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Year-2026 nuclear electric quadrupole moments

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A curated 'year-2026' set of nuclear quadrupole moments, Q, is presented. Compared to the previous, 'year-2017' set, changes are proposed for 36 cases. Direct links to the original sources are given.

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1. Introduction

Atomic nuclei with the nuclear spin $I \geq 1$ have nuclear electric quadrupole moments. As emphasized in the previous reviews,[1–4] the currently best way to determine such quadrupole moments, eQ, at least for light elements, is to combine nuclear quadrupole coupling constants, (NQCC), ν^X (also denoted e^2qQ/h, eqQ/h, eqQ, B, or b, all in frequency units), with careful *ab initio* calculations of the electric field gradient, q, at this nucleus. The atomic, molecular or solid-state calculation methods and the computer hardware are steadily improving and new experimental spectroscopic data are appearing. The main competitor of this method, at least for the heavier nuclei, is the 'mesonic' way, based on measuring the hyperfine structure of the essentially coulombic energy levels of muons or π mesons. Due to their high masses, their orbits are near the nucleus studied, where the potential is nearly coulombic. No such experiments have been published for about four decades and the apparatus has been demounted. Low-precision determinations of Q are available from nuclear Coulomb scattering, nuclear rotational energy levels, and from nuclear theory. The knowledge of the nuclear quadrupole moments is important in nuclear physics for testing nuclear models. Although most nuclei are axially symmetric, triaxial nuclear shapes also occur.[5] See Section 4.2 below.

In contrast to the absolute value of the nuclear quadrupole moment, which can hence not be directly measured, isotopic ratios between the quadrupole coupling constants for two isotopes of the same element in the same system can be directly measured by spectroscopic methods. Such ratios are available from optical spectroscopy, radiofrequency measurements on atomic and molecular beams, as well as nuclear magnetic resonance, nuclear quadrupole resonance or Mössbauer spectroscopy and from perturbed angular correlation (PAC) measurements. Such ratios are also being measured for a number of exotic isotopes. As a counterexample, if a Mössbauer experiment can be performed only on one isotope in one system, but an atomic experiment can be performed on another isotope in a different system, the ratio can not be experimentally determined.

The knowledge of reliable Q is also important in chemical spectroscopy. Spectroscopic quadrupole splittings act as a gauge of the electron distribution, and studies of molecular dynamics require Q in systems where nuclear quadrupole effects determine the spin-lattice relaxation time, T_1. That is usually the case for the NMR of quadrupolar nuclei and sometimes the case for spin-$\frac{1}{2}$ nuclei, scalar-coupled to quadrupolar nuclei.

For a general, recent review on quadrupole coupling, including the historical origins, and the Sternheimer polarization effects, see Fabbro *et al.*[6] The history is also told by Brix.[7] Original treatises by Casimir,[8] Cohen and Reif,[9] Das and Hahn,[10] and Lucken[11] exist for readers with a magnetic resonance (NMR/NQR) background.

In addition to composite nuclei, the Ω^- hyperon can have a quadrupole moment whose magnitude, however, is unknown.[12] The Δ excited state of the nucleon is calculated to have a Q of −0.43 mb.[13]

Upper limits have been set for the M3 magnetic octupole moment, Ω, of ^{45}Sc.[14] Values for ^{69,71}Ga are provided by Li and Tang.[15]

2. Background

2.1. Earlier compilations

The available nuclear electric quadrupole moments were reviewed in 1969 by Fuller and Cohen,[16] in 1976 by Fuller,[17] in 1978 by Lederer and Shirley,[18] and in 1989 by Raghavan.[19]

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The Q reviews by the present author include the ''year-1992'' set ($Z \leq 20$ from ref. 1, $Z > 20$ from ref. 19), the ''year-2001'' set,[2] the ''year-2008'' set,[3] and the ''year-2017'' set.[4] A compilation of both magnetic and electric nuclear moments was that by Stone.[20] Later summaries of the Q by Stone are ref. 21–23. A publicly available data base was published by Mertzimekis *et al.*[24] For later updates from the IAEA nuclear moments group, see.[23] Further, secondary sources are the CRC Handbook of Chemistry and Physics,[25–28] and the IUPAC compilations.[29,30] Note also the WebElements.[31] The Table of Isotopes[32] partially includes these Q changes, to the extent they have been further quoted in nuclear data sheets.

