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DEVELOPMENT OF A DEDICATED ONLINE DATABASE FOR NUCLEAR MOMENTS DATA

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June 2016

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ABSTRACT

The present document reports on the development and deployment of a web-based database of nuclear electromagnetic moments experimental data. Measurements of nuclear magnetic dipole and electric quadrupole moments are considered quite important for the understanding of nuclear structure both near and far from the valley of stability. As more and more nuclear moments data become available due to the routine use of radioactive beams at large facilities, the necessity of an efficient scheme that will make available non-evaluated experimental data to researchers, soon after their publication, motivated the development of a dedicated, online database. The database supersedes existing printed compilations, incorporating additional relevant meta–data, while putting strong emphasis on frequent updates. The scope, features and extensions of the database are reported.

June 2016

TABLE OF CONTENTS

1. INTRODUCTION

The importance of nuclear magnetic dipole and electric quadrupole moments (EM moments) in understanding the structural properties of nuclides is well known (Ref. [1]). Magnetic dipole moments of ground and excited states provide reliable input on the nature of the wave function in terms of proton and neutron contributions, while the electric quadrupole moment is the most important tool to extract information on the shape of the nucleus. The advent of radioactive ion beam facilities worldwide has made it possible to study nuclei far from stability expanding thus the investigation of EM moments to the extreme limits of the nuclear chart, and providing important insights to exotic nuclear structures.

Given the wealth in available experimental EM moments data, the organization of the experimental nuclear EM moments data into an efficient scheme that would facilitate systematic search, access and use is considered a necessity. Tabulations of nuclear EM moments data were attempted already in the fifties (Refs. [2], [3], [4]) and continued throughout the decades (Refs. [5 – 9]), while they were sometimes accompanied by theoretical interpretation of moments (Ref. [10]).

The most recent compilation existing today is the extensive work by Stone (Ref. [11]). Stone's work organizes experimental data of nuclear EM moments horizontally in a systematic tabulated format. It has been the main reference in the field for over a decade (Ref. [12], [13], [9], [14], [11]), and includes data and meta-data from earlier compilations, mainly from Raghavan (Ref. [6]) and Pyykkö (Ref. [8]).

Although the printed compilations guarantee coherence and completeness of the data up to the given cut-off date, the release of updates occurs in intervals of two to six years, due to the time-consuming nature of horizontal compilations. In view of the rapidly growing production rate of new data, especially in the extremely neutron-rich regions, it is becoming more urgent to enrich and update the existing EM moments compilations with recently published data at a faster rate, and at the same time provide the research community with easy access to these data taking advantage of modern technology. This is the main purpose of creating the online database.

2. DATABASE SCOPE AND STRUCTURE

The primary scope of the online database is to provide published experimental data collected during low- and intermediate-energy nuclear experiments and associated meta-data. The adaptation of database source files, structure and interface in compliance with the IAEA IT security requirements and the IAEA NDS database system, and the installation of the database on the IAEA NDS web server were major steps towards enhancing the dissemination of information to the wider scientific community. In addition, the frequent upgrade, update and maintenance of the database to include the latest compilations and evaluations published in the scientific literature are expected to make the database an important credible tool that is routinely used by the scientific community.

To that end, the database was expanded significantly in size: existing tabulated data until 2014 were transferred directly from print material, such as Stone's compilations existing both in print (Ref. [14], [11]) and peer-reviewed versions (Refs. [13], [9]). Recent experimental data have been collected by searching articles in more than twenty international peer-reviewed journals, as well as in Proceedings Volumes of International Conferences with relevant material. The searching procedure has been greatly assisted by modern technologies offering dynamical content, currently available in most online journals (e.g. RSS/XML feeds), social networks and online archiving tools that provide automation at several stages. Additional data sets have been found by researching listings in the Nuclear Science References (NSR) database (Ref. [15]). The NSR, hosted at the National Nuclear Data Center (NNDC), has been invaluable in tracking down citations and links to original articles missing from previous compilations. The EM moments database comprises all the available experimental data that have *not* been evaluated and are presented "as is". However, for the QEMs, it also includes the recommended values from Stone's printed tables (Ref. [14]).

