The NUBASE2016 evaluation of nuclear properties [*]

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Abstract: This paper presents the NUBASE2016 evaluation that contains the recommended values for nuclear and decay properties of 3437 nuclides in their ground and excited isomeric ($T_{1/2} \geq 100$ ns) states. All nuclides for which any experimental information is known were considered. NUBASE2016 covers all data published by October 2016 in primary (journal articles) and secondary (mainly laboratory reports and conference proceedings) references, together with the corresponding bibliographical information. During the development of NUBASE2016, the data available in the "Evaluated Nuclear Structure Data File" (ENSDF) database were consulted and critically assessed for their validity and completeness. Furthermore, a large amount of new data and some older experimental results that were missing from ENSDF were compiled, evaluated and included in NUBASE2016. The atomic mass values were taken from the "Atomic Mass Evaluation" (AME2016, second and third parts of the present issue). In cases where no experimental data were available for a particular nuclide, trends in the behavior of specific properties in neighboring nuclides (TNN) were examined. This approach allowed to estimate values for a range of properties that are labeled in NUBASE2016 as "non-experimental" (flagged "#"). Evaluation procedures and policies used during the development of this database are presented, together with a detailed table of recommended values and their uncertainties.

AMDC: http://amdc.impcas.ac.cn/

1   Introduction

NUBASE is a database containing values of the main nuclear properties, such as masses, excitation energies of isomers, half-lives, spins and parities, and decay modes and their intensities, for all known nuclides in their ground and excited isomeric states. The information presented in NUBASE represents the fundamental building blocks of modern nuclear physics, and specifically, of nuclear structure and nuclear astrophysics research. The first version of NUBASE was published in 1997 [1] and since then it has been widely used in many fields from fundamental physics to applied nuclear sciences. The present publication includes updated information of all nuclear properties given in the previous publications of NUBASE [1–3].

One of the main applications of NUBASE2016 is the "Atomic Mass Evaluation" (AME2016, second and third parts of this issue) where it is imperative to have an unambiguous identification of all states involved in a particular de-

cay, reaction or mass-spectrometric measurement. This is the primary reason for which the two evaluations are published jointly in the present issue, for the third time since the publication of the NUBASE2003 [2].

Furthermore, with the advances of modern mass-spectrometry techniques (see for example the special issue of "one hundred years of mass spectrometry" for relevant topics [4]) and the availability of intense stable and rare-isotope beams, a large number of unstable nuclei can be produced in a single experiment in their ground and/or isomeric states, and their masses can be measured with high precision. Thus, NUBASE2016 can be particularly useful in future mass measurements, where an unambiguous identification of complex mass-spectrometric data would be required.

Applications of this database in astrophysics network calculations and in theoretical studies of nuclear properties, where complete and reliable data for all known nuclei are needed, are also envisioned.

Last, but not least, the evaluated data presented in NUBASE2016 are also useful for specialists in applied nuclear fields, such as reactor engineering and design, fuel manufacture and transport, waste management, material analysis, medical diagnostics and radiotherapy, and others, where one needs to access basic information for a given nuclide.

The information presented in NUBASE2016 fulfills several user-demanded requirements, namely that it is: a) *complete* − includes all measured quantities and their uncertainties, b) *up-to-date* − results from the most recent publications are included, c) *credible and reliable* − identifies and resolves contradictory results that exist in the scientific literature, as well as in other nuclear physics databases, d) *properly referenced* − provides comprehensive information for the traceability of all included data.

Most of the data included in NUBASE2016 are in principle available in two other evaluated databases: the "Evaluated Nuclear Structure Data File" (ENSDF) [5] and the "Atomic Mass Evaluation" (AME2016). Therefore, the demand for NUBASE could be partially fulfilled by combining these two databases into a single, 'horizontal' structure, which exists in AME, but not in ENSDF. Therefore, NUBASE2016 can be considered at a first level as a critical combination of those two evaluations.

During the development of the present version of NUBASE, it was imperative to examine all available literature for several nuclides in order to revise results adopted in ENSDF, and to ensure that the recommended data are presented in a consistent way (*credibility and reliability* requirements). It was also necessary to include all the available experimental data, i.e. not only results that were published recently (*up-to-date* requirement), but also older data that were missing in ENSDF (*completeness* requirement). This implied that some extra evaluation work was necessary. The corresponding conclusions are added as remarks in the NUBASE2016 table, and in the discussions below. Complete bibliographical references are given for all added experimental data in Table I (see Section 2.8).

There is no strict literature cut-off date for the results presented in the NUBASE2016 evaluation: all data available to the authors until October 2016 have been included. Results that were not incorporated for special reasons, e.g. the need for a heavy revision of the evaluation at too late a stage of development, are added, whenever possible, in remarks to the relevant data.

During the preparation of NUBASE2016, we noticed that Ref. [6] reports important decay data for proton-rich nuclides ^{67}Kr, ^{63}Se and ^{59}Ge, where a two-proton emission from ^{67}Kr was observed. We found that it was too heavy an effort at this stage to include these results into NUBASE2016, especially to establish the atomic mass surface in this region. They are not included in the current evaluation, but the original paper is just mentioned here.

The contents of NUBASE2016 are described below, together with the adopted policies that were used during the development of this database. Section 3 presents the updating procedures, while the electronic distribution and interactive display of NUBASE2016 contents by means of a stand-alone PC-program are described in Section 4.

2   Contents of NUBASE2016

The NUBASE2016 evaluation contains recommended values for the basic nuclear ground-state properties, for 3437 nuclides, derived from all available experimental results, together with some values estimated by extrapolating neighboring ones. It also contain data for 1318 nuclides which have one or more excited isomeric states with half-lives longer than 100 ns.

Similar to the previous editions, NUBASE2016 also contains data on 186 isobaric analog states (IAS), which have their excitation energies determined either through an "internal relation" and taken from ENSDF, or through an "external relation" and then determined by the AME2016 evaluation.

For each nuclide (A, Z), and for each state (ground or excited isomer), the following properties were compiled and, when necessary, evaluated: mass excess, excitation energy of excited isomeric states, half-life, spin and parity, decay modes and their intensities, isotopic abundance (for a stable nuclide), year of discovery and the corresponding bibliographical information for all experimental data.

References to published articles in the description sections below are given by means of the keynumber style used in the "Nuclear Science Reference" (NSR) bibliographical database [7]. However, references quoted in the NUBASE2016 tables are abbreviated with the first two digits of the year of publication being omitted from the NSR keynumbers. The complete reference list is given at the end of this issue, together with the references used in AME (see AME2016, Part II).

At the time the work on NUBASE2016 was completed, superheavy elements (SHE) up to Z = 118 were officially named by The Commission on Nomenclature of Inorganic Chemistry of the International Union of Pure and Applied Chemistry (IUPAC) [8]:

  113   Nihonium   (Nh),
  115   Moscovium   (Mc),
  117   Tennessine   (Ts),
  118   Oganesson   (Og).

We were not able to include the new names in AME2016 and NUBASE2016, but instead we used the provisional symbols Ed, Ef, Eh, and Ei for elements 113, 115, 117, and 118, respectively.
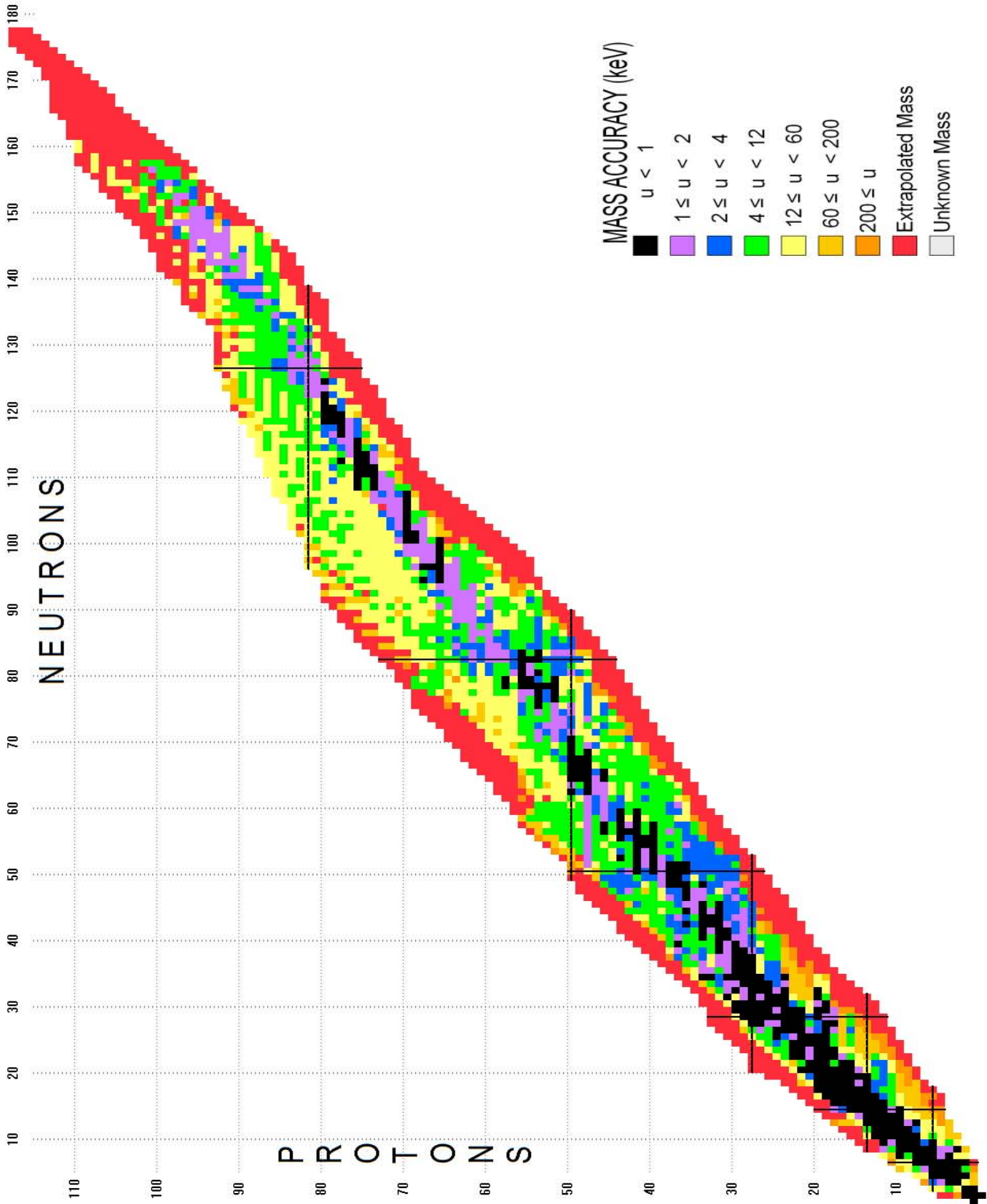
Figure 1.   Chart of the nuclides displaying the accuracy 'u' of masses (created by NUCLEUS-AMDC).

NUBASE2016 contains numerical and bibliographical data for all known nuclides for which at least one property is known experimentally in their ground state, excited isomeric states with $T_{1/2} \geq 100$ ns, and/or IAS. It also includes information on yet unobserved nuclides, estimated from the observed experimental trends of neighboring nuclides (TNN). This ensures continuity in the set of considered nuclides simultaneously in N, in Z, in A and in $N - Z$. The chart of nuclides defined in this way has a smooth contour.

For experimentally unknown properties, values were also estimated from TNN. Similarly to AME2016, the estimated values are flagged with the symbol '#' to indicate non-experimental information.

As a rule, one standard deviations (1σ) are used in NUBASE2016 to represent the uncertainties associated with the quoted experimental values. Unfortunately, authors of research articles do not always define the meaning of their reported uncertainties and those values were assumed to be one standard deviations . In many cases, uncertainties are not even given at all and were estimated by us, considering the limitations of the experimental method.

Values and corresponding uncertainties for properties given in NUBASE2016 are rounded , even if unrounded values were given in the literature or in ENSDF. In cases where the two furthest left significant digits in the uncertainty were larger than a given limit (set to *30* for masses and energies to be consistent with AME2016, and set to *25* for all other quantities, as used in ENSDF), values and uncertainties were rounded accordingly (see examples in the 'Explanation of table'). In a few cases that were deemed essential for traceability purposes (e.g. isotopic abundances) the original (unrounded) value is also provided in an associated comment.

2.1   Mass excess

In NUBASE2016 the mass excess values (in keV), defined as being differences between the atomic mass (in mass units) and the mass number, together with their one-standard-deviation uncertainty, are taken from the mass tables of the AME2016 evaluation.

In general, knowledge of masses can provide valuable information on decay modes, in particular for a particle-decay instability, or β-delayed particle-decay, for nuclei far from the line of stability. Such information is used in NUBASE2012, for example for ^{10}He, ^{39}Sc, ^{62}As, or ^{63}As. In some cases, the claimed observations of decay modes were rejected when it was found that they were not allowed through simple energetics.

Figure 1 displays the mass accuracy from the main table, as a function of N and Z.

2.2   Isomers

In the first version of NUBASE [1], a definition for excited isomers was adopted: excited states with a half-life longer than one millisecond. Within this definition, all β-decaying states were included in this category, since they have a lower half-life limit of one millisecond. However, already at that time, it was noticed that such a definition had several drawbacks, particularly for neutron-deficient alpha- and proton-decaying nuclides, where much shorter-lived states were known to exist. Moreover, several cases are known where isomers with half-lives far below one millisecond survive longer than the ground state itself, e.g. ^{216}Fr.

With the publication of NUBASE2003 [2], the definition of isomers was extended to half-lives longer than 100 ns, and such states are now included in NUBASE2016. The main reasons for this change were to include:

a) all proton- and alpha-decaying states observed in many neutron-deficient nuclei,

b) isomers that may be detected in mass-spectrometric experiments performed at accelerator facilities following the immediate detection of the produced nuclei, and

c) all possible isomers that may be detected in such experiments in the future.

In NUBASE2016, isomers are tabulated in order of increasing excitation energy and identified by appending the letters 'm', 'n', 'p', 'q', or 'r' to the nuclide name, e.g. ^{90}Nb for the ground state, ^{90}Nb^{m} for the first excited isomer, ^{90}Nb^{n} for the second one, and ^{90}Nb^{p}, ^{90}Nb^{q}, and ^{90}Nb^{r} for the third, fourth and fifth ones, respectively. In the cases of ^{179}Ta and ^{214}Ra a sixth isomer had to be included, and they were labeled provisionally with the letter 'x'.

Suffix 'x' also applies to mixtures of levels which are used in the atomic mass evaluation. These mixtures occur in spallation reactions or in fission and they appear in mass measurements performed using mass spectrometers. For each mixture, the excitation energy and the relative production rate of isomeric state with respect to ground state are given.

The excitation energy of a given isomer can be determined using different experimental methods, which, in general, belong to the category of either internal or external relations. A typical internal relation is via the γ-ray decay energy, or a combination of such γ-ray energies. The most accurate values for the excitation energies of isomers deduced by this approach can be found in ENSDF, where a least-squares fitting procedure is applied to all γ rays along the decay path of a particular isomer. However, when no such internal relations can be established, then the relation to other nuclides (external relations) can be used to deduce the mass (or energy) difference between excited and ground-state isomers. In all such cases, the most accurate values can only be derived using the AME evaluation procedure and the values are therefore taken from AME2016. The origin (the method used to establish the external relation) of each isomer data element is then indicated by a two-letter code, next to the isomer excitation energy, in the NUBASE2016 table. For internal relations, the origin field is left blank and the numerical values are taken either from ENSDF or from literature updates. In the latter case, a least-squares fit to the measured γ-ray decay energies from

complex level schemes was applied, in accordance with the current ENSDF policies.

It also happens that connections between excited and ground state isomers can be obtained by both internal relations and one, or more, external relations with comparable accuracies. All relations are then combined within the AME2016 data by adding an equation that relates the excitation energy obtained from ENSDF (or from literature), so that AME2016 derives the best combination of all data. For example, the AME2016 derives the mass of ^{178}Lu^m at 66% from E_x(IT)=120(3) keV [1993Bu02] and at 34% from ^{176}Lu(t,p)^{178}Lu^m=4482(5) keV [1981Gi01]. The adjusted excitation energy is thus 123.8(2.6) keV.