The Q values below are quoted in barn (1 b = 10^{-28} m^2) or in millibarn (1 mb = 10^{-31} m^2). An alternative unit is Fermi (10^{-15} m) squared, 1 fm^2 = 10 mb.

2.2. Improvements in electronic calculations

Molecular theory. A tour de force was the treatment of HD and D_2 by Adamowicz' group,[33] yielding for the deuteron a new Q of 2.85783(30) mb. The claimed error limit is entirely coming from the experimental uncertainty of the J = 1 HD coupling constant. Born–Oppenheimer (BO) surfaces and a set of explicitly correlated shifted Gaussians (ECSG) were used. The BO calculation included relativistic corrections.

The latest value is 2.85699(15)(18) mb by Puchalski *et al.*[34]

Solid-state theory. A four-component DFT approach for q calculations in solids was presented by Joosten *et al.*[35]

We record here that values of the coupling constant in solids can also be obtained from their specific heats, as in the case of As, Sb and Bi.[36]

3. Review of new data

Deuterium. The previous Q value by Pavanello[33] was further sharpened by Puchalski,[34] whose new value is 2.85699(15)(18) mb. The first error estimate comes from higher-order relativistic and QED terms and the second from the experiment on J = 1 HD. Non-adiabatic effects were now included. Further improvements of the molecular Q are foreseen. Their preceeding value was 2.856(2) mb.[37]

An interesting historical reference is Bishop and Cheung.[38] Please note that their q' is $q/2$, where

$$q = \langle (3z^2 - r^2)/r^5 \rangle \quad (1)$$

over the electrons and other nuclei. The working formula for extracting Q from the quadrupole coupling constant B is

$$Q = \frac{B}{234.9647q} \quad (2)$$

with B in MHz, Q in barn, and q in au. Here the 2022 CODATA

$$\frac{e^2(a_0^{-3})(1b)}{4\pi\varepsilon_0 h} = 234.96478\,\text{MHz}. \quad (3)$$

Interestingly, nuclear theory by Filin *et al.*[39] gives $Q = 2.854^{+38}_{-17}$ mb.

Lithium Fabbro *et al.*[40] used data for LiX, X = H, F, Cl to extract a new $Q(^7\text{Li})$ of −38.624(292) mb. As a confirmation, Fabbro *et al.* quote the atomic Li^+ $Q(^7\text{Li})$ of −38.6(5) mb by Guan *et al.*[41] An example of the previous molecular standard values was the LiF-based $Q(^7\text{Li})$ of −40.55(80) mb.[42]

Concerning the ratio $Q(^6\text{Li})/Q(^7\text{Li})$, a value of +0.0176(1) was reported from molecular-beam measurements on LiF by Wharton *et al.*[43] Later it was refined to 0.020161(13) by Cederberg *et al.*[44] Solid-state NMR measurements by Kempgens *et al.*[45] on LiSiON and $LiSi_2N_3$ support it.

The Fabbro $Q(^7\text{Li})$ value would hence give a $Q(^6\text{Li})$ of −0.7787 mb.

Guan *et al.*[41] would actually challenge this ratio and propose 0.101(13) instead, yielding $Q(^6\text{Li})$ = −3.9(5) mb. This value is supported by their own nuclear theory calculations.

