle identification in these experiments [1-6,9]. Also, known β-decays will also be used to calibrate the system [10]. The pixellated active silicon stopper will be instrumented by a collaboration between the groups at IFIC Valencia, the University of Santiago de Compostela and the University of Surrey (see later).

RISING Array Geometry, The Active Stopper Set-up and Implantation Rate Limitations

The active stopper experiments proposed to the current EA are expected to have a common experimental set-up. This will consist of the Stopped Beam RISING gamma-ray array of 15 clover detectors, placed in two rings or seven and eight cluster detectors respectively (see figures 2 and 3).

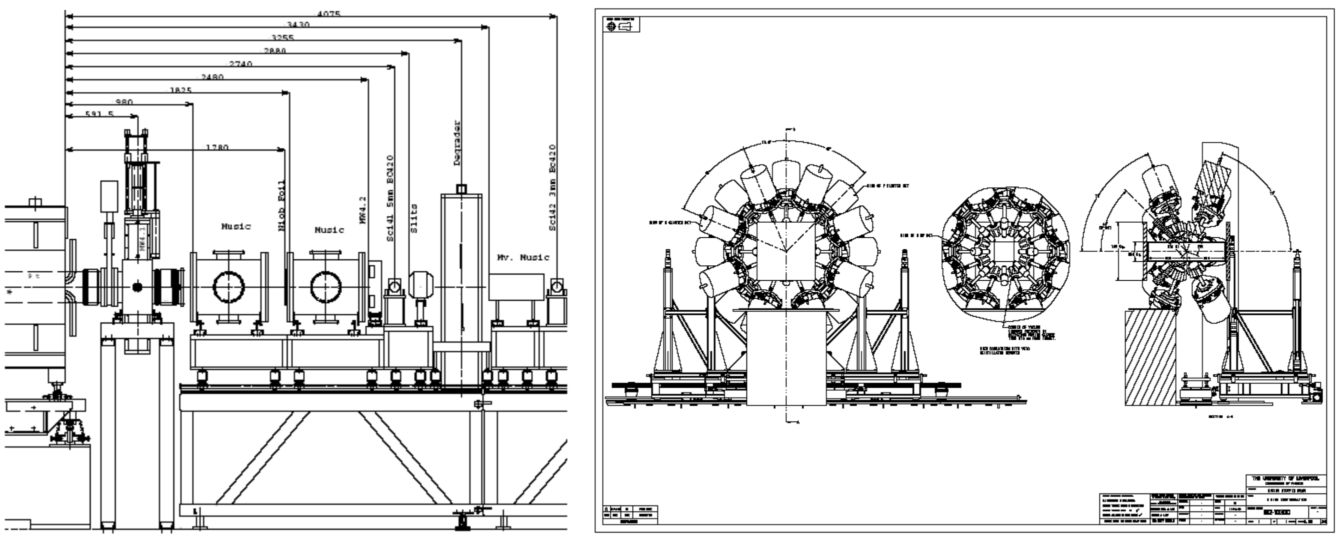

Figure 2 ***Left*** Suggested beam-line particle identification detectors prior to the DSSSD Active Stopper. ***Right:*** CAD design for the RISING array in the Stopped Beam Active Stopper Configuration.

In this geometry, the calculated photopeak efficiency for gamma-ray detection from the active stopper detector placed in the centre of the RISING array (see below) is calculated between 11% for an gamma-ray energy of 1.33 MeV and 20% for 662 keV. In addition, an array of 8 BaF_2 detectors will also be placed in the gamma-ray array for the ‘fast-timing’ of lifetimes in the hundreds of pico to few nanoseconds time range. This may also be utilised in specific cases where the ordering of newly observed transitions in a cascade needs to be measured.