In some cases, excitation energies known from internal relations are essential in order to determine the mass of the ground state. Those values are labeled in the NUBASE table with 'IT' in the origin field. They are entered as an equation in AME2016 so that the ground state mass can be derived. For example, the mass of ^{62}Mn was listed as unknown in AME2012, since it was the excited isomer that was measured in a Penning trap experiment [2012Na15]. However, the excitation energy of ^{62}Mn^m was determined recently via γ-ray spectroscopy [2015Ga38], so the mass of the ground state is established experimentally. An interesting case is the mass and excitation energy of ^{186}Tl^n, where its mass is experimentally known from a Penning trap (ISOLTRAP) measurement [2014Bo26]. The well known transition from ^{186}Tl^n to ^{186}Tl^m allows to determine not only the mass of the latter, but also the excitation energy of the α-decaying isomers in the parent nuclides ^{190}Bi^m, ^{194}At^m and ^{198}Fr^m.

When the existence of an isomer is ambiguous, it is flagged with 'EU' ("existence uncertain") in the origin field (e.g. ^{73}Zn^n). A comment is generally added to indicate why this existence is questioned, or where this matter is discussed in more detail. Five isomers, namely ^{73}Zn^n, ^{138}Pm^n, ^{141}Tb^m, ^{185}Bi^n, ^{273}Ds^m are treated in this way in the present evaluation and the mass excess and excitation energy values are given for them all except ^{138}Pm^n, for which the existence is strongly doubted.

When a particular isomer was initially reported as "discovered", but later it was proved to be an error, it is flagged with 'RN' in the origin field, indicating "reported, non existent". Three isomers, namely ^{117}La^m, ^{156}Tm^n and ^{181}Pb^m are treated in this way. In these cases, no mass-excess or excitation energy values are given, and, similarly to the 'EU' choice above, a "non existent" label is added.

Note: the use of the two flags, 'EU' and 'RN', was extended to cases where the discovery of a nuclide is questioned (e.g. ^{260}Fm or ^{289}Lv). However, an estimate for the ground state mass, derived from trends in the mass surface (TMS), is always given in AME2016 and NUBASE2016.

In several instances, lower and higher limits for the excitation energy of a particular isomer are presented in ENSDF. The policy of NUBASE2016 is that a uniform distribution of probabilities is assumed, which yields a mid-range value and a 1σ uncertainty corresponding to 29% of the range (see Appendix B of the AME2016, Part I in this issue for a complete description of this procedure). For example, the excitation energy of the ^{162}Tm^m isomer is known from ENSDF to be above the 66.90 keV level. On the other hand, there is also solid experimental evidence that it is below the 192 keV level, and so this information is presented as $E_x = 130(40)$ keV in NUBASE2016. However, if such a value is based on theoretical considerations, or from TNN, the resulting E_x is considered as a non-experimental quantity and the value is consequently flagged with the '#' symbol.

In cases where the uncertainty of the excitation energy, σ, is relatively large as compared to the E_x value, the assignment of the level as a ground or isomeric state is uncertain. If $\sigma > E_x/2$, a '$*$' flag is added in the NUBASE2016 table.

The ordering of several ground and excited isomeric states were reversed as compared to the recommendations in ENSDF. These cases are flagged with the '&' symbol in the NUBASE2016 table. In several other instances, evidence was found for states located below the adopted ground state in ENSDF. There are also cases where the trends in neighboring nuclides, with the same parities in N and Z, strongly suggest that such a lower state should exist. Such results were added in the NUBASE tables and can be easily located, as they are flagged with the '&' symbol. In a growing number of cases, new experimental information on masses led to a reversal of the ordering between previously assigned ground and excited isomeric states. Thanks to the coupling of the NUBASE2016 and AME2016 evaluations, all changes in the ordering of nuclear levels have been carefully synchronized.

Finally, there are cases where data exist on the ordering in energy of the isomers, e.g. if one of them is known to decay into the other one, or if the Gallagher-Moszkowski rule [9] points strongly to one of the two as being the ground-state. Detailed discussions can be found in Ref. [10].

2.2.1 Isobaric analog states (IAS)

In the previous version of NUBASE [3] we have included the $T = 3/2$ to $T = 3$ experimentally observed (IAS). These states are also included in NUBASE2016 and generally labelled with i or j superscripts, for members of successively higher multiplets. The experimental information about IAS has been evaluated in more detail recently in Ref. [11]. Some nuclides belong simultaneously to several categories, for example, they may be in their ground state but they may also be IAS of some other ground state nucleus, as is the general case for ground state mirror nuclei. Here, the IAS label is not present, since these nuclides are already naturally included in the database. Another exception is the set of $N = Z$, $T = 1$ odd-odd ground state nuclides which are also already part of the original dataset of ground state masses. They are: ^{34}Cl$_{17}$, ^{42}Sc$_{21}$, ^{46}V$_{23}$, ^{50}Mn$_{25}$, ^{54}Co$_{27}$, ^{62}Ga$_{31}$ and ^{70}Br$_{35}$. The reader may note that the $Z = 29$ and $Z = 33$ nuclides are not included in this series, since their ground states are $T = 0$, as

expected from theory. Finally, there are eight excited isomers, $^{16}N^m$, $^{26}Al^m$, $^{34}Cl^m$, $^{38}K^m$, $^{46}V^m$, $^{50}Mn^m$, $^{54}Co^m$ and $^{72}Ga^m$, which are also IAS. In such cases, the isomer labels ('m', 'n',...) are used preferentially over the IAS labels. Here we note with interest that five of them have experimentally determined excitation energies, at least partly, by the JYFLTRAP-Jyväskylä Penning trap.

In NUBASE2016 there are roughly 181 unique IAS masses, of which 113 are evaluated in the AME via external relations, and 68 cases evaluated through internal relations and published in ENSDF. There are five cases where no clear experimental data is available, and although some Isobaric Multiplet Mass Equation (IMME) [12] and Coulomb Displacement Energy (CDE) [13] calculations point to a likely IAS state, their existence cannot yet be certified experimentally (for example $^{15}O^i$).

The isospin multiplet assignment given in the table is the logical IAS multiplet value, and has not necessarily been deduced experimentally.

2.3 Half-life

Fig. 2 displays the half-lives of nuclides in NUBASE2016. In the light mass region, nuclides beyond the particle driplines can be studied with modern radioactive ion facilities. Most of these unbound nuclides exist for a very short time before they directly decay via particle emission. For some of them, such as ^{19}Mg and ^{26}O, the half-lives can be determined experimentally with novel experimental methods. For most unbound nuclei, only the total level width (Γ_{cm}) can be measured and therefore the half-life ($T_{1/2}$) can be deduced using the equation $\Gamma_{cm} T_{1/2} \simeq \hbar \times \ln 2$ so that

$$T_{1/2}\,(s) \simeq 4.562\,10^{-22}/\Gamma_{cm}\,(MeV).$$

The following units are used for convenient display in NUBASE2016: seconds (s) and its sub-units, minutes (m), hours (h), days (d) and years (y) and its sub-units. Conversion between years and seconds or days could follow various definitions: Julian year, Gregorian year, tropical year 1900, epoch 2000, etc., differing only slightly from each other. A fixed value of:

1 y = 31 556 926 s   or
1 y = 365.2422 d

was adopted in NUBASE2016.

Asymmetric uncertainties for half-lives, $T_{1/2}{}^{+a}_{-b}$, are often presented in the literature. However, for these values to be used in practical applications, they need to be symmetrized. A rough symmetrization procedure was used earlier (see AME1995) where the central value was taken as the mid-value between the upper and lower 1σ-equivalent limits, $T_{1/2} + (a-b)/2$, and the uncertainty was defined to be the average of the two uncertainties, $(a+b)/2$. A strict statistical

derivation (see Appendix A) shows that a better approximation for the central value can be obtained by using

$$T_{1/2} + 0.64 \times (a-b).$$

The exact expression for asymmetric uncertainties, adopted in NUBASE2016, is presented in Appendix A.

When two or more independent measurements were reported in the literature, the corresponding values were weighted by their reported precisions and then averaged. While doing this, the NORMALIZED CHI, χ_n (or 'consistency factor' or 'Birge ratio'), as defined in AME2016, is considered. When χ_n is larger than 2.5, departure from the statistical result is allowed and the external uncertainty for the average result is adopted. This follows the same policy that is discussed and adopted in AME2016. Very rarely, when χ_n is so large that all individual uncertainties can be considered as irrelevant, the arithmetic (unweighted) average is adopted and the corresponding uncertainty is based on the dispersion of the values. In such cases, the list of values that were averaged, together with the χ_n value (when relevant) and the reason for this choice, are given in the NUBASE2016 table. When contradictory (conflicting) results were identified in the literature, attention was focused on establishing the reason for such discrepancies, and consequently, any bad data were rejected. The justification for such decisions are given as comments in the NUBASE2016 table.