For ^{8,9}Li, see Borremans *et al.*[46]

Beryllium Puchalski *et al.*[47] use atomic data on a 2s 2p ^3P_J state of the Be atom to obtain a $Q(^9\text{Be})$ of 53.50(14) mb. The Puchalski $Q(^9\text{Be})$ is supported by the Be^{2+} results of Qi *et al.*[48] and by the 2s 2p ^3P_J result of 53.20(50) mb by Zhang *et al.*[49]

A previous, 'atomic' value using a slightly different experimental B was the $Q(^9\text{Be})$ of 52.88(38) mb by Sundholm and Olsen.[50]

Although no Q values were discussed there, we quote the study of ^{10}Be by Li *et al.*,[51] where evidence was presented for a molecular-type nuclear structure of two α particles, bound by a pair of valence neutrons.

Boron. The previous $Q(^{10,11}\text{B})$ of 84.59(24) and 40.59 mb, respectively, from Sundholm and Olsen[52] have stayed essentially constant since Nesbet's 1970 paper.[53] He had 84.72(56) and 40.65(26) mb, respectively.

For $Q(^{12}\text{B})$, Ohtsubo *et al.*[54] obtain 13.21(26) mb.

The $Q(^8\text{B})$ of 68.3(21) mb corresponds to a proton halo around a neutron core.[55]

Carbon. The 20.3 minute isotope ^{11}C has $I = \frac{3}{2}$ and the latest Q by Carette and Godefroid[56] from various states of C and C^- is +33.36(19)(2) mb. A preceding value by Sundholm and Olsen[57] was 33.27(24) mb.

Nitrogen Gregorović[58] carried out high-precision DFT-based calculations for H-bond-rich molecular crystals and found the previous $Q(^{14}\text{N})$ of 20.44 mb[59] acceptable, but did discuss minor possible adjustments. That value was based on atomic N^{2+} ($2p^2P_{3/2}$) and N^+ ($2p^2$; $^3P_2$ and $^1D_2$).

A rotational spectrum of gaseous CN^- yielded a B of −4.238(32) MHz,[60] in good agreement with a theoretical calculation[61] using the Tokman[59] $Q(^{14}\text{N})$ of 20.44(3) mb. That value has stayed essentially constant since.[62,63]

Oxygen. The previous standard value of $Q(^{17}\text{O})$ is −25.58(22) mb.[57]

Fluorine. The ^{19}F nucleus has an $I = \frac{1}{2}$ ground state and hence no Q. The $I = \frac{5}{2}$ excited state at 197 keV has a Q of −94.2(9) mb.[64] Quadrupole interactions have been observed by perturbed angular correlations.

Nuclear theory predicts about −105 mb.[65]

Neon. Xue *et al.*[66] calculate for the 2_1^+ state of ^{20}Ne a Q of −0.20 b, compared with an experimental Q of −0.22(2) b from Mehl *et al.*[67]

The exact reference for the $Q(^{21}\mathrm{Ne})$ of 101.55(75) mb is.[57] The later value of 101.44(20) mb by Li *et al.*[68] has a smaller error margin.

Sodium. The reference for $Q(^{23}\mathrm{Na})$ of 104(1) mb is.[69] It was based on NaF and NaCl diatomic molecules and CCSD(T) level calculations. For a discussion on the muonic and atomic values, see.[2] The Sundholm–Olsen atomic 3p-based Q was 108.9(32) mb.[70]

Keim *et al.*[71] used the Jönsson *et al.*[72] $Q(^{23}\mathrm{Na})$ of 105.6 mb to report their results on $^{26-29}$Na.[71]

Magnesium. Tang[73] uses the 3s 3p $^3P_{1,2}$ states of Mg to derive an averaged $Q(^{25}\mathrm{Mg})$ of 203(2) mb. It is close enough to the previous atomic standard value of 199.4(20) mb,[70] the muonic value of 201(3) mb[74] or the nuclear scattering value of 196(4) mb.[75]

For ^{29,33}Mg, see ref. 76.