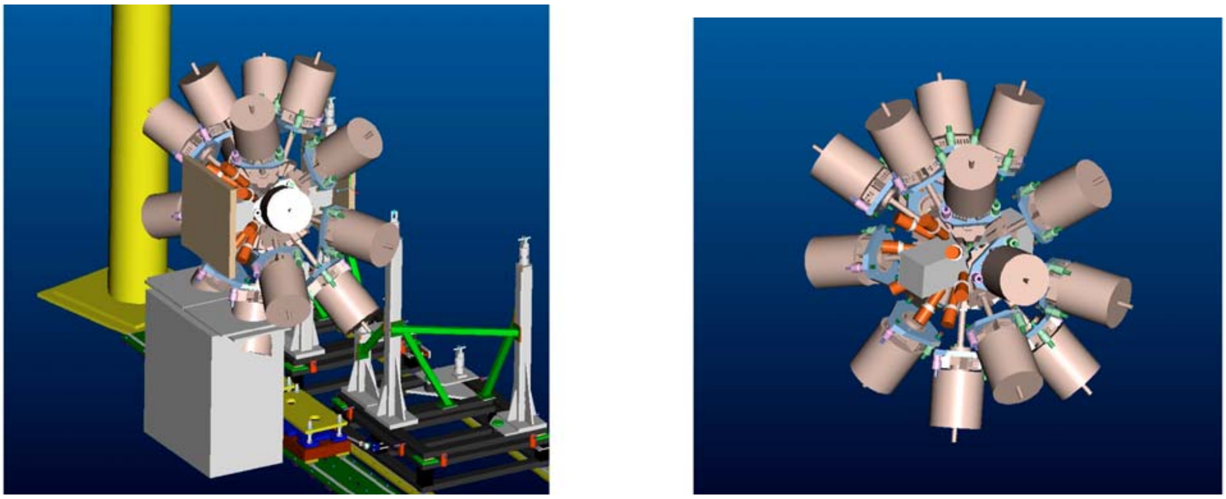

Figure 3 CAD drawings of the Stopped Beam RISING array, plus 8 BAF2 detectors for fast timing placed at forward angles. (left) Showing the support structure and space/plates for fast plastic scintillation detectors and (right) Shows space for the 25cm x 25cm vacuum chamber in which to house the DSSSDs.

The FRS will be used in the monochromatic mode which will enable specific ions to be stopped in a single 1mm thick silicon detector. This means that the experimenters can select specific elements of interest for β-delayed study. Figure 4 shows the effect of this from the recent experiment of Benlliure et al., following the fragmentation of a ^{208}Pb beam on a ^{9}Be target at a beam energy of 1 GeV per nucleon.