In experiments where extremely rare events are detected and where the results are very asymmetric (e.g. studies of super-heavy nuclei), the half-life values reported in different publications were not directly averaged. Instead, when the information presented in the literature was sufficient (e.g. ^{264}Hs), the decay times associated with the individual events were combined, as prescribed by Schmidt *et. al.* [1984Sc13].

Some experimental results are reported in the literature as a range of values with a most probable lower and upper limit. These are treated, as in the case of isomer excitation energies (see preceding page), as a uniform distribution of probabilities.

In the NUBASE2016 table, an upper or lower limit on the half-life value is given for nuclides identified using a time-of-flight technique. The following policies were considered:
i) For *observed* nuclides, the lower limit for the half-life is given in place of the uncertainty (e.g. ^{44}Si). However, such limits should be used with caution, since they may be far below the actual half-life. In order to avoid confusion, a somewhat more realistic estimate (flagged with #), derived using TNN is also given. ii) For nuclides that were sought, but *not observed*, the upper limit is given in place of the actual half-life uncertainty. Upper limits for a dozen undetected nuclides were evaluated by F. Pougheon [1993Po.A], based on the time-of-flight of the experimental setup and the production yields expected from TNN (e.g. ^{21}Al).
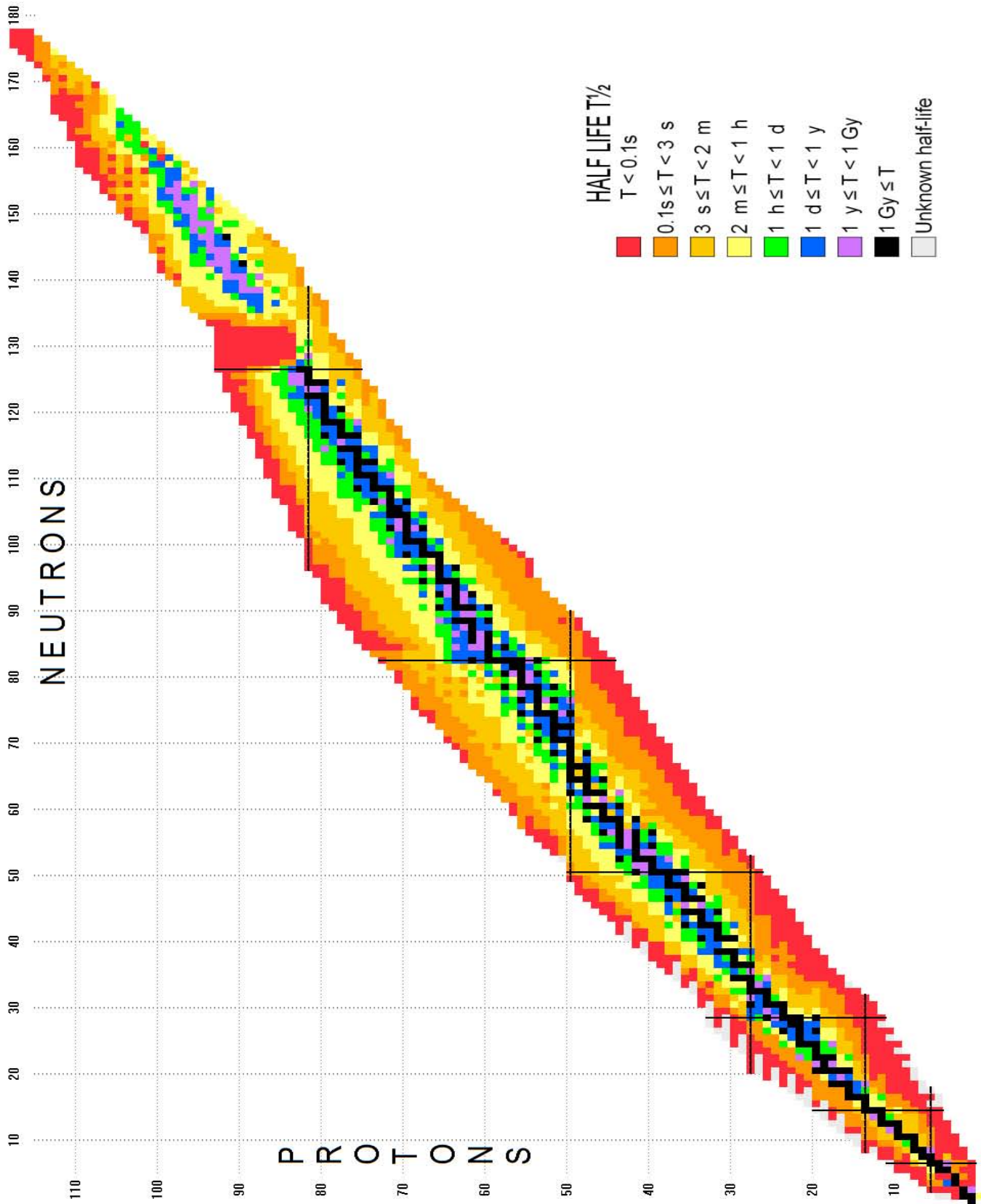
Figure 2.   Chart of the nuclides displaying half-lives (created by NUCLEUS-AMDC).

When ground-state half-lives for nuclides with the same parities in Z and N are found to vary smoothly, interpolation or extrapolation (TNN) is used to obtain reasonable estimates for unknown cases.

The super-allowed $0^+ \rightarrow 0^+$ nuclear β decays between isospin analog states with isospin $T=1$ and spin-parity $J^\pi=0^+$ are of particular interest due to their pivotal role in the precise determination of V_{ud} to test the unitarity of the Cabibbo – Kobayashi – Maskawa (CKM) Matrix. The evaluation of super-allowed decays, including their half-lives, is a long-standing work carried out by J.C Hardy and I.S. Towner. In the most recent survey [14], experimental data of 20 super-allowed transitions have been compiled and carefully evaluated. Half-lives of these nuclides are compared in Fig. 3. It can be seen clearly that the values listed in NUBASE2016 agree well with the values from Ref. [14]. The only significant differences occur for ^{18}Ne and ^{42}Ti, for which new experimental results were published after the publication of Ref. [14].
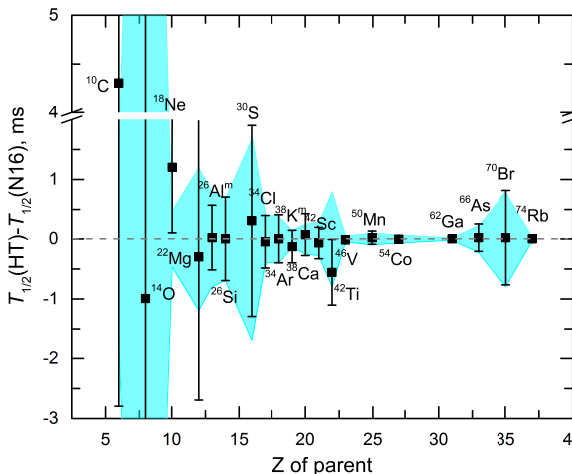

Figure 3.   Comparison of $T_{1/2}$ for 20 super-allowed β emitters from NUBASE2016 (N16) and Ref. [14] (HT). The error bars at the points display the uncertainties from Ref.[14], and the shaded area displays the uncertainties in NUBASE2016.

2.4   Spin and parity

As for ENSDF, spin and parity values are presented with and without parentheses, based on strong and weak assignment arguments, respectively (see the introductory pages of Ref. [15]). Unfortunately, parentheses in ENSDF are also applied to estimates from theory or from TNN. In NUBASE2016, following our policy of making a clear distinction between experimental and non-experimental information, parentheses are used if the so-called "weak" argument is based on experimental observations, while the symbol '#' is used for the other cases. It should also be noted that despite the well-defined evaluation policies [15], there are a number of inconsistencies in ENSDF regarding the spins

and parities for nuclear states. Often, the proposed assignments reflect the interpretation of a particular ENSDF evaluator, rather than that of firm policy rules. As a result, assignments to similar states in neighboring nuclides are put in parenthesis by one evaluator, but not by another, although similar experimental information is available.

We have tried to use a consistent approach in assigning spins and parities to nuclear states, but the survey is still far from complete and the reader may still find inconsistencies. The authors would gratefully appreciate feedback from users for such cases, to improve future versions of NUBASE.

