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An online database of nuclear electromagnetic moments

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ABSTRACT

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. The recent advent of radioactive beams has resulted in a plethora of new, continuously flowing, experimental data on nuclear structure – including nuclear moments – which hinders the information management. A new, dedicated, public and user friendly online database (http://magneticmoments.info) has been created comprising experimental data of nuclear electromagnetic moments. The present database supersedes existing printed compilations, including also non-evaluated series of data and relevant meta-data, while putting strong emphasis on bimonthly updates. The scope, features and extensions of the database are reported.

1. Introduction

Just over a hundred years after the discovery of the atomic nucleus by Rutherford, the field of Nuclear Physics is going through its second blooming season. The principal reason of flourishing is the advent of radioactive beams (RIB) that have become available at a routine basis in several international facilities around the world, providing new and exotic probes for nuclear-structure and reactions studies. As a direct consequence, several novel experiments are planned and carried out in RIB factories, resulting in a plethora of new data spanning all edges of the nuclear chart. Observables, such as lifetimes, electromagnetic moments and spectroscopic factors in exotic species are measured, taking advantage of newly developed or upgraded methods.

The importance of nuclear magnetic dipole and electric quadrupole moments (hereafter EM moments) in understanding the structural properties of isotopes is well recognized (see for example [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 collect evidence on the shape of the nucleus. With RIB factories creating nuclei far from stability and making them accessible to experimenters, investigations of EM moments have been expanded to these new species, thus providing important feedback to nuclear structure. For the same reason, experimental data of nuclear EM moments are now collected at fast rates, offering invaluable understanding of the extremes limits in the Segré chart.

Gathering and organization of the experimental nuclear EM moments data into an efficient scheme that would be able to facilitate systematic search and usability of those data is thus considered of paramount importance. Along the same line, tabulations of nuclear electromagnetic moments data were attempted already in the 1950s [2–4] and continued [5–9], while they are sometimes accompanied by theoretical interpretation of moments [10].

The latest and most complete compilation existing today is the extensive work by N.J. Stone [11]. Stone's compilation organizes horizontally evaluated experimental data of magnetic dipole and electric quadrupole moments in tables in a systematic way. It has established itself as the main reference in the field for longer than a decade [9,11–13], including data and meta-data from earlier compilations, mainly from the works of Raghavan's [6] and Pyykkö's [8].

Independently of the integrity and completeness of tabulation, updates (if any) of all existing printed compilations have appeared sporadically, essentially been left in an asynchronous mode compared to experimental data accumulation. The important evaluation procedure is also time consuming. The necessity to enrich and expand the existing EM data compilations with recently published data, but mainly the intention to provide the scientific community with easy access to those data by means of modern online technology, is the main motivation behind the present work. It has to be noted that continuous maintenance and frequent updates of the database are also important issues confronted on the practical end.

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2. Database scope and structure

The primary scope of the online database is to provide published experimental data collected during low-energy and intermediate-energy nuclear experiments and associated metadata involving nuclear EM moments. Existing tabulated data until 2010 were transferred directly from published material, such as Stone's compilations existing in both preprint [12] and published versions [9,13]. More recent data have been collected by searching articles in more than twenty (20) international peer-reviewed journals, as well as Proceedings Volumes of International Conferences (e.g. AIP and IoP series), 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 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 [14]. 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. NNDC also hosts the ENSDF [15] and XUNDL [16] databases. XUNDL acted as a role model at the beginning for the EM database development. However, the archiving and evaluation of EM data differs significantly from XUNDL's. The EM moments database is enriched with experimental data that have not been evaluated. Despite evaluated nuclear moments data are considered crucial for the community, thorough evaluation presents a great level of difficulty, demanding close collaboration of experts in the field of nuclear moments at an international level. If the nuclear community moves towards such a direction in the near future, the nuclear EM moments database will incorporate those data sets.

There has been significant effort in updating the EM moments database at a frequent, regular basis in a consistent and systematic way so as to preserve the integrity of information embodied to the database. In the recent past, the time interval between updates has averaged a period of two months. This time interval seems to be optimal for the amount of work required compared to the number of available experimental data published in various sources. Once gathered, the information is filtered offline to obtain the EM moments data, the data are then post-processed and formatted before being uploaded to the server.

The database is currently hosted on a leased cloud server under a privately own URL, equipped with the latest version of the Apache webserver [17], MySQL database backend [18] and PHP handlers [19]. The server 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.

The structure of the database is sketched in Fig. 1. Its essential parts are described in more detail below.

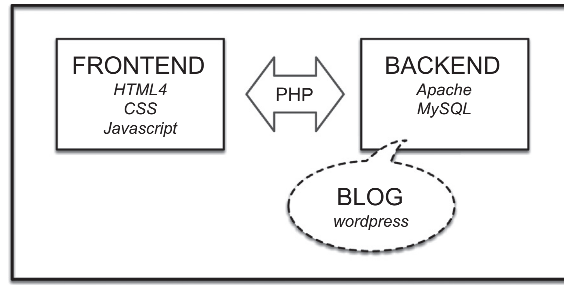

Fig. 1. Outline of the database structure. The technologies supporting the main components are shown in smaller font.