A large effort has been invested in setting up an updating mechanism to perform updates on a frequent, regular basis in a consistent and systematic way, so as to maintain the database constantly up to date. In the last year, the updates were undertaken on a regular basis every two to three months. These time intervals seemed to be optimal for the amount of work required to compile the EM data compared to the number of available experimental data published in various sources, however it also depends on the amount of data published in-between. Once all published data are gathered, the relevant information is processed offline to obtain the EM moments data, which are subsequently formatted and uploaded to the server.

Before it was installed on the IAEA server and incorporated into the IAEA LiveChart, the EM database was hosted on a leased cloud server under a privately owned URL (http://magneticmoments.info) (Ref. [16], equipped with the latest version of webserver software. That server is currently used as a testing platform and is accessible over the standard SSH communication protocol, additionally safeguarded by firewall software. Automatic backups occur weekly on both the server end and the offline mirrored directory.

A brief layout of the main database components is sketched in Fig. 1. A more detailed description of their features and role in the database is provided in the following paragraphs.

2.1. The frontend of the database

The main user interface (UI) is contained in the frontend of the database. Using the UI, the researcher can submit a query to the database. This query is then processed and through a series of internal procedures the data are retrieved and displayed back to the frontend. The frontend was built in standard HTML4, assisted by CSS and JavaScript web technologies. The main design idea was to keep things simple and fast at the frontend, while focusing on fast query processing. For that reason, advanced web technologies, such as AJAX programming, were not considered for implementation at this version, while functionality and user friendliness have been central requirements during design implementation.

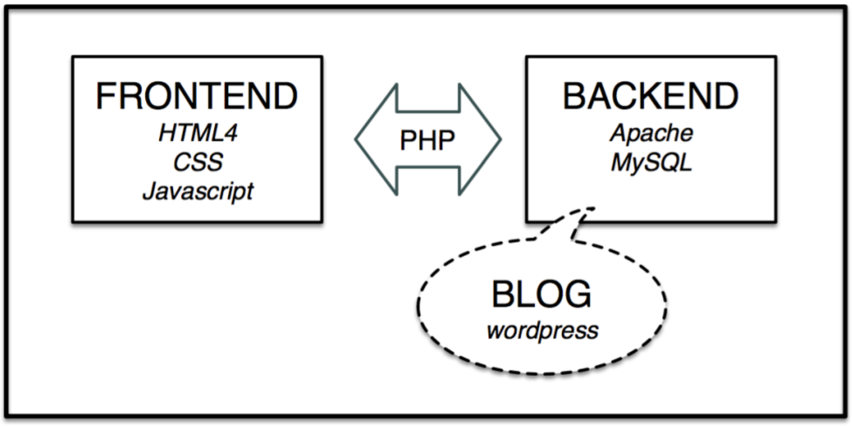

Fig. 1: *An outline of the database structure. The balloons display the fundamental parts of the structure and the software technologies used during development (in smaller font).*

The user is offered two ways of interaction (UI) with the database. The first UI option utilizes a standard periodic table graphical structure (see Fig. 2). The second UI is a helix-type graphical interface, where information can be retrieved by selecting the atomic number, Z, of the element (Fig. 3). Both UI options use the exact same backend. Once an element (i.e. the corresponding Z) is selected, all available isotopes of that element appear in a horizontal list. The user can select the isotope of interest from the output list. For each isotope, all available moments data are presented in a table format (see detailed explanation below). In addition to these two methods of data retrieval from the backend, a webform is provided in the former UI, where the user can type queries for Z, A or both. This selection operates dynamically and can be used in a more powerful way (e.g. the user can retrieve isobar data simultaneously).

For each isotope requested, a table of data is displayed, organized in rows and columns.

Abbreviations are adopted from Stone's compilations to maintain user's familiarity with earlier conventions. All abbreviations and annotations are described in the Help Section of the website.

Columns provided in the output are given below (see example in Fig. 4)

- Column 1: The selected isotope (e.g. ^{26}Mg)
- Column 2: The level energy in keV (e.g. 1809)
- Column 3: The half-life of the level (e.g. 476 fs)
- Column 4: Spin and parity of the level (e.g. 2^{+})