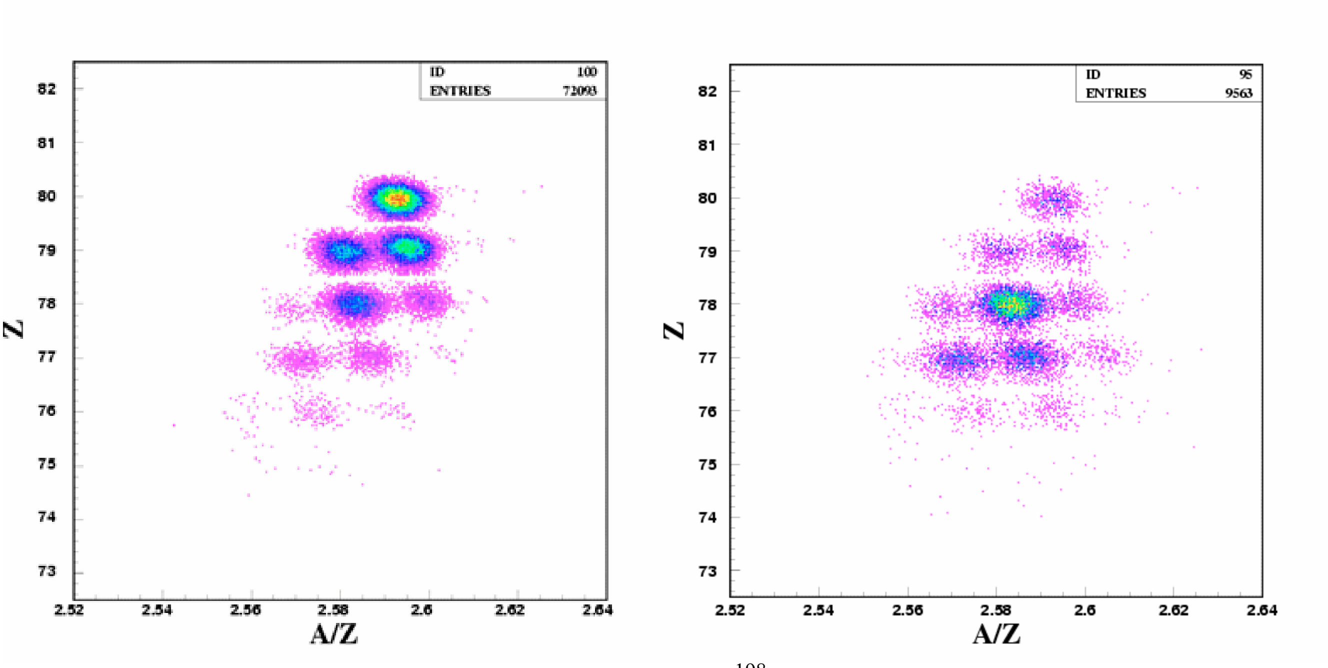

Figure 4 Particle identification plots centred on ^{198}Ir ions produced following the fragmentation of 1 GeV per nucleon ^{208}Pb beam on a ^{9}Be target with the FRS used in monochromatic mode. The left hand figure shows the total production yield at the end of the FRS, while the right hand side is limited to those ions which stopped in the 1mm thick silicon detector.

The active stopper will consist of three 5cm by 5cm double sided silicon strip detectors (DSSSDs) each with 16 horizontal and 16 vertical strips (giving each detector defined 256 pixels, or 768 pixels for the active stopper as a whole). The active stopper detectors are 1 mm thick, which is enough to stop all the ions of a given element if the FRS is used in monochromatic mode. (Heavier elements are stopped in the degrader or plastic scintillator which precedes the active stopper, as shown schematically on the left hand side of figure 2, while the lower-Z elements pass through the active stopper and are detected in to the plastic veto scintillator detector.

A number of the proposed experiments for the Active Stopper RISING campaign rely on rate estimates assuming 'cold fragmentation' of the primary beam [12]. Figure 5 shows the robustness of these estimates when compared with the measured cross-sections for cold-fragmentation products following reactions between a ^{197}Au beam on ^{9}Be target at 950 MeV per nucleon [12].