2.1. The frontend

The frontend of the database is the place where the user sends a query to the database. This query is processed, the data are retrieved and presented back to the frontend. In the present paper, version 2 of the database is discussed, as it evolved from version 1 that was built exclusively in HTML. Version 1 was developed in 2009 [20] and included a limited set of experimental data found in literature up to 2005, about 30% of what the database contained when this manuscript is written.

Version 2 of the database has been completely redesigned from scratch to improve functionality and user friendliness. Cutoff date of the database reported here is early 2012. Two ways of interaction with the user are currently available. The first option of a user interface (UI) utilizes a standard periodic table graphical structure (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 same backend, assisted by standard CSS3 web technology. Once an element (i.e. the corresponding Z) is selected, all available isotopes of the element appear in a horizontal list. That list may be explored further by choosing the desired isotope. For each isotope, all available EM data are presented in a table format that is explained below. In addition to those two methods of retrieving data from the backend, a webform is provided in the first UI, where the user can input queries for Z, A or both. This method functions dynamically and can be used in a more powerful way (e.g. obtain data for a specific mass chain simultaneously).

For each isotope requested, a table of data is printed on the frontend, organized in columns and rows. Columns given are the following:

- The isotope selected (e.g. ^{26}Mg).
- The level energy in keV (e.g. 1809).
- The halflife of the level (e.g. 476 fs).
- Spin and parity of the level (e.g. 2^+).
- The magnetic dipole moment value, μ, given in nuclear magneton units (μ_N); in case several measurements exist, typically the most recent value appears on top (e.g. +1.0(3)).
- The electric quadrupole value, Q, in units of $e \cdot b$; for multiple values, data are given as described above.
- The reference isotope and corresponding energy level in case of a relative measurement (e.g. ^{24}Mg 1369 keV).
- The experimental method used to perform the measurement, abbreviated (e.g. TF for "Transient Field"). Abbreviations are adopted from Stone's compilation to maintain user's familiarity with earlier conventions. A short description of the technique is provided when hovering the mouse over the abbreviation listed in the table.
- The NSR keyword, e.g. 1981Sp04. The corresponding URL has been added to hyperlink the NSR to the relevant citation [14].
- The Digital Object Identifier (DOI) [21] 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.

Besides nuclear EM moments data, the database has included evaluated data of elementary particle magnetic moments, incorporated directly from the Particle Data Group website [22]. Data are listed per particle in a simple data format, selecting from the categories: baryons, mesons, leptons, gauge. It is noted that no magnetic moment data are yet available for mesons. This category is included only for the sake of completeness.

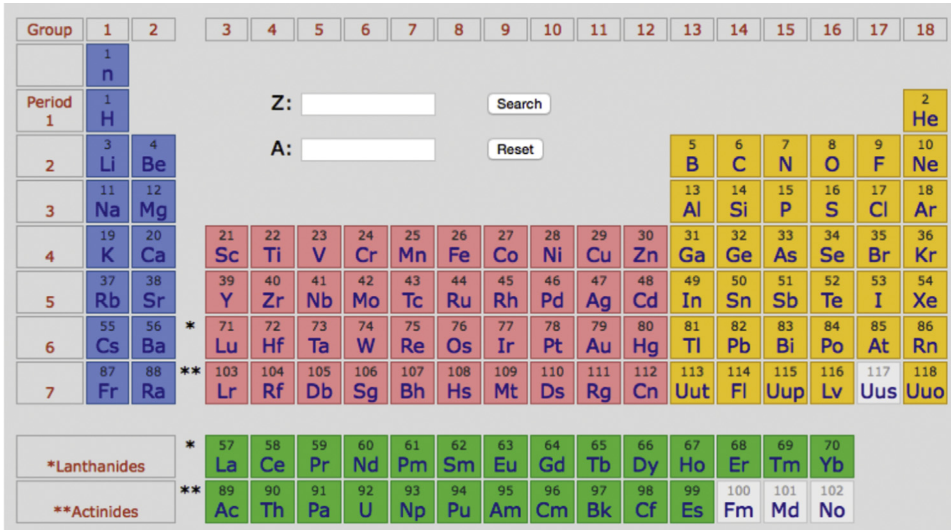

Fig. 2. The main user interface as a periodic table. A webform with two input fields, *Z* and *A*, located in the middle of the screen can be used alternatively.