- Column 5: The magnetic dipole moment value, μ, given in nuclear magneton units μ_N; in case several measurements exist, typically the most recent value appears first (e.g. *+1.0(3)*).
- Column 6: The electric quadrupole moment value, Q, in units of *eb*; for multiple values, data are displayed as above. Often the value is followed by the text "Rec": This abbreviation marks a Recommended value as proposed by Stone (Ref. [14]).
- Column 7: If the measurement has been carried out relative to a level of a particular isotope (reference), the latter appears together with its corresponding level energy (e.g. *^{24}Mg 1369 keV*).
- Column 8: The experimental method, in an abbreviated format (e.g. TF for "*Transient Field*"). A short description of the technique is also provided when hovering the mouse over the abbreviation listed in the table.
- Column 9: The NSR keyword, e.g. *1981Sp04*. The corresponding URL has been added to hyperlink the NSR to the relevant citation (Ref. [15]).
- Column 10: The Digital Object Identifier (DOI) is provided for easy access to the published material containing the original measurement (e.g. *10.1016/0370-2693(81)90200-8*). The DOI is provided with a URL to lead the user to the original source. To the best of our knowledge this is the only specialized nuclear database (other than NSR) that provides *direct* link to the publication via the DOI.

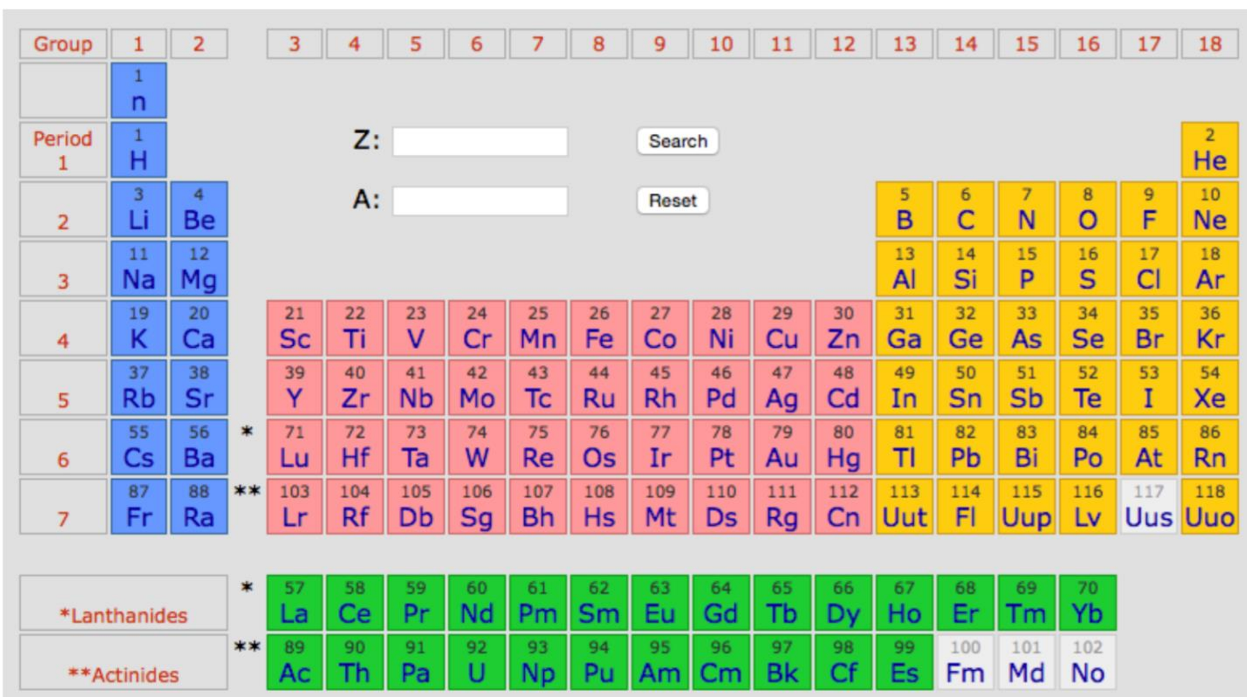

Fig. 2: *A web-active periodic table is used as the main user interface. In addition to standard element selection, a webform with two input fields, Z and A, located in the middle of the screen, can be used as an alternative way to submit a query.*

In addition to nuclear moments, the database has incorporated evaluated data of elementary particle magnetic moments, retrieved directly from the Particle Data Group's website (Ref. [17]). Data are listed per particle in a simple data format from the following categories: baryons, mesons, leptons, and gauge. It is noted that no magnetic moment data are yet available for mesons. This category – despite being empty – is included for the sake of completeness.

