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Sensitivity studies for *r*-process nucleosynthesis in three astrophysical scenarios

R. Surman[1,2,a], M. Mumpower[2], J. Cass[2], I. Bentley[3], A. Aprahamian[2], and G.C. McLaughlin[4]

[1] *Department of Physics and Astronomy, Union College, Schenectady, NY 12308 USA*
[2] *Department of Physics, University of Notre Dame, Notre Dame, IN 46556 USA*
[3] *Department of Chemistry and Physics, St Mary's College, Notre Dame, IN 46556 USA*
[4] *Department of Physics, North Carolina State University, Raleigh, NC 27695 USA*

Abstract. In rapid neutron capture, or *r*-process, nucleosynthesis, heavy elements are built up via a sequence of neutron captures and β decays that involves thousands of nuclei far from stability. Though we understand the basics of how the *r* process proceeds, its astrophysical site is still not conclusively known. The nuclear network simulations we use to test potential astrophysical scenarios require nuclear physics data (masses, β decay lifetimes, neutron capture rates, fission probabilities) for all of the nuclei on the neutron-rich side of the nuclear chart, from the valley of stability to the neutron drip line. Here we discuss recent sensitivity studies that aim to determine which individual pieces of nuclear data are the most crucial for *r*-process calculations. We consider three types of astrophysical scenarios: a traditional hot *r* process, a cold *r* process in which the temperature and density drop rapidly, and a neutron star merger trajectory.

1 Introduction

One of the major open questions in nuclear astrophysics is the site of the formation of the heaviest elements in the *r*-process of nucleosynthesis (for a review, see e.g., [1]). The *r* process proceeds via rapid neutron captures, so the challenge is to identify a site that has the requisite neutron-to-seed ratio to form nuclei up through $A > 200$ [2]. Galactic chemical evolution studies favor supernovae [3]. However, modern simulations of the most promising site within a supernova — the neutrino-driven wind off the newly-formed protoneutron star — do not show sufficiently neutron-rich conditions to obtain an *r* process [4–7], though uncertainties in the neutrino physics and hydrodynamics remain (e.g., [8, 9]). Modern simulations of neutron star mergers, on the other hand, show robustly neutron-rich outflows with vigorous *r*-processing [10, 11], and there may even be a hint of the radioactive decay of *r*-process material observed in a merger event [12]. However, given the long evolutionary timescales of binary merger events, it is difficult to understand observations of *r*-process nuclei in very old stars [13] if mergers are the sole *r*-process site.

Simulations of *r*-process nucleosynthesis that investigate these astrophysical scenarios rely on nuclear data such as masses, β-decay rates, and neutron capture rates for thousands of nuclei on the neutron-rich side of stability. Theoretical calculations of these quantities can disagree by large factors,

[a] e-mail: surmanr@union.edu

and experimental information is only available for a handful of the needed masses and β-decay rates, though the situation is improving dramatically as the next generation of radioactive beam facilities begin to take data. We have developed a program of r-process sensitivity studies to determine which of the thousands of pieces of nuclear data needed should be the targets of new experimental campaigns. In these sensitivity studies, a baseline r-process simulation is chosen, then each piece of nuclear data is varied individually and the simulation re-run. Then the pieces of nuclear data with the greatest impact on the final r-process abundance pattern are identified and the mechanisms of their influence are determined. So far r-process sensitivity studies have been performed for neutron capture rates [14–17], nuclear masses [18, 19], and β-decay rates [19, 20].

Here we review the notable features of the sensitivity study results for separate nuclear mass, β-decay rate, and neutron capture rate sensitivity studies for a main ($120 < A < 200$) hot r process. These studies start with a single set of astrophysical conditions and point out the most important pieces of nuclear data for those conditions. However, exactly how the r process proceeds and which nuclei far from stability are populated depend strongly on the (very uncertain) astrophysical site. We therefore repeat our sensitivity studies assuming two additional distinct types of astrophysical conditions: a neutrino-driven wind cold r process, where the temperature and density drop quickly and equilibrium between captures and photodissociations, (n,γ)-(γ,n) equilibrium, holds only briefly, and a low entropy, very neutron-rich r process from a neutron star merger simulation.