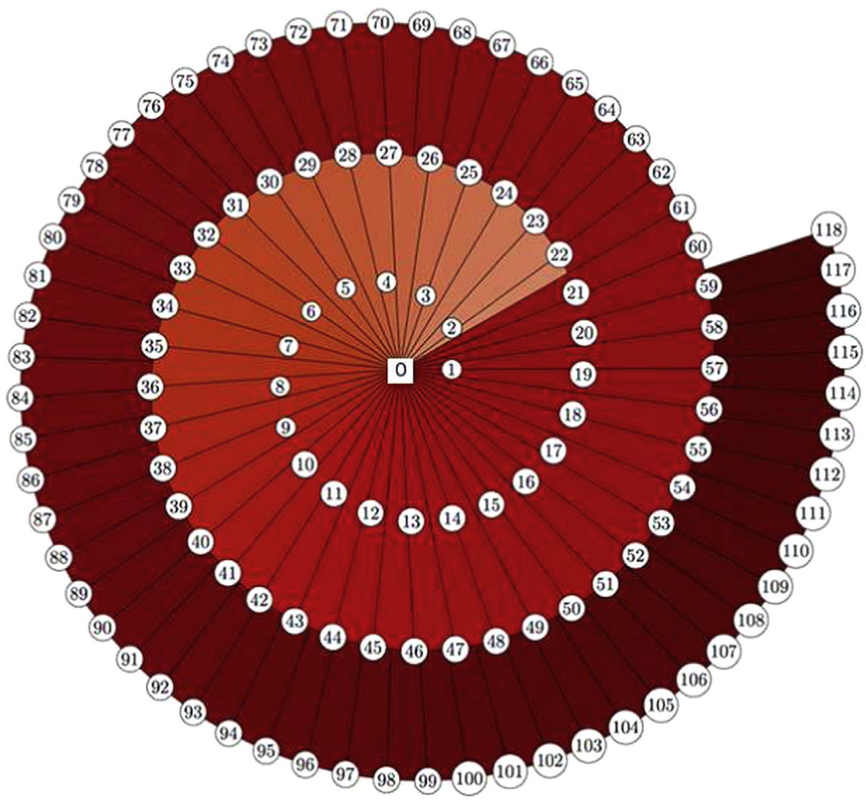

Fig. 3. The alternative user interface as a Z-helix.

2.2. The backend

While the frontend of the database is where interaction between the user and the data takes place, the backend is the real core of the database. The backend comprises all components that stay invisible to the user while performing data searching, data retrieval, and data output formatting.

There are two main parts in the backend: the database tables and the database script handlers. The former are MySQL tables containing all information mentioned in Section 2.1. Version 2 of the database holds more than 4500 rows in the table of EM moments values, corresponding to ≈ 1000 levels. The vast majority of the database entries have been checked 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), while all available DOI numbers were found and added.

The latter is the major breakthrough of the database: a dedicated column holding the DOI metadata for each single entry has been added in the tables. In most cases, every NSR keyword has a one-to-one correspondence to a DOI. However, in a few cases, the NSR server is missing a 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

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.

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.

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).

Special care was given during construction of the backend so as to be able to accommodate additional nuclear observables in case of a major expansion (e.g. addition of nuclear radii).

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.

2.3. The data handlers

Communications between the frontend and backend are handled by a set of PHP scripts. These scripts have hard-coded operations responsible for decoding the query, accessing the SQL tables, retrieving and processing the data, and formatting output. Depending on the initial query by the user, the data handlers can return information on specific isotopes or a group of isobars (depending if *Z*, *A* or *A* alone is requested initially). The script handlers can be easily modified to serve potential expansions of the database.

2.4. The accompanying blog

The database is accompanied by a blog, where an informal archiving of resources 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. The blog is built on top of the popular Wordpress engine [23], hosted on the same server with the database (http://magneticmoments.info/wp). It is open, but moderated, to subscribers from the scientific community.

3. Examples of database use

Two typical examples of the database usage are described below.

A typical operation of the database is when the user queries 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.

In the output webpage produced dynamically by the data handlers, the table contains basic spectroscopic information (e.g. lifetime, spin/parity, etc.), available μ and Q moments values, and complementary bibliographical and informational data (e.g. experimental method, NSR keywords, etc.). For ^{26}Mg, only one measurement of the magnetic moment is known ($\mu = +1.0(3)$, with 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 also four known electric quadrupole moment measurements, listed in consecutive rows, all measured by Coulomb Excitation Reorientation (“CER”). The NSR keywords and DOI numbers are hyperlinked to the corresponding entries on the NNDC NSR server and the electronic version of the original sources, respectively.

A second example is a query for EM moments for a set of isobars with $A = 26$. Such a query can only be requested by using the input field “*A*” in the provided webform. Besides ^{26}Mg that was described in the previous example, two more isobars exist in the database for $A = 26$, i.e. ^{26}Na and ^{26}Al. The tables for each of these nuclides are listed in ascending *Z*, as illustrated in Fig. 5. Tables have the same format as in the previous example.

4. Conclusions and future work

A new, online database (http://magneticmoments.info) for nuclear electromagnetic moments has been created at the University of Athens, Greece. The main ambition of the project is to supersede all existing printed compilations, by providing frequent updates of published experimental data to the scientific community. The database is accessible via a web browser and is open to the scientific community. A strong feature of the database is the cross-checking of the information contained with the original published work in combination with meta-information (NSR, DOI) that enhances the user's accessibility to original data. Furthermore, the adoption of modern computing techniques has facilitated the development of a user-friendly interface, incorporating also a relative blog. Future work focuses on maintaining the updates frequency constant, synchronize spectroscopic data (lifetimes, etc.) with ENSDF, include additional nuclear observables (such as nuclear charge radii experimental data) and provide plotting capabilities for systematic trends of the EM moments data across a range of nuclei.

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