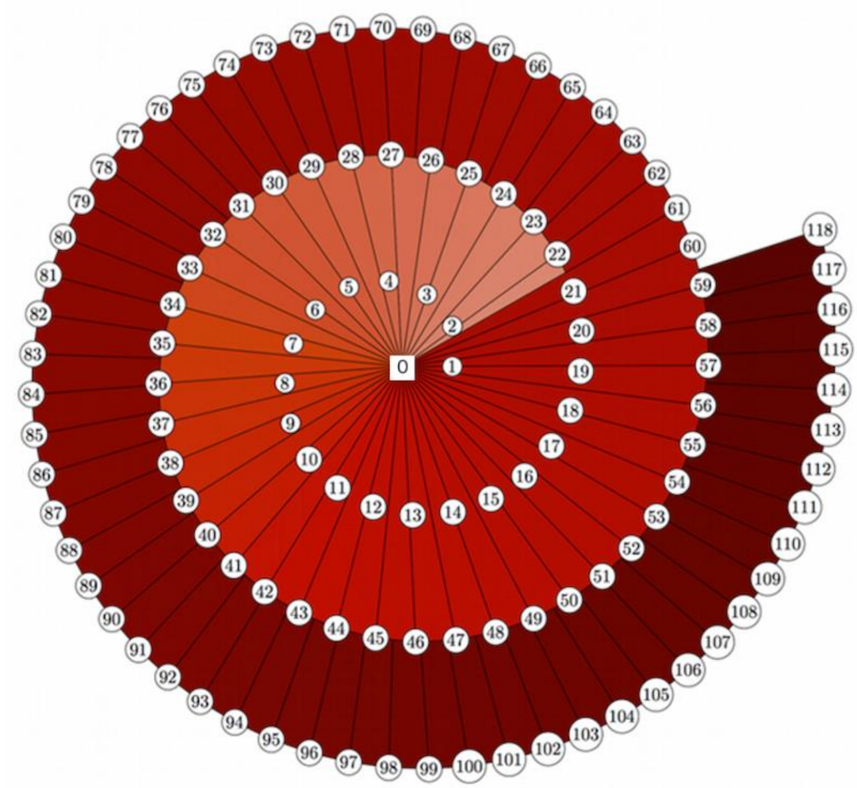

Fig. 3: *The alternative UI, in the form of a Z-helix (the user can click on the element's corresponding atomic number, Z)*

2.2. The backend

The backend is the actual content of the database. The backend comprises all components that stay invisible to the user during the search, retrieval, and display operations. There are two main parts in the backend: the *database tables and* the *database script handlers.*

2.3. The data tables

The database tables are stored in ANSI MySQL format containing all information mentioned earlier. The current version of the database has more than 5200 rows in the table of nuclear EM moment values, corresponding to ≈1000 levels. This number changes slightly after every update, depending on the number of new entries added to the database. The entries have been checked thoroughly to ensure reliability and data integrity with respect to original sources. For entries adopted from the printed compilations a few typographical errors were located and corrected including citations, NSR keywords and EM moments values (see Appendix for a Corrigendum). The list of errors has been submitted to authors of the print compilations and the NSR manager.

In addition, all available DOI numbers were found and added. The latter is perhaps the major new feature of the database: a dedicated column holding the DOI metadata for each single entry has been incorporated in the tables. In the vast majority of cases, all NSR keywords have a one-to-one correspondence with a DOI. However, in a rather limited number of cases, the NSR server is missing the corresponding DOI, most often because the source is not available online or the journal has still not entered the NSR database (the majority of such cases correspond to terminated journal series or articles prior to 1990). All available DOI have been inserted in the database and hyperlinked to the original source using the official DOI name-resolving server (i.e. http://dx.doi.org, Ref. [18]).

For future expansions of the database, special care was taken so that the backend is able to accommodate additional nuclear observables.

The database tables are first organized in a spreadsheet-like structure then reorganized to MySQL format. The file holding the data and associated metadata is uploaded to the server after each update.

2.4. The data handlers

The connection between the front- and back-end is handled by a set of PHP scripts. Hard-coded operations responsible for decoding the query, accessing the SQL tables, retrieving and processing the data, and formatting output are included in the PHP scripts. Depending on the initial query by the user, the data handlers can provide information on specific isotopes or a group of isobars (depending on the initial Z-A or A-alone query). The script handlers are written so that they could be easily modified to serve future expansions of the database.