2 Sensitivity studies

We run our sensitivity studies as described in [15, 18, 19]. We use an r-process nuclear network code from [21], and we take nuclear masses from the finite-range droplet model (FRDM) [22], β-decay rates from the quasiparticle random phase approximation (QRPA) calculations (including first forbidden decays) of [23], and neutron capture rates from NON-SMOKER [24], wherever experimental data is not available. Fission is included as in [25]. We chose a set of astrophysical conditions and produce a baseline r-process simulation. For each baseline trajectory chosen, we then run three separate sensitivity studies: a nuclear mass sensitivity study, where we vary individual binding energies by ±1 MeV as in [19], a β-decay rate sensitivity study, where we vary individual β-decay rates by a factor of 10 as in [20], and a neutron capture rate sensitivity study, where we vary individual capture rates by a factor of 100 as in [15, 17]. Finally we compare the final abundance patterns produced with the nuclear data variations to the baseline pattern using the sensitivity measure F:

$$F = 100 \times \left\{ \sum_A |AY_{\mathrm{baseline}}(A) - AY_{\mathrm{increase}}(A)| + \sum_A |AY_{\mathrm{baseline}}(A) - AY_{\mathrm{decrease}}(A)| \right\} /2 \qquad (1)$$

where $Y_{\mathrm{baseline}}(A)$ are the final baseline abundances, and $Y_{\mathrm{increase}}(A)$ and $Y_{\mathrm{decrease}}(A)$ are final abundances of the simulations where a single piece of nuclear data is increased or decreased, respectively.

For this work we chose three distinct astrophysical scenarios for the baseline simulations, with final abundance patterns shown in Fig. 1. The first is a classic hot r process similar to that studied in [14–20]. A classic hot r process is characterized by an (n,γ)-(γ,n) equilibrium phase during which the main r-process peaks at $A \sim 130$ and $A \sim 195$ are produced, followed by a freezeout phase triggered by the depletion of free neutrons. During the freezeout phase, photodissociations, neutron captures, β decays, and β-delayed neutron emission all compete to set the final abundance pattern and to form the smaller abundance peak near $A \sim 162$ called the rare earth peak [26, 27]. For this example we take a parameterized wind trajectory from [28] as implemented in [17], with entropy $s/k = 50$, dynamical timescale $\tau_{\mathrm{dyn}} = 80$ ms, and initial electron fraction $Y_e = 0.250$.

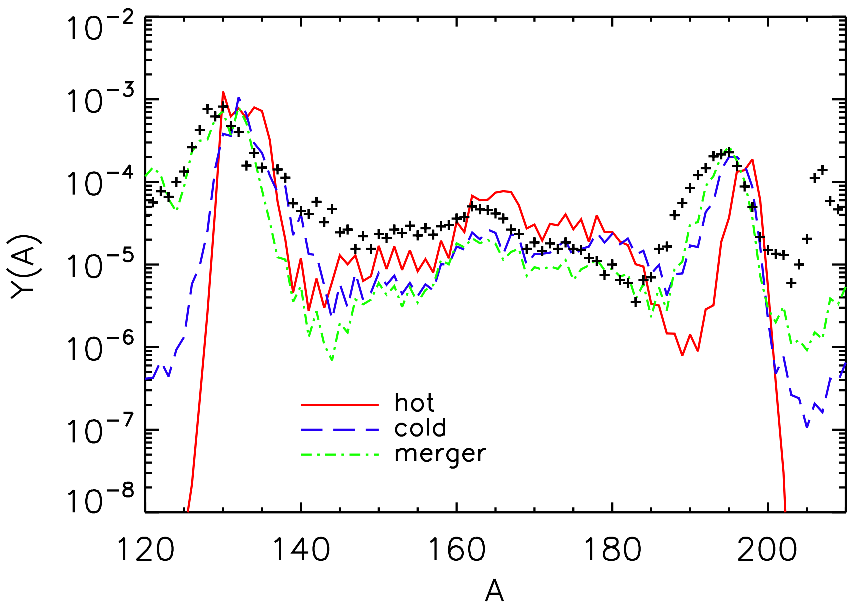

Figure 1. Abundances versus mass number for the three baseline *r*-process simulations described in the text: a parameterized wind hot *r* process (solid red line), supernova neutrino-driven wind cold *r* process (long-dashed blue line), and a neutron star merger *r* process (dot-dashed green line). The scaled solar *r*-process abundances, obtained by subtracting the modeled *s*-process abundances from the raw solar system values, from [13] (crosses) are shown for comparison.