Aluminum. Fabbro *et al.*[40] used AlY, Y = H, F, Cl, Br to derive a $Q(^{27}\mathrm{Al})$ of 146.598(1) mb, in excellent agreement with the previous standard value of 146.6(10) mb.[4,77] The same value, based on AlF, AlCl and the Al atom[77] was used as the reference for $Q(^{27-32}\mathrm{Al})$ by Heylen *et al.*[78] A closely similar value of 146.0(4) mb was obtained by Pernpointner and Visscher.[79]

A competing $Q(^{27}\mathrm{Al})$ of 148.2(5) mb was presented by Aerts and Brown[80] and utilised by Rickey *et al.*[81] The possible reasons for the slight deviation from Fabbro *et al.* are discussed in ref. 40.

Silicon, Phosphorus. See the IAEA tables for short-lived isotopes or excited nuclear states.[23]

Sulphur. We keep the previous $Q(^{33,35}\mathrm{S})$ of −69.4(4) and 48.3(3) mb, respectively, of Stopkowicz and Gauss[82] from CS and SiS molecules.

Chlorine. The previous $Q(^{35,37}\mathrm{Cl})$ were based on neutral Cl atom.[4] A new 'window' is opened by the B-like, Cl^{12+} ions. This time not only relativistic but also QED corrections have been included.[83,84] We so far keep the previous Q values of Chaudhuri *et al.*[85] but wait for the convergence of the new approach.

Argon. The $Q(^{37,39}\mathrm{Ar})$ of Sundholm and Pyykkö[86] of 76(3) and −116(2) mb, respectively, are kept, as explained in ref. 4.

Potassium. The $Q(^{40,41}\mathrm{K})$, −75.0(8) and 73.4(7) mb, of Teodoro *et al.*[87] are molecular. They agree with the Sundholm and Olsen[88] −74.9(19) and 73.3(18) mb, respectively. The molecular values have smaller error margins.

Calcium. Tang[89] uses the 4s 4p $^3P_{1,2}$ and 4s 3d $^1D_2$ states of Ca to derive an averaged $Q(^{43}\mathrm{Ca})$ of −47.9(6) mb. This new value is 17 percent larger than the earlier value −40.8(8) mb of Sundholm and Olsen[88] and also 7.9 percent larger than the Ca^+-based value −44.4(6) mb by Sahoo.[90] Chakraborty *et al.*[91] now obtain −44.1(4) mb. A nuclear shell model calculation gives a $Q(^{43}\mathrm{Ca})$ of −35 mb.[92]

Using the ratio $Q(^{41}\mathrm{Ca})/Q(^{43}\mathrm{Ca})$ = 1.630(11) from Arnold *et al.*[93] we obtain a $Q(^{41}\mathrm{Ca})$ of −78.1(10) mb.

Scandium. Dognon and Pyykkö[94] used the diatomic data on ScF, ScCl, ScBr and ScN and CCSD-T level calculations to obtain a $Q(^{45}\mathrm{Sc})$ of −223(3) mb, close to the previous standard value of −220(2) mb.[95] Note that the triple-bonded ScN had a very different electronic structure from the three halides but yet the obtained Q was similar. An atomic confirmation of the value as −222(5) mb was obtained by Tang *et al.*[96] using data on Sc^+ states.

Experimental B values for several 3d 4s and 3d 4p states of $^{45}Sc^+$ are available.[97]

Nuclear shell-model calculations give $Q(^{45}\mathrm{Sc})$ values of about −210 mb.[98]

Titanium. The ^{49}Ti Q remains at 247(11) mb,[99] based on atomic data for Ti^+. The measured $Q(^{49}\mathrm{Ti})/Q(^{47}\mathrm{Ti})$ = 0.819(1)[100] yields $Q(^{47}\mathrm{Ti})$ = 302(13) mb.