2.5. The accompanying blog

A useful resource of the database is an associated blog, where an informal archiving of information related to EM moments, experimental data and theoretical studies takes place. The blog is useful for the updates due to easy archiving of journal, conference or preprint papers that can be accessed at a later stage, before a formal release takes place. The blog is built on top of the open-source Wordpress engine, hosted on http://magneticmoments.info/wp. It is open, but moderated, to subscribers from the scientific community.

3. EXAMPLES OF USE

Two typical examples of the database usage are described below.

A typical operation of the database is when the user places a request to the database for information regarding a particular isotope, either by using the periodic table UI or the web form. Such a query produces a typical output as in Fig. 4. Here, the example considered is the ^{26}Mg nucleus.

Magnesium (Z=12)

^{21}Mg	^{23}Mg	^{24}Mg	^{25}Mg	^{26}Mg	^{27}Mg	^{29}Mg	^{31}Mg	^{33}Mg

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	μ [nm]	Q [b]	Ref. Std	Method	NSR keyword	doi
^{26}Mg	1809.	476 fs	2^+	+1.0(3)		[^{24}Mg 1369]	TF	1981Sp04	10.1016/0370-2693(81)90200-8
					-0.21(2)		CER	1991He09	10.1103/PhysRevC.43.2546
					-0.14(3)		CER, R	1981Sp07	10.1016/0370-1573(81)90177-0
					-0.14(3) or -0.10(3)		CER	1982Sp05	10.1016/0375-9474(82)90466-3
					-0.11(6)		CER	1977Sc36	10.1016/0375-9474(77)90108-7

Fig. 4 *A screenshot of the database output for the case of ^{26}Mg*

In the dynamically produced webpage, the data handlers display a table containing basic spectroscopic information (e.g. lifetime, spin/parity etc), available μ and Q moments values, and supplementary bibliographical and informational data (e.g. experimental method, NSR keywords etc).

For the case of ^{26}Mg used as an example earlier, only one measurement of the magnetic moment is known $\mu=+1.0(3)$ (the number in the parenthesis being the uncertainty of the last significant digits), measured by the Transient Field technique (abbreviated as "*TF*") relative to the known magnetic moment of the 1369 keV level in ^{24}Mg. There are additionally four known electric quadrupole moment measurements, listed in the following rows, all measured by Coulomb Excitation Reorientation ("*CER*"). The NSR keywords and DOI numbers for each entry are hyperlinked to the corresponding entries on the NNDC NSR server and the electronic version of the original sources, respectively.

A second example deals with a query for EM moments for a set of isobars with A=26. Such a query can be requested by using exclusively the input field "*A*" in the provided webform. Besides ^{26}Mg that was described in the previous paragraph, two more isobars exist in the database for A=26, namely ^{26}Na and ^{26}Al. The corresponding tables for these nuclides are listed in ascending Z, as illustrated in Fig. 5. Tables still have the same format as previously.

Sodium (Z=11)

^{20}Na | ^{21}Na | ^{22}Na | ^{23}Na | ^{24}Na | ^{25}Na | ^{26}Na | ^{27}Na | ^{28}Na | ^{29}Na | ^{30}Na | ^{31}Na

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	μ [nm]	Q [b]	Ref. Std	Method	NSR keyword	doi
^{26}Na	0.	1.07 s	3^+	+2.851(2)		[^{23}Na]	ABLS	1978Hu12	10.1103/PhysRevC.18.2342
					-0.0053(2)	[^{23}Na]		2000Ke09	10.1007/s100500070117
					-0.08(5)		ABLS	1982To05	10.1103/PhysRevC.25.2756

Magnesium (Z=12)

^{21}Mg | ^{23}Mg | ^{24}Mg | ^{25}Mg | ^{26}Mg | ^{27}Mg | ^{29}Mg | ^{31}Mg | ^{33}Mg

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	μ [nm]	Q [b]	Ref. Std	Method	NSR keyword	doi
^{26}Mg	1809.	476 fs	2^+	+1.0(3)		[^{24}Mg 1369]	TF	1981Sp04	10.1016/0370-2693(81)90200-8
					-0.21(2)		CER	1991He09	10.1103/PhysRevC.43.2546
					-0.14(3)		CER, R	1981Sp07	10.1016/0370-1573(81)90177-0
					-0.14(3) or -0.10(3)		CER	1982Sp05	10.1016/0375-9474(82)90466-3
					-0.11(6)		CER	1977Sc36	10.1016/0375-9474(77)90108-7