The second astrophysical scenario considered is a cold *r* process. In a cold *r* process, the temperature and density drop quickly, so (n, γ)-(γ, n) equilibrium is established only briefly. Once the temperature drops, photodissociation effectively turns off, and an a new equilibrium is established between neutron captures and β decays. For our cold *r*-process example we take a trajectory from the neutrino-driven wind simulations of [4] where we artificially reduce the electron fraction to $Y_e = 0.31$ from the simulation value of just below 0.5 to produce a main *r* process.

The final scenario we consider is the ejection of mildly heated ($T \sim 10$ GK), very neutron-rich material from the tidal tails of a neutron star merger. We start with a trajectory from a simulation by Bauswain and Janka, similar to those from [10]. We then extrapolate it out to low temperatures, $T \sim 0.01$ GK, keeping the entropy constant, as validated by recent merger simulations followed to late times [29]. The resulting *r* process proceeds in (n, γ)-(γ, n) equilibrium as in the classic hot *r* process, but here freezeout is prompted by the drop in temperature and density rather than an exhaustion of free neutrons as in the hot *r*-process case. Neutrons are in fact so plentiful that fission recycling occurs.

3 Results

Fig. 2 shows the results of the mass/binding energy sensitivity studies for each of the three astrophysical scenarios. As described in [18, 19], masses appear explicitly in an *r*-process network code only in the calculation of photodissociation rates via detailed balance. Thus, these sensitivity studies point out the importance of nuclear masses in (1) determining abundances along the r-process path while (n,γ)-(γ,n) equilibrium holds, and (2) setting the individual photodissociation rates that become important when (n,γ)-(γ,n) equilibrium fails. Both of these effects are important for the classic hot r process, as demonstrated in [18, 19] and shown in the top panel of Fig. 2. High sensitivity measures F are found for nuclei along the equilibrium r-process path, particularly at the closed shells where the main peaks form, as well as for nuclei along the decay paths toward stability, particularly in the rare earth region as the rare earth peak forms. In contrast, the cold r-process study (middle panel of Fig. 2) and the merger study (bottom panel of Fig. 2) show high sensitivities only along the equilibrium r-process path. In the cold r process, the temperature drops so quickly that equilibrium fails before even the $A \sim 195$ peak is formed, and photodissociation plays almost no role in the subsequent dynamics. In the merger case, the main abundance features are indeed formed in (n,γ)-(γ,n) equilibrium, but since the onset of freezeout is due to the declining temperature photodissociations are not important during the decay back to stability.

The neutron capture rate sensitivity measures for the same three trajectories are shown in Fig. 3. Individual neutron capture rates become important only after (n,γ)-(γ,n) equilibrium begins to break down. Therefore, for a hot r process, there is little sensitivity to neutron capture rates of nuclei along the r-process path during the equilibrium phase, as described in [14, 15, 17] and as shown in the top panel of Fig. 3. The greatest sensitivities are found for nuclei along the β-decay pathways of the equilibrium r-process path nuclei, particularly near the closed shells where the abundances are highest and in the rare earth region where they impact the rare earth peak formation mechanism. In contrast, in a cold r process (n,γ)-(γ,n) equilibrium is quickly replaced by a new equilibrium between β decays and neutron captures. Thus, the cold r-process example shown in the middle panel of Fig. 3 demonstrates sensitivity to neutron capture rates of nuclei along the early-time r-process path, as well as along the β-decay pathways of these nuclei. The merger example shown in the bottom panel of Fig. 3 indicates similar systematics to the hot r-process example, except for a much broader range of nuclei since the equilibrium r-process path is so far from stability.

Finally in Fig. 4 we show the results from the three β-decay rates sensitivity studies. β-decay rates are of key importance in setting the relative abundances of nuclei along the r-process path, and they remain important during the freezeout phase for as long as β decay competes with neutron capture [20]. Thus we expect the highest β-decay sensitivities for nuclei along the early-time r-process path, with nonzero sensitivities extending through nuclei quite close to stability regardless of the astrophysical scenario, as shown in all three panels of Fig. 4. An additional notable feature of the β-decay sensitivity measures is that they are significantly larger for even-N nuclei than odd-N nuclei. This is because odd-N nuclei are much more likely to be depopulated by neutron capture or photodissociation than β decay.