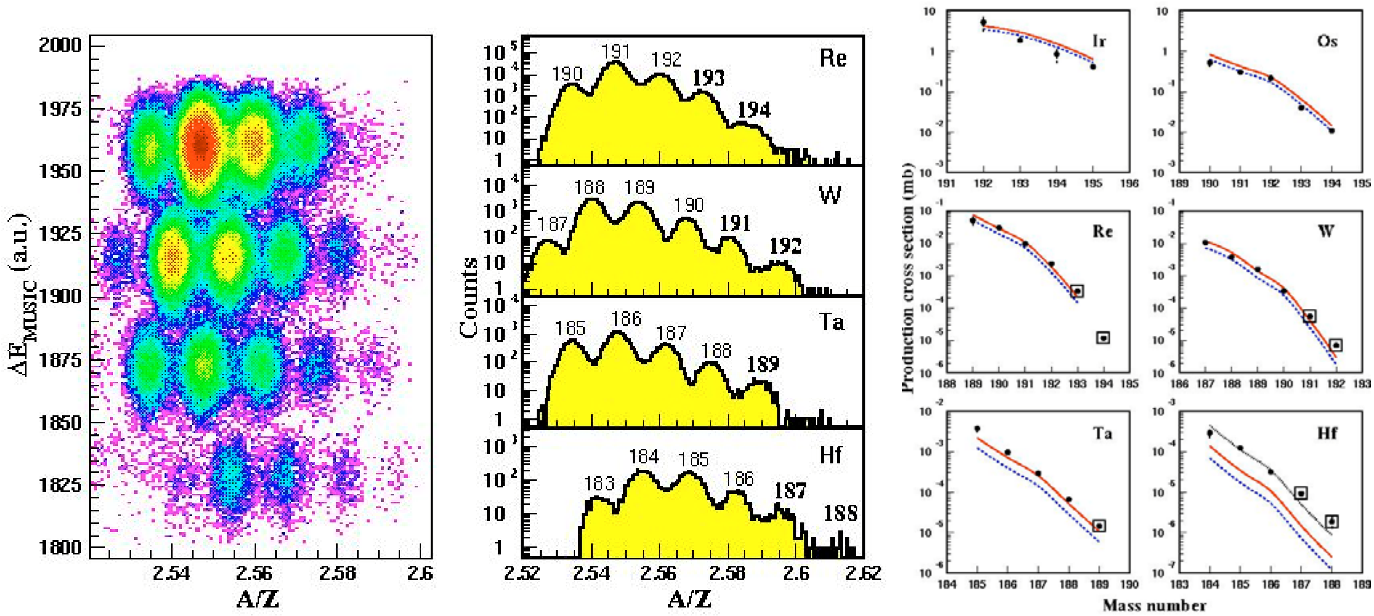

Figure 5: Particle identification plots and experimental cross-sections for the 'cold fragmentation' products in the ^{197}Au+^{9}Be reaction, highlighting the good agreements with the theoretical predictions for the cross-section given in reference. (Data taken from ref. [12]).

Assuming upper-limit β-decay half-life measurements of up to 30 seconds for the less exotic nuclei such as ^{204,5}Au, [11], this implies each pixel can be hit by a new ion on average every 150 seconds (5 typical half-lives) for a reasonable peak to total ratio. This assumption leads to a maximum implantation rate at the active stopper of around 5 ions in total per second, or 144k per 8 hour shift. The DSSSD array will have dual gain pre-amplifiers to obtain energy measurements for both the implanted heavy ion and the subsequently emitted β^--particle. Each event will be time stamped with a MHz clock to allow time correllation between the implantation and the subsequent β-decay in the same pixel. Most of the nuclei of interest have predicted β-decay half-lives of less than 10 seconds (see figures 6-9) which should significantly improve the experimentally useful correlation-time limit.

TIMELINESS

The proposal preceedes a massive investment in the GSI-FAIR facility. This €700M upgrade will make GSI the world's leading laboratory to study heavy, radioactive nuclei. This proposal represents a unqiue opportunity for the nuclear structure community to build on its initial projectile fragmentation isomer and reaction work at GSI and to drive a major physics initiative in nuclear spectroscopy through the RISING project. The combination of the FRS and the RISING array mean that the experimental technology is only now available to enable the measurements outlined in the following proposals.

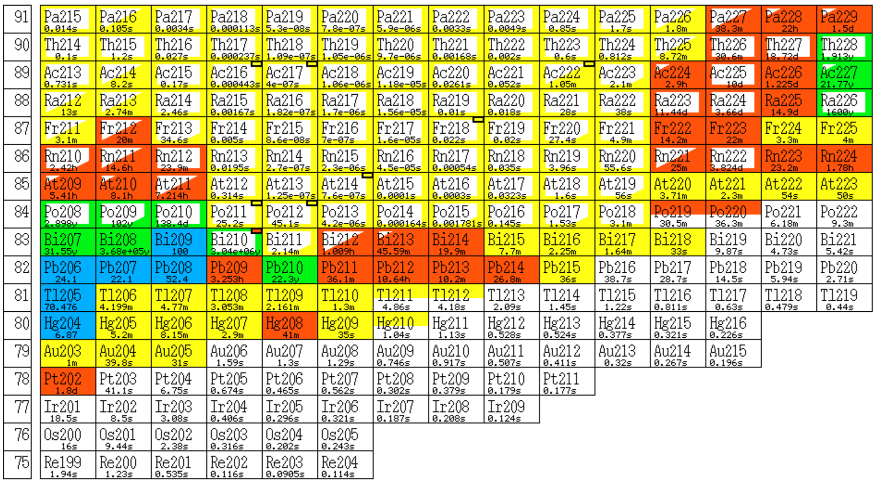

Figure 6: Predicted (white squares) β-decay half-lives for the neutron-rich N~126 region [9].