Aluminium (Z=13)

^{23}Al | ^{24}Al | ^{25}Al | ^{26}Al | ^{27}Al | ^{28}Al | ^{30}Al | ^{31}Al | ^{32}Al | ^{33}Al | ^{34}Al

Isotope	Energy [keV]	$t_{1/2}$	Spin/Parity	μ [nm]	Q [b]	Ref. Std	Method	NSR keyword	doi
^{26}Al	0.	7x10*5 y	5^+	+2.804(4)		[^{27}Al]	ABLS	1996Co04	10.1088/0954-3899/22/1/008
					+0.27(3)	[^{27}Al]	ABLS	1997Le19	10.1088/0954-3899/23/9/015

***Fig. 5** Data for A=26 isobars*

4. CONCLUSIONS AND FUTURE WORK

A new web-based database for nuclear electromagnetic moments experimental data has been created. The main ambition behind the project is to supersede all existing printed compilations, by providing frequent updates of published experimental data openly to the scientific community via a common browser. Dissemination of data to the community is the highest priority in this work.

During its gradual development, the database has been facilitated by modern web computing technologies. The provision of reliable data has been a central motivation from the beginning. A rather exhaustive check of the incorporated data has been carried out during development. The feature of linking information contained in the database to the original published source, mainly by the newly provided meta-information (DOI), is a key feature of the database enabling the user to cross-check the provided information.

The future plans include: keeping the frequency of updates constant, expanding the database with additional nuclear observables, and adding plotting capabilities to facilitate the search for systematic trends in the EM moments data across a range of nuclei.

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APPENDIX A

During extensive cross-checks and examination, a number of database entries were identified with an incorrect or missing DOI number in the NSR database. See Table A.1 for a corrigendum. This information was provided to the NSR manager.

Table A.1 Missing DOI in NSR keys (last access 30.11.2015)

#	NSR Key	Corresponding DOI
1	1968Lu07	10.1515/zna-1968-0815
2	1968Ep01	10.1515/zna-1968-0933
3	1975Ep02	10.1515/zna-1975-0805
4	1986El09	10.1515/zna-1986-1-205
5	1986Ha49	10.1515/zna-1986-1-223
6	1978Ta24	10.5169/seals-114973
7	1962Ca14	10.1139/p62-099
8	1970Jo27	10.1088/0031-8949/2/1-2/003
9	1971Go31	10.1515/zna-1971-1126
10	1972Bl07	10.1515/zna-1972-0113
11	1973Bu24	10.1515/zna-1973-1102
12	1973Lu06	10.1515/zna-1973-0819
13	1973Lu08	10.1515/zna-1973-0923
14	1974Be50	10.1007/BF01680407
15	1974Lu08	10.1515/zna-1974-1013
16	1974Sa24	10.1515/zna-1974-1208
17	1974Sa25	10.1515/zna-1974-1209
18	1977Bu29	10.1515/zna-1977-1110
19	1977Ho33	10.1063/1.434262
20	1978Ko39	10.1515/zna-1978-0906
21	1981Ha11	10.1007/BF01441279
22	1981Ha26	10.1007/BF01419866
23	1982Si15	10.1007/BF01420153
24	1986Bo31	10.1007/BF01294609
25	1986St16	10.1515/zna-1986-1-207
26	1987Mo34	10.1364/JOSAB.4.001297
27	1988AsZY	10.1063/1.37023
28	1989Un01	10.1007/BF01438497
29	1992Ba68	10.1007/BF02399000 (citation vol/page should be checked)
30	1992Be51	10.1007/BF02398986 (citation vol/page should be checked)
31	1998Ha40	10.1515/zna-1998-6-716
32	1998Ju10	10.1007/BF03185342
33	2002Mi37	10.1515/zna-2002-6-755

An additional change is proposed throughout NSR database: "*Proc. 5th Int. conf. Nuclear Far from stability, Rosseau Lake, ON, Canada, Ed. I.S. Towner 1987*" should be replaced by "*AIP Conf. Proc.* ***164*** *(1987)*". The particular volume contains several individual articles, of which the corresponding DOI numbers are currently missing from NSR, e.g. 10.1036/1.37028, 10.1036/1.37060 etc.