4 Discussion

Studies of r-process nucleosynthesis suffer from large uncertainties in the nuclear physics input due to lack of experimental data and in the astrophysics due to the unsolved quest for the r-process site. Here we have examined the sensitivity of the final r-process abundance pattern to individual masses, β-decay rates, and neutron capture rates in three very different potential astrophysical scenarios: a traditional hot r process, a supernova neutrino-driven wind cold r process, and a neutron star merger fission cycling r process. The resulting sensitivities highlight the differences in how the r process proceeds in each case. However, there is one key similarity: the most important pieces of nuclear data in all cases are for nuclei near the closed shells and in the rare earth region 10-20 neutrons from stability. We recommend these nuclei be targets of the next generation of experimental campaigns.

Acknowledgements

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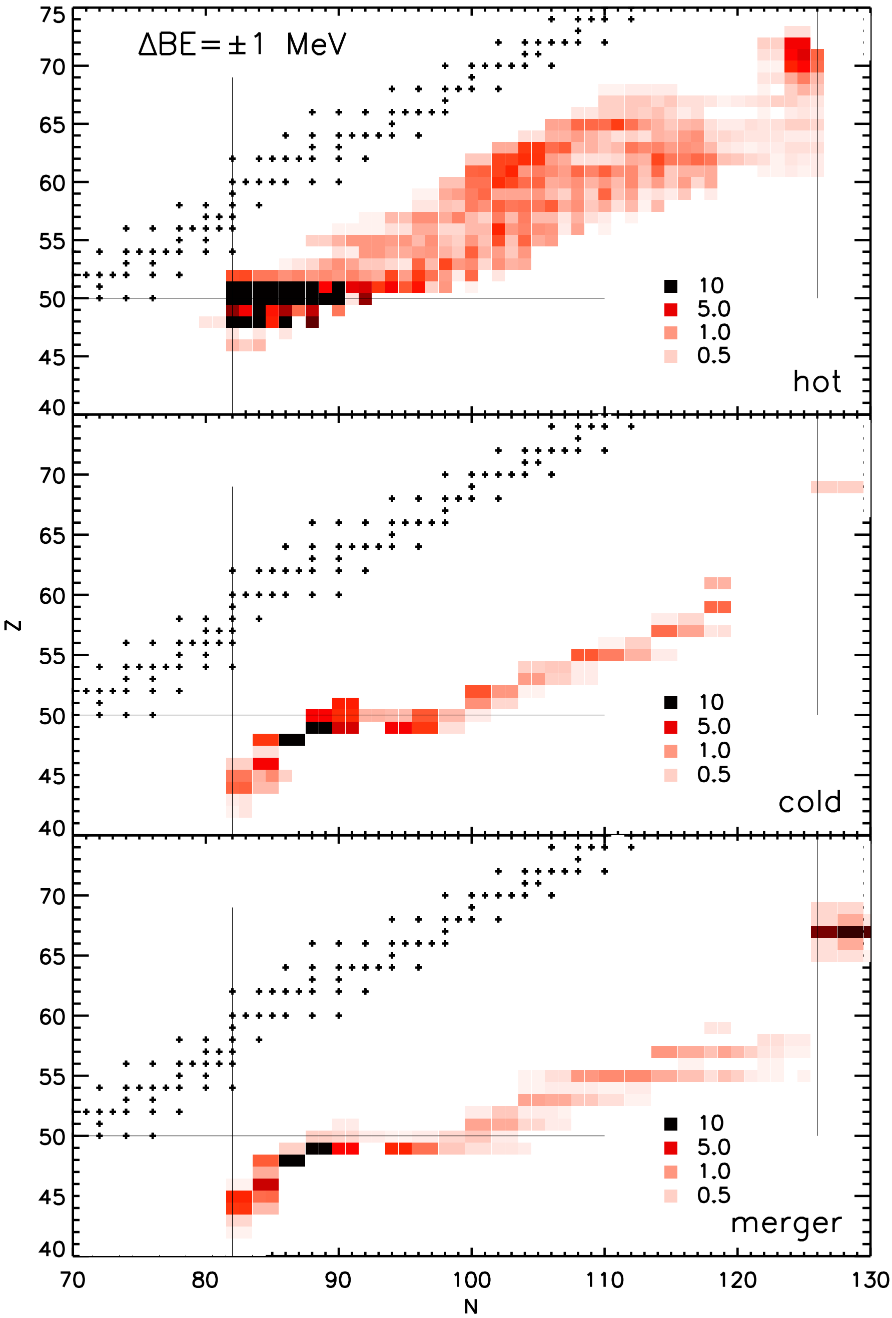