If spins and parities are not determined experimentally, they can be estimated from TNN with the same parities in N and Z. Although, this is frequently the case for odd-A nuclides, such trends are also sometimes valid for odd–odd nuclides, especially in the neighborhood of magic numbers. In all cases, the estimated values are flagged with the '#' symbol.

The review of nuclear radii, moments and spins by Otten [1989Ot.A], as well as the recent compilation by MacDonald [16], were used to check and complete the spin values in NUBASE2016.

The spins and parities of odd-even, even-odd, odd-odd nuclides in their ground states are displayed in Fig. 4, Fig. 5 and Fig. 6, respectively.

2.5   Decay modes and their intensities

Fig. 7 displays the main decay modes of all known nuclides. The most important policy in assembling the information for the decay modes was to establish a clear distinction between a decay mode that is energetically allowed, but not yet experimentally observed (represented by a question mark alone, which refers to the decay mode itself), and a decay mode which is actually observed, but for which the intensity could not be determined (represented by '=?', the question mark referring here to the quantity after the equal sign).

As in ENSDF, no corrections were made to normalize the primary intensities to 100%.

In addition to applying direct updates from the literature, partial evaluations completed by other authors were also considered and properly referenced. Those cases are mentioned below when discussing some particular decay modes.

β^+ decay

In the NUBASE evaluations some definitions and notations for β^+ decay were refined to provide a clearer presentation of the available information. Specifically, β^+ denotes the decay process that includes both electron capture, labeled ε, and decay by positron emission, labeled e^+. One can then symbolically write: $\beta^+ = \varepsilon + e^+$. It is well known that for an available energy below 1022 keV, only electron capture, ε, is allowed, while above that value the two processes are in competition.

Remark: this notation is **not** the same as the one used implicitly in ENSDF, where the combination of both modes is denoted "$\varepsilon + \beta^+$".

When the two modes compete, the separated intensities are not always experimentally available and frequently they are deduced from model calculations, as is the policy in ENSDF. In continuation of one of the general NUBASE policies, in which only experimental information is used whenever possible, it was decided not to retain the separated values calculated in ENSDF (which are scarce and not always updated). Only in a few very specific cases, where the distinction is of importance, such as rare processes (^{91}Nb, ^{54}Mn, ^{119}Te^m), separate values are given.

By the same token, both electron-capture-delayed fission (εSF) and positron-delayed fission (e^+SF) are given with the same symbol β^+SF.

Double-β decay

In the course of this work it was found that half-lives for double-β-decaying nuclides were not always consistently given in ENSDF. Since the two-neutrino gs-gs transition is the dominant decay process (one exception may be ^{98}Mo, for which the neutrinoless decay is predicted to be faster, see [2002Tr04]), only those half-life values or their upper-limits were presented in the NUBASE2016 table. No attempt was made to convert the upper limit results given by different authors to the same statistical confidence level (CL).

The excellent compilation of Tretyak and Zdesenko [2002Tr04] was of great help in evaluating such decays.

β-delayed particle decays

For delayed particle decays, intensity relations must be carefully considered. By definition, the intensity of a decay mode is the percentage of decaying parent nuclei in that mode. But traditionally, the intensities of the pure β decay are summed with those of the delayed particles in order to give an intensity that is assigned to the pure β decay. For example, if the (A, Z) nuclide has a decay described traditionally by 'β^-=100; β^-n=20', this means that for 100 decays of the parent, 80 (A, Z+1) and 20 (A–1, Z+1) daughter nuclei are produced and that 100 electrons and 20 delayed neutrons are emitted. A strict notation in this case, using the definition above, would be 'β^-=80; β^-n=20'. However, in the present work, it has been decided to follow the above traditional notation.

This also holds for more complex delayed emissions. For example, a decay described by: 'β^-=100; β^-n=30; β^-2n=20; $\beta^-\alpha$=10' corresponds to the emission of 100 electrons, (30+2×20=70) delayed-neutrons and 10 delayed-α particles; and in terms of residual nuclides, to 40 (A, Z+1), 30 (A–1, Z+1), 20 (A–2, Z+1) and 10 (A–4, Z–1). More generally, the number of emitted neutrons per 100 decays, P_n, can be written as:

$$P_n = \sum_i i \times \beta_{in}^-;$$

and similar expressions can be written for α and proton emis-

sion. The number of residual daughter nuclides (A, Z+1) populated via β^- decay is then:

$$\beta^- - \sum_i \beta_{in}^- - \sum_j \beta_{j\alpha}^- - \cdots$$

Another special remark concerns the intensity of a particular β-delayed mode. In general, the primary (parent) β decay populates several excited states in the daughter nuclide, which can further decay by particle emission. However, in a case where the ground state of the daughter nuclide decays also by the same particle emission, some authors included its decay in the value for the corresponding β-delayed intensity. It has been decided to not use such an approach in NUBASE2016 for two main reasons. Firstly, the energies of delayed particles emitted from excited states are generally much higher than those emitted from the ground state, implying different subsequent processes. Secondly, the characteristic decay times from excited states are related to the parent, whereas decays from the daughter's ground state are connected to the daughter nuclide itself. For example, ^{9}C decays via β^+ with an intensity of 100% of which 12% and 11% populate two excited proton-emitting states in ^{9}B, and 17% goes to an α-emitting state. Thus, β^+p=23% and $\beta^+\alpha$=17%, from which the user of the NUBASE2016 table can derive a 60% direct feeding of the ground state of ^{9}B. In a slightly different example, ^{8}B decays to only two excited states in ^{8}Be, which in turn decay by α- and γ-ray emissions, but not to the ^{8}Be ground state. Thus, one may write β^+=100% and $\beta^+\alpha$=100%, the difference of which leaves 0% for the feeding of the daughter's ground state.

Finally, the users should be aware that the percentages given in the NUBASE2016 table are related to 100 parent decaying nuclei, rather than to the primary beta-decay fraction. An illustrative example is given by the decay of ^{228}Np, for which the delayed-fission probability is given in the original paper as 0.020(9)% [1994Kr13], but this value is relative to the ε process, which has an intensity of 60(7)%. Thus, the renormalized delayed-fission intensity is 0.020(9)% × 0.60(7) = 0.012(6)% of the total decay intensity.

In compiling the data for β^+-delayed proton and α activities, the remarkable work of Hardy and Hagberg [1989Ha.A], in which the corresponding physics was reviewed and discussed in detail, was consulted. The review of Honkanen, Äystö and Eskola [17] on delayed proton decays has also been consulted.

Similarly, the review of delayed neutron emission by Hansen and Jonson [18] was carefully examined and used in the NUBASE tables, together with the evaluation of Rudstam, Aleklett and Sihver [1993Ru01].