APPENDIX B

Missing information and typographical errors in the latest printed Stone compilation (Stone, 2014) have been identified and corrected in the online database. See the following tables for a set of proposed corrections.

Table B.1 A corrigendum to NSR keys/Citations included in INDC(NDS)-0658

#	Isotope	Existing info	Proposed change
1	17O	1957Ka01	1957Ka68
2	66Cu	2011Lo03	2011Lo01
3	65Zn	1992Be51/1975WE08	1992Be51
4	65Zn	CJP 53 2544 (75)	HFI 75 301 (92)
5	69Ga	1998To**	1998To31
6	70Ga	2011Pr11	2012Pr11
7	71Ga	1998To**	1998To31
8	83Kr	1977Ho**	1977Ho33
9	86Y	2010Ru03	2010Ru07
10	91Zr	1993Yo**	1993Yo11
11	95Nb	1085Oh08	1985Oh08
12	111Ag	1956Wo**	1956Wo27
13	106In	1982Ya21	1982Va21
14	107In	1982Ya21	1982Va21
15	108In	1982Ya21	1982Va21
16	109In	1981Ha**	1981Ha11
17	110In	1981Ha**	1981Ha11
18	117Sn	1086Bo31	1986Bo31
19	124Sn	PR C84 061303®	PR C84 061303 (11)
20	124Sn	2011Al35	2011Al25
21	126Sn	PR C84 061303®	PR C84 061303 (11)
22	126Sn	2011Al35	2011Al25
23	128Sn	PR C84 061303®	PR C84 061303 (11)
24	128Sn	2011Al35	2011Al25
25	130Xe	1985Ku15	1984Ku14
26	134Nd	89OgZY	1989OgZY
27	208Tl	1992La23	1992La03
28	203Pb	1987Mo**	1987Mo34
29	203Pb	1987Mo**	1987Mo34
30	211Bi	1996Wi**	No related NSR key

Table B.2 A corrigendum to values written in decimal powers, as listed in INDC(NDS)-0658

#	Isotope	Existing info	Proposed change
1	26Al	7x10*5 y	7.0 x 10^5 y
2	40K	1.3x10*9 y	1.3 x 10^9 y
3	81Kr	2.3 x 10*5 y	2.3 x 10^5 y
4	87Rb	4.9 10*10y	4.9 x 10^10 y
5	99Tc	2.1x10*5y	2.1 x 10^5 y
6	113Cd	9x10*15 y	9.0 x 10^15 y
7	115In	4.4x10*14 y	4.4 x 10^14 y
8	123Te	>1x10*15 y	> 1.0 x 10^15 y
9	129I	1.6x10*7 y	1.6 x 10^7 y
10	135Cs	3x10*6 y	3.0 x 10^6 y
11	137La	6 x 10*4 y	6.0 x 10^4 y
12	138La	1.1x10*11y	1.0 x 10^11 y
13	137Sm	1.1x10*11y	1.1 x 10^11 y
14	149Sm	>2x10*15 y	> 2.0 x 10^15 y
15	176Lu	3.6x10*10 y	3.6 x 10^10 y
16	180Ta	>1.2x10*15y	> 1.2 x 10^15 y
17	187Re	4 x 10*10 y	4.3 x 10^10 y
18	205Pb	1.5x10*7y	1.5 x 10^7 y
19	208Bi	3.7x10*5y	3.7 x 10^5 y
20	210Bi	3.0x10*6y	3.0 x 10^6 y
21	231Pa	3.3x10*4y	3.3 x 10^4 y
22	233U	1.6x10*5y	1.6 x 10^5 y
23	235U	7.0x10*8y	7.0 x 10^8 y
24	237Np	2.1x10*6y	2.1 x 10^6 y
25	239Pu	2.4x10*4y	2.4 x 10^4 y
26	247Cm	1.6x10*7y	1.6 x 10^7 y
27	158Dy	a x 10*3=	a x 10^3 =
28	160Dy		
29	170Yb		
30	170Yb		
31	174Yb		
32	174Yb		

APPENDIX C

List of NSR keynumbers of publications used in the latest database update, in addition to the references included in Stone's most recent printed tabulations (INDC(NDS)-0650, INDC(NDS)-0658). Each reference may correspond to multiple entries in the EM moments database.

Table C.1 List of NSR keynumbers of updates.

#	NSR key
1	2013Ka27
2	2015Ba49
3	2015De28
4	2015He28
5	2015Ru02

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