Figure 2. Sensitivity measures F for three binding energy sensitivity studies starting from the different astrophysical conditions as described in the text: a parameterized wind hot r process (top panel), supernova neutrino-driven wind cold r process (middle panel), and a neutron star merger r process (bottom panel).

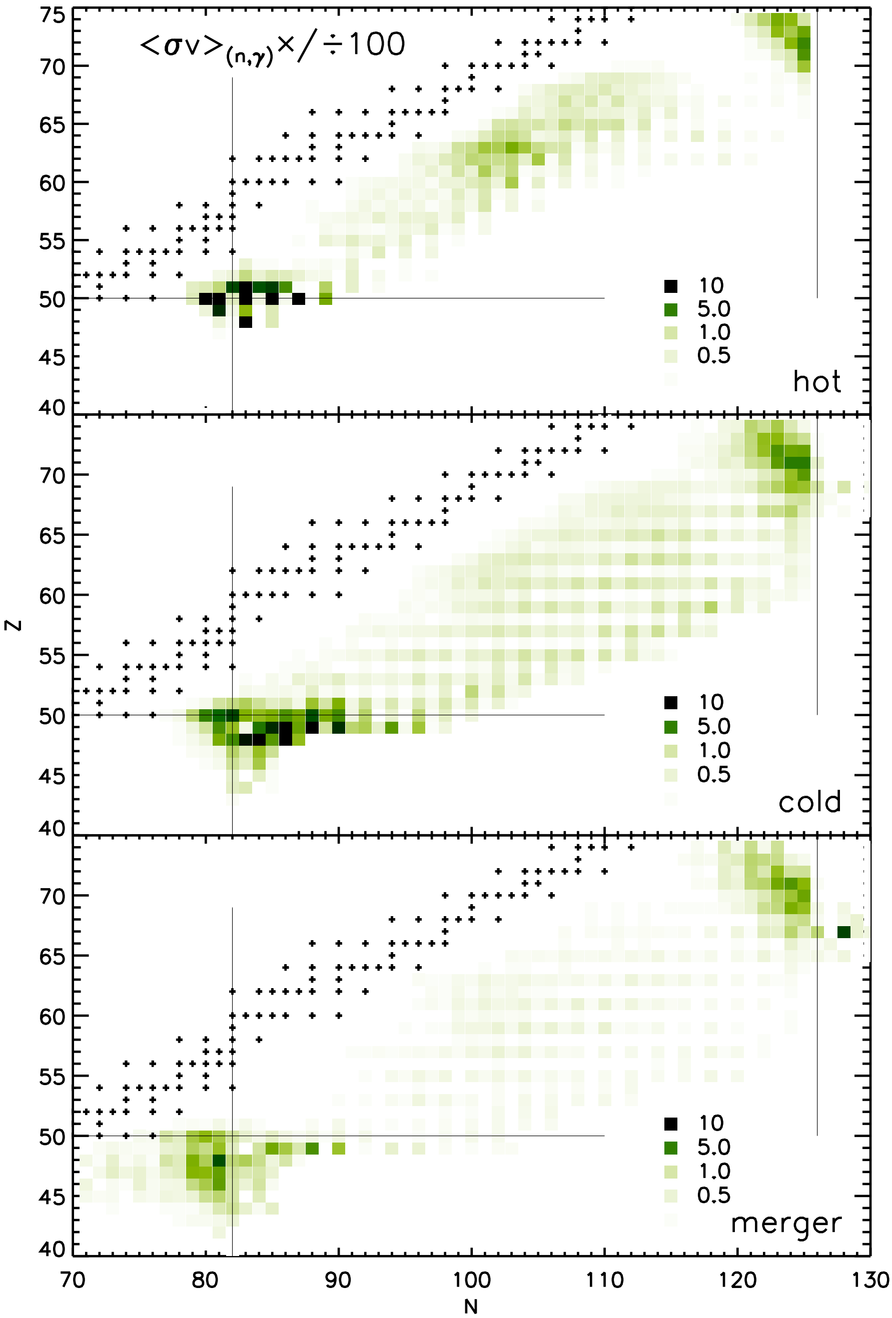

Figure 3. Sensitivity measures *F* for three neutron capture rate sensitivity studies, as in Fig. 2.