2.6 Isotopic abundances

Isotopic abundances are taken from the compilation of M. Berglund and M.E. Wieser [2011Be53] and the values are listed in the decay field with the symbol *IS*. These data
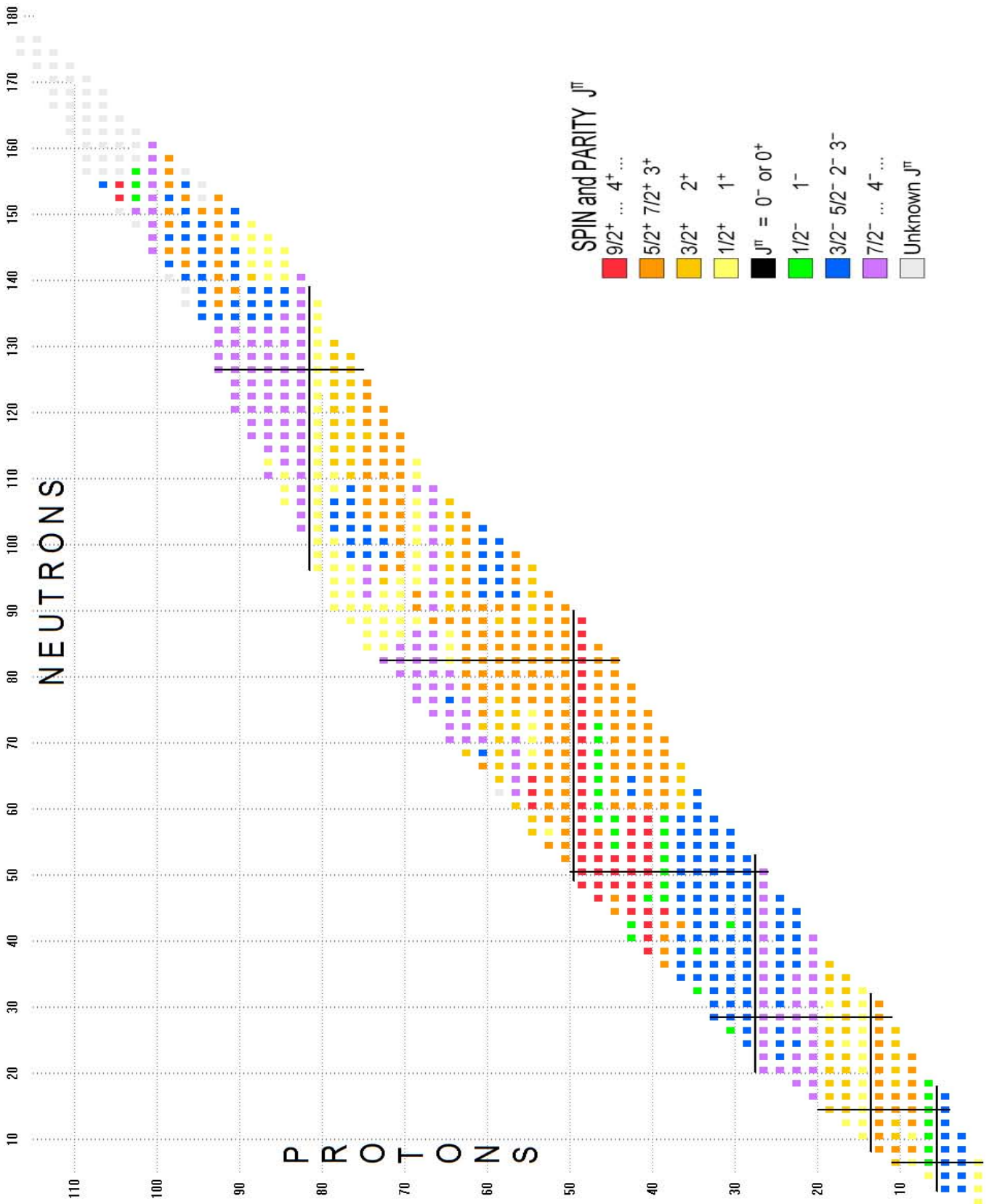
Figure 4.   Chart of the nuclides displaying spins and parities. Only the odd-Z even-N nuclides are shown (created by NUCLEUS-AMDC).
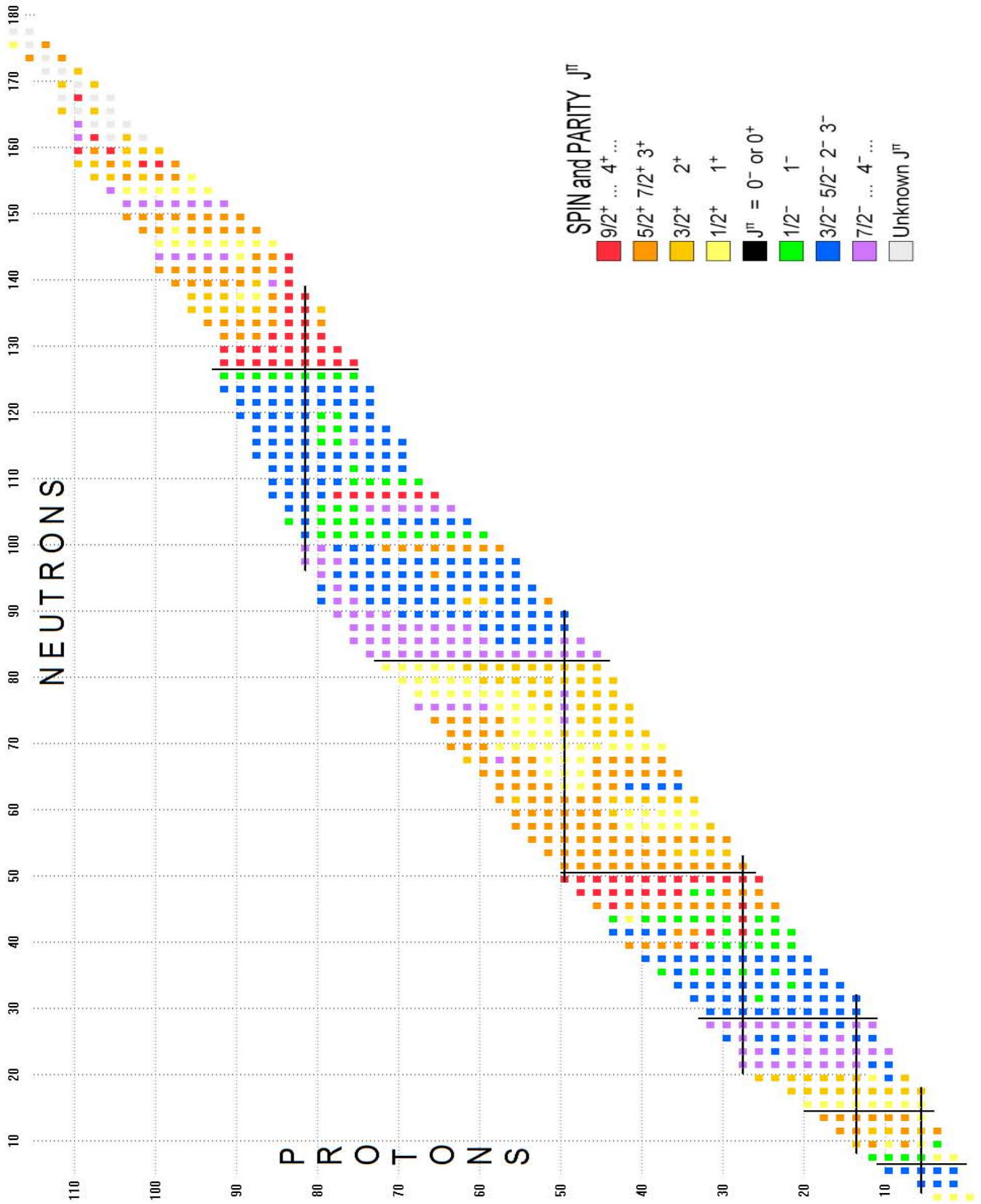