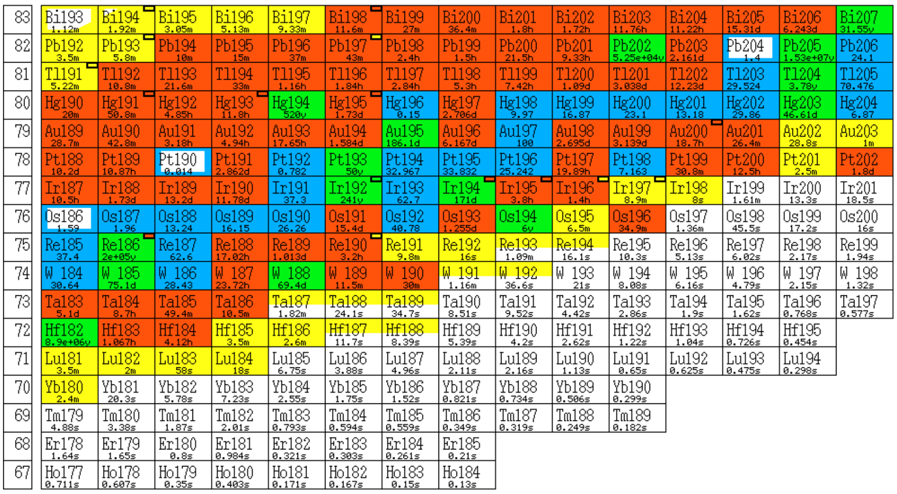

Figure 7 Predicted (white squares) β-half-lives for the ^{190}W Region [9].

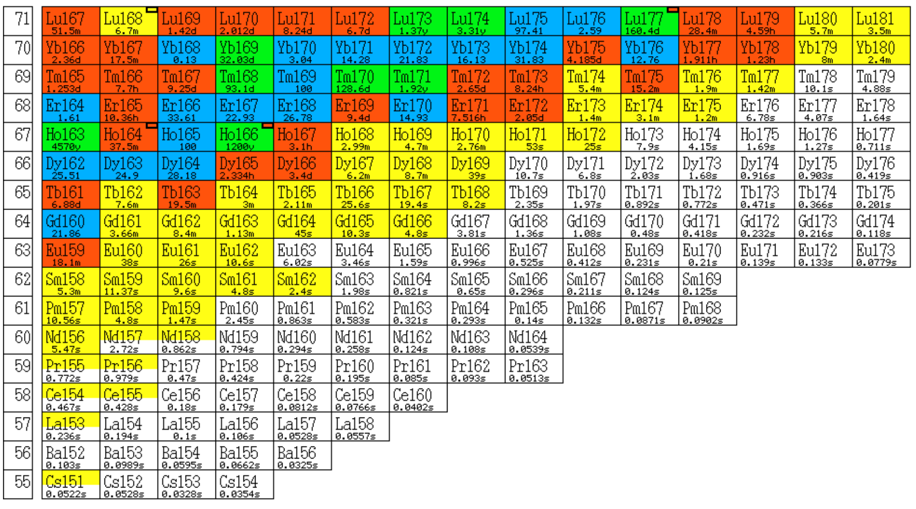

Figure 8 Predicted β-decay half-lives for the ^{170}Dy Region [9].

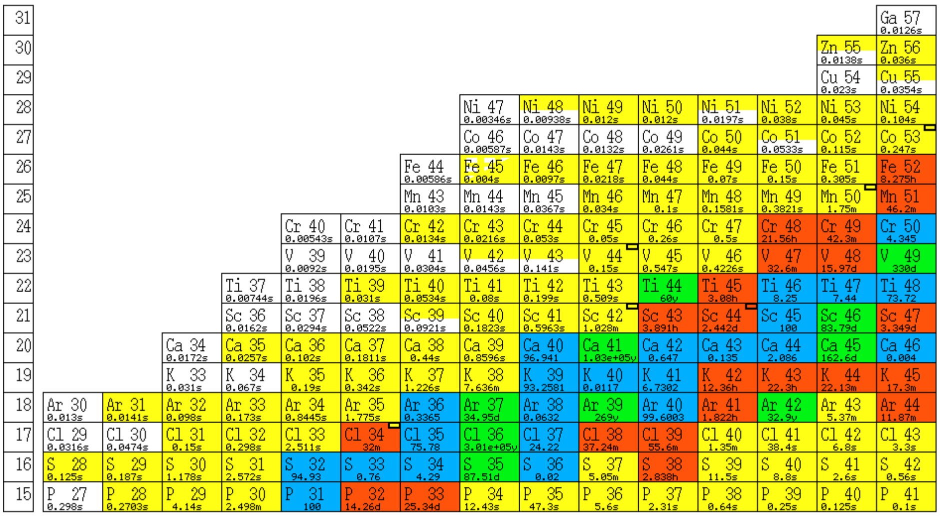

Figure 9 Predicted decay half-lives for the region around ^{50}Fe [9].

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