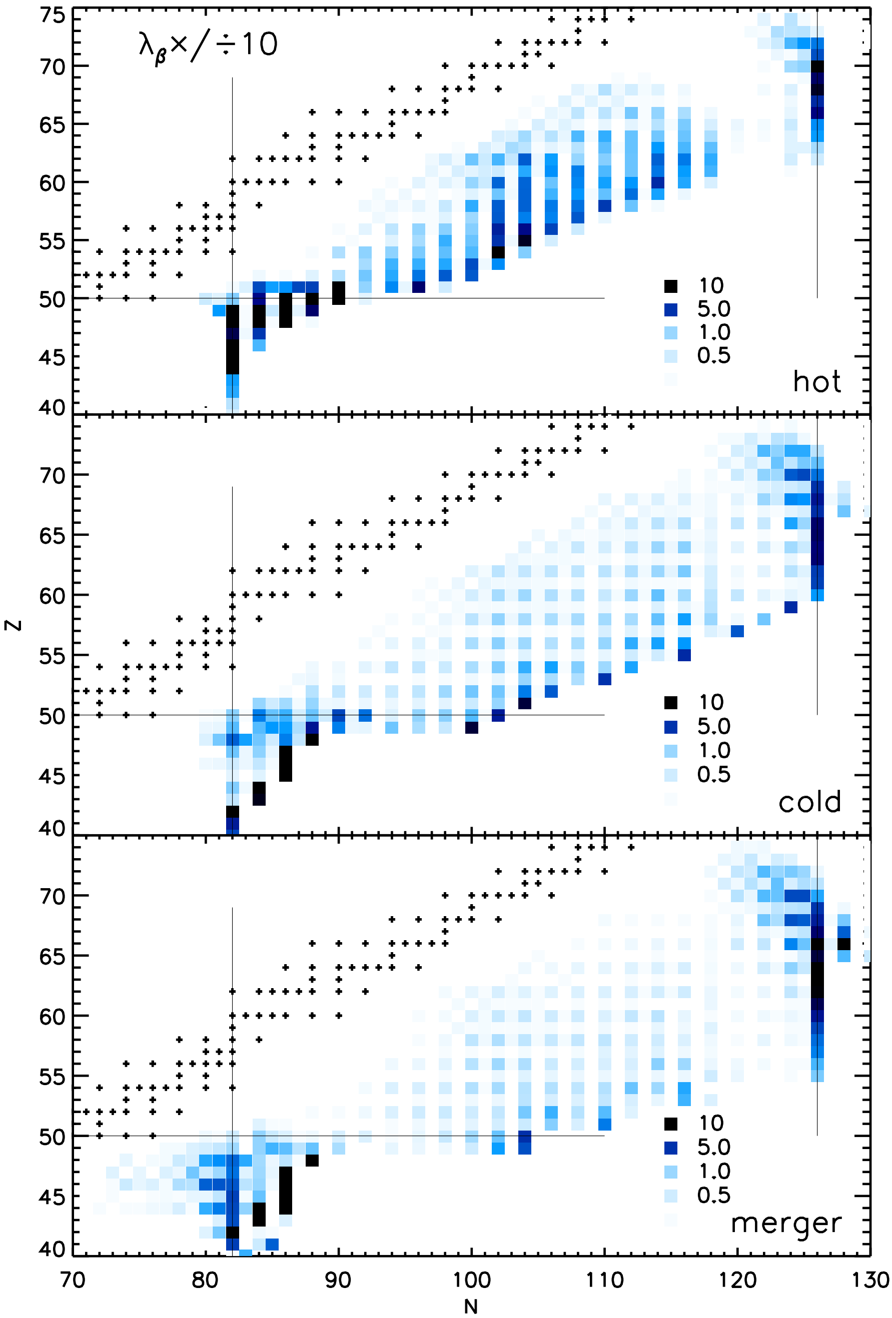

Figure 4. Sensitivity measures F for three β-decay rate sensitivity studies, as in Fig. 2.