Figure 5.   Chart of the nuclides displaying spins and parities. Only the even-*Z* odd-*N* nuclides are shown (created by NUCLEUS-AMDC).
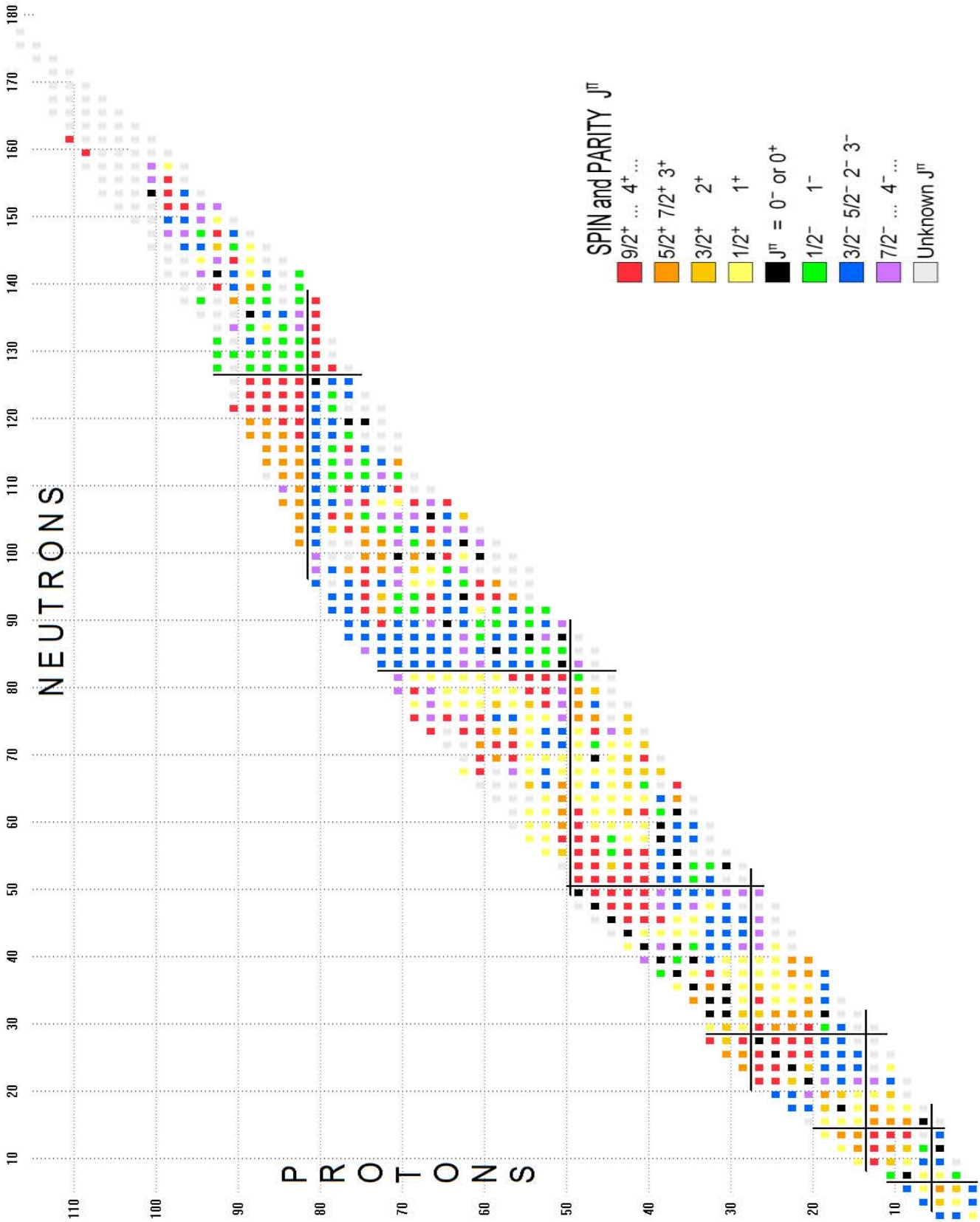
Figure 6.   Chart of the nuclides displaying spins and parities. Only the odd-Z odd-N nuclides are shown (created by NUCLEUS-AMDC).
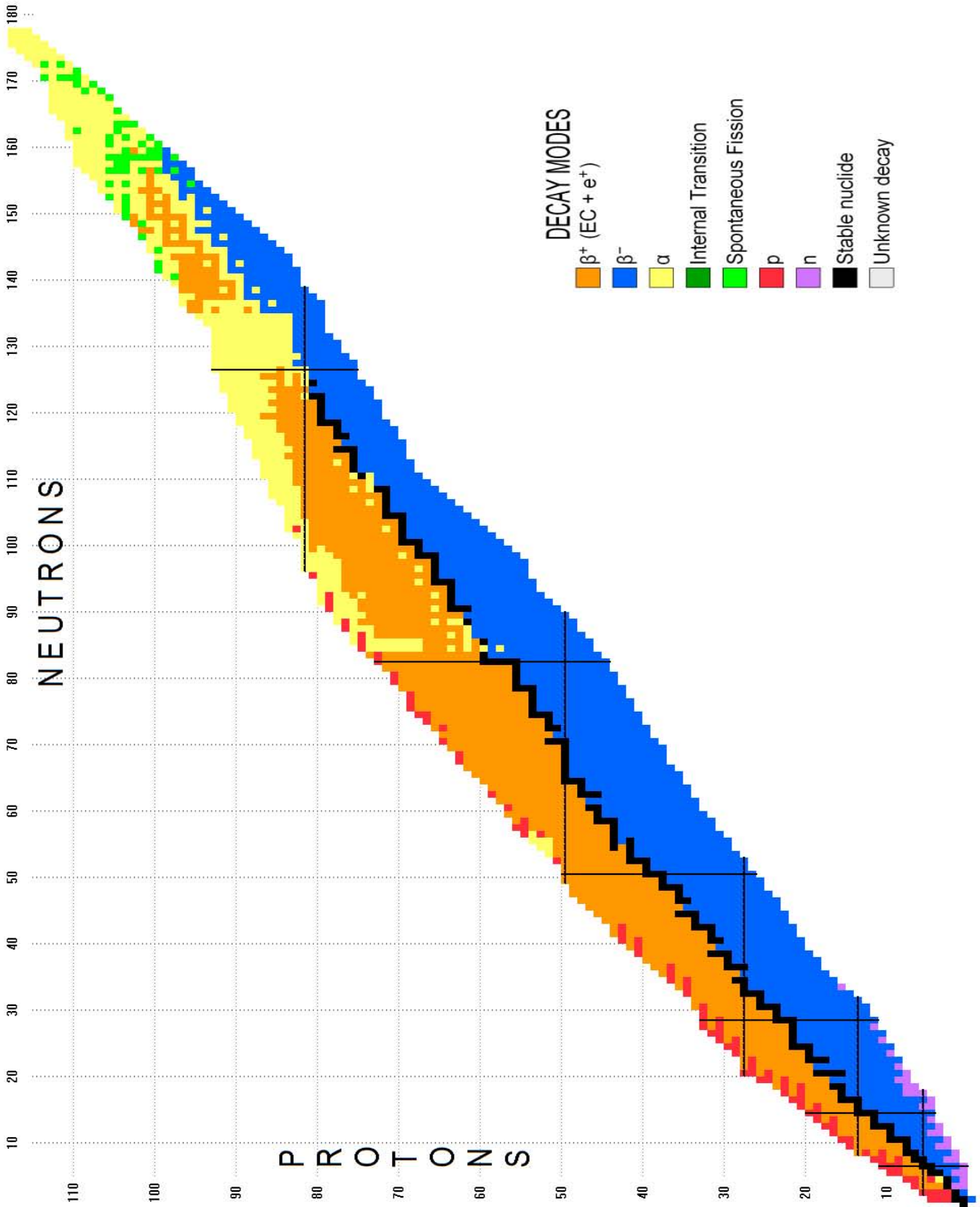
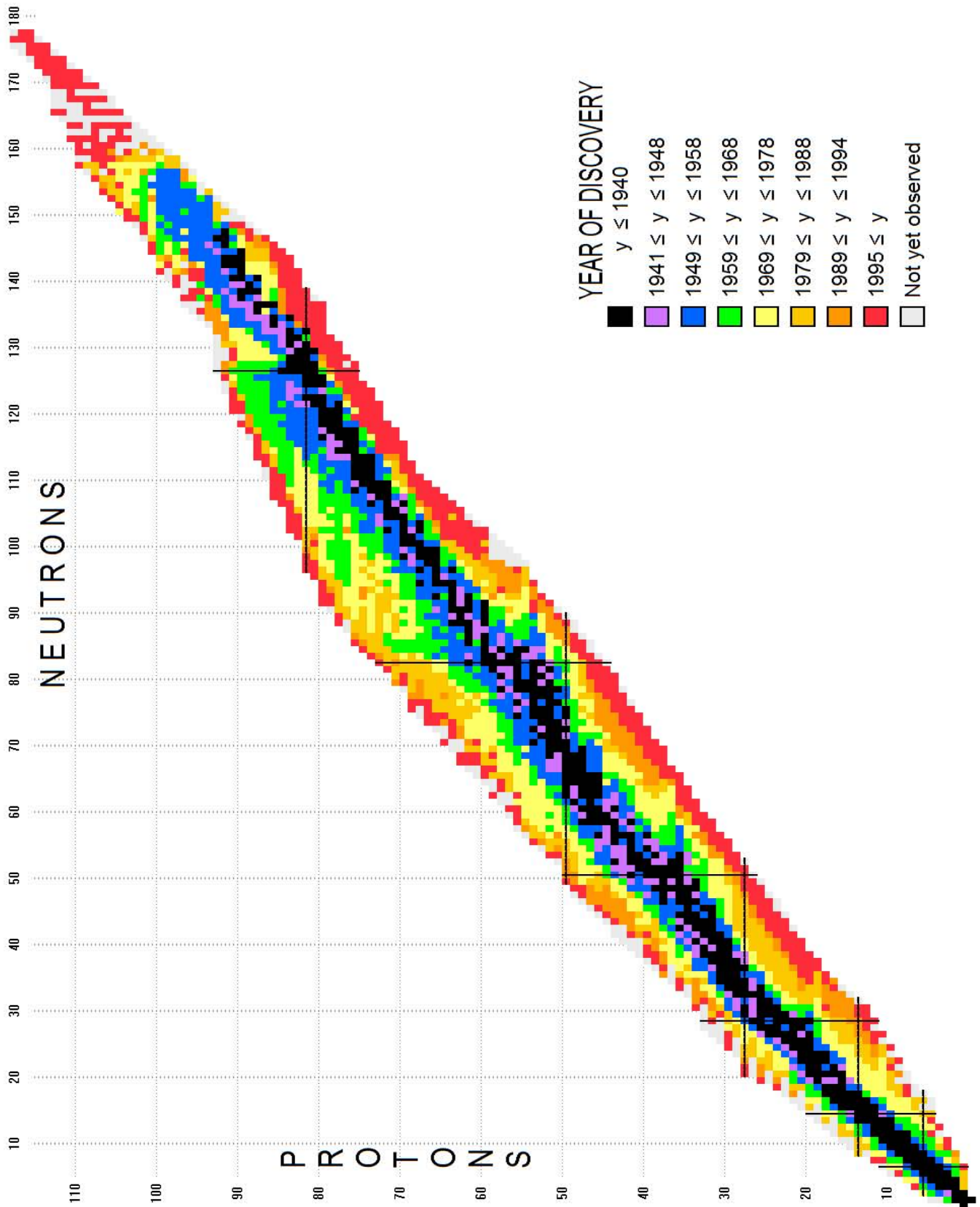Figure 7.   Chart of the nuclides displaying decay modes (created by NUCLEUS-AMDC).

Figure 8.   Chart of the nuclides displaying the years of discovery (created by NUCLEUS-AMDC).

are given in the NUBASE tables as presented originally in [2011Be53], and so in this case the rounding policy was not applied.

2.7   Year of discovery

As in NUBASE2012, the present tables include information of the year of discovery for each nuclide in its ground or isomeric state. For the former, recent evaluations performed by a group at Michigan State University [19] were adopted. Similar criteria was used when assigning the year of discovery for isomeric states. The information about the year of discovery is illustrated in Fig. 8.

2.8   References

The year of the archival file for the nuclides evaluated in ENSDF is indicated, otherwise this entry is left blank.

References for all of the experimental updates are given by the NSR keynumber style [7], and are listed at the end of this issue. They are followed by one, two or three one-letter codes which specify the added or modified physical quantities. In cases where more than one reference is needed to describe a particular update, they are given as a remark. No reference is given for estimated values. The initials of the former and present evaluators, AHW, FGK, GAU, HWJ, JBL, MMC, WGM, XUX, are used as reference keys in cases where it may not be precisely clear that the re-interpretation of data were made by the authors.

3   Updating procedure

In general, NUBASE was updated via two routes: from ENSDF after each new *A*-chain evaluation is published (or from the bi-annual releases), and directly from the literature. Data available in the "eXperimental Unevaluated Nuclear Data List " (XUNDL)[20] database were also regularly consulted.

ENSDF files are retrieved from NNDC using the on-line service [5]. Computer programs, originally developed by O. Bersillon and J. Blachot [21], were used to successively:
• check that each *Z* in the *A*-chain has an 'adopted levels' data set; if not, a corresponding data set is generated from the 'decay' or 'reaction' data set,
• extract the 'adopted levels' data sets from ENSDF,
• extract the required physical quantities from these data sets, and convert them into the NUBASE format.

The processed data were used to manually update the previous version of NUBASE.

ENSDF is updated generally by *A*-chains and more recently also by individual nuclides. Its contents are extensive, since it encompasses all of the complex nuclear structure and decay properties. This is a huge effort, and it is not surprising that occasionally some older data (in particular annual reports, conference proceedings, and theses) are missing and that some recent data have not yet been included. When such

cases were revealed, they were analyzed and evaluated, as described above, and the NUBASE2016 database was updated accordingly. In principle, these new data will be included in future ENSDF evaluations and the corresponding references can then be removed from future NUBASE distributions. Unfortunately, it has been observed in the past that such a procedure was not always adhered to. In fact, in some newer ENSDF files, quotations to earlier NUBASE publications were found, which leads to an undesirable loop resulting in nontraceable information. For this reason, in such cases the original references are repeated here again.

4   Distribution and displays of NUBASE2016

The full contents of the present evaluation is available on-line at the Atomic Mass Data Center (AMDC) website [22], as well as at a mirror website maintained by the International Atomic Energy Agency (IAEA) [23]. An electronic ASCII file for the NUBASE2016 table is also distributed at the AMDC website. Any work that uses those files should make reference to the present publication and not to the electronic files.

The contents of NUBASE2016 can be displayed by the stand-alone PC-program called "NUCLEUS". The charts of nuclides shown in this paper were created by using this program. The program "NUCLEUS" has been updated according to the present NUBASE2016 evaluation and can be downloaded from the AMDC website [22] and the IAEA [23].

5   Conclusions

The 'horizontal' evaluated database, NUBASE2016, which contains the recommended values for the main properties of all known nuclides in their ground and excited isomeric states, has been updated. These data originate from the intersection of two evaluated databases: ENSDF, followed by a critical assessment of the validity and completeness of those data, including new updates from the literature, and AME2016. The main requirement in developing NUBASE2016 was to cover as completely as possible all available experimental data and to provide proper references to them, especially for cases that are not already included in ENSDF. This traceability allows any user to check the recommended data and, if necessary, to undertake a re-evaluation.

As a result of this 'horizontal' work, better homogeneity in handling and presentation of all data was obtained for all known nuclides. Furthermore, isomeric assignments were examined more critically and the data of their excitation energies were improved.

6   Acknowledgments

Appendix A   Symmetrization of asymmetric uncertainties

Experimental data are sometimes given with asymmetric uncertainties, X^{+a}_{-b}. If these data are to be used in some practical applications, their uncertainties may need to be symmetrized. A simple method (Method 1) that was developed earlier, uses the central value to be in the middle between the upper and lower 1σ-equivalent limits

$$X + (a-b)/2, \text{ with the uncertainty defined}$$

to be the average of the two uncertainties

$$(a+b)/2.$$

An alternative method (Method 2) considers the random variable x associated with the measured quantity. For this random variable, one assumes that the probability density function is an asymmetric normal distribution having a modal (most probable) value of $x = X$, a standard deviation b for $x < X$, and a standard deviation a for $x > X$ (Fig. 9). Then the

average value of this distribution is

$$\langle x \rangle = X + \sqrt{2/\pi}\,(a-b),$$

with variance

$$\sigma^2 = (1 - 2/\pi)(a-b)^2 + ab. \tag{1}$$

The median value m which divides the distribution into two equal areas is given, for $a > b$, by

$$\text{erf}\left(\frac{m-X}{\sqrt{2}\,a}\right) = \frac{a-b}{2a}, \tag{2}$$

and by a similar expression for $b > a$.

One can then define the equivalent symmetric normal distribution that have a mean value equal to the median value m of the previous distribution with same variance σ.

If the shift $m - X$ of the central value is small compared to a or b, expression (2) can be written [24]:

$$m - X \simeq \sqrt{\pi/8}\,(a-b)$$

$$m - X \simeq 0.6267\,(a-b).$$

In order to allow for a small non-linearity that appears for higher values of $m - X$, the relation

$$m - X = 0.64\,(a-b).$$

was adopted for Method 2. In NUBASE2016, Method 2 is used for the symmetrization of asymmetric half-lives and decay intensities. Table A illustrates the results from both methods.
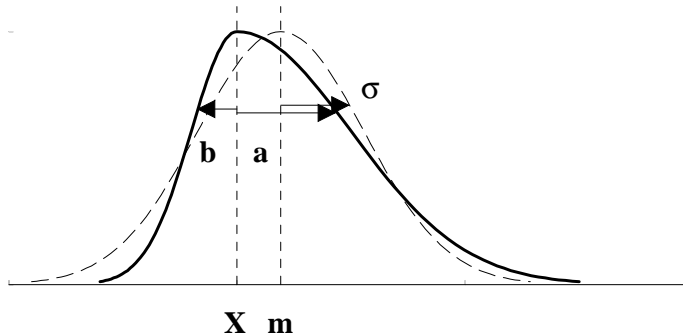

Figure 9.   Simulated asymmetric probability density function (heavy solid line) and the equivalent symmetric one (dashed line).

Table A. Examples of two different treatments of asymmetric half-life uncertainties.
Method 1 is the classical method, used previously, as in the AME1995.
Method 2 is the one developed in NUBASE2003, described in this Appendix.

Nuclide	Original $T_{1/2}$		Method 1	Method 2
^{83}Mo	6+30–3	ms	20 ± 17	23 ± 19
^{100}Kr	7+11–3	ms	11 ± 7	12 ± 8
^{264}Hs	327+448–120	μs	490 ± 280	540 ± 300
^{266}Mt	1.01+0.47–0.24	ms	1.1 ± 0.4	1.2 ± 0.4

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