Vanadium. The classical atomic $Q(^{51}\mathrm{V})$ of Childs[101] is −52(10) mb. Combined with a solid-state $|^{50}\mathrm{V}/^{51}\mathrm{V}|$ ratio of 4.019(4) from Bleaney *et al.*[102] it yields a $Q(^{50}\mathrm{V})$ of 209(40) mb. Another, atomic measurement by Ertmer *et al.*[103] confirms the ratio as −4.03(3).

An attempt to correct the primary ^{51}V Q for Sternheimer polarization would give −43(5) mb.[104] A solid-state determination using $AlVO_4$ gave (−)48(1) mb[105] and this could be a serious competitor.

New measurements for the B of $^{50,51}V^+$ have just been published by Karadimas *et al.*[106]

An early nuclear model by Talmi[107] yielded a $Q(^{51}\mathrm{V})$ of −58 mb.

Chromium. The current standard value of $Q(^{53}\mathrm{Cr})$ remains the −150(50) mb from $3d^4\ 4s^2$, ^{5}D states of a Cr atom.[108] The experimental B constants have 5-figure accuracy, but the electric field gradients were deduced from the magnetic hfs. Later, accurate calculations have not yet been reported. Jarosz *et al.*[109] suggest a Q of −220(10) mb.

Manganese. The current $Q(^{55}\mathrm{Mn})$ of 330(10) mb comes from Dembczyński *et al.*[110] Values for several Mn isotopes are given by Babcock *et al.*[111]

Iron. The previous reference for the $I = \frac{3}{2}$ 14.41 keV Mössbauer state of ^{57}Fe was 160 mb.[112,113] Martínez-Pinedo *et al.*[114] closely agree with 150(20) mb, which we take as the current value. A value in this range is supported by later work by Casassa and Ferrari[115] and by Datta *et al.*[116]

The ground-state moments of ^{53}Fe were determined and calculated by Miller *et al.*[117]

Cobalt. The $Q(^{59}\mathrm{Co})$ of 420(30) mb in ref. 2–4 came from Murakawa.[118] Dembczyński[119] landed at 410(10) mb with q from magnetic hfs. Elantkowska[120] favored 380–390 (20) mb, based on the accurate experiments of Koszorús.[121]

Nickel. The $Q(^{61}\mathrm{Ni})$ of 162(15) mb comes from Childs and Goodman.[122] This reference value was used to discuss the Q of other Ni isotopes by Müller *et al.*[123]

Copper. The previous standard $Q(^{63}\mathrm{Cu})$ of −220(15) mb was muonic.[124] An atomic determination with Sternheimer corrections gave −211(4) mb.[125] Molecular calculations on CuF support the −220 mb value.[126]

For exotic isotopes $^{73-78}$Cu, see de Groote *et al.*[127]

Zinc. The previous $Q(^{67}\mathrm{Zn})$ of 122(10) mb[128] was based on 4s 4p states of the Zn atom. It agrees with a value of 125(5) mb

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from atomic, molecular and solid-state data.[129] A new B ($^3P_1$) of −18 995(10) MHz has been published by Waldherr.[130]

Gallium. The previous molecular standard Q value for ^{69}Ga was 171(2).[79] Multiplication by the ^{71}Ga/^{69}Ga ratio of 0.630158 of Daly and Holloway[131] would give a $Q(^{71}\text{Ga})$ of 108(1) mb. These values were supported by the atomic calculations of Yakobi *et al.*[132]

Germanium. The current $Q(^{73}\text{Ge})$ of −196(1) mb is based on the work of Kellö and Sadlej[133] on diatomic GeO and GeS at CCSD(T) level.

The latest Fock space coupled cluster atomic work yields −198(4) mb.[134]

Arsenic. The experimental B by Leung *et al.*[135] and the CCSD(T) calculation by Demović *et al.*[136] on diatomic AsP combine to give the current $Q(^{75}\text{As})$ of 311(2) mb. A 'muonic' value of 314(6) mb[137] also existed.

Selenium. The $^{77}_{34}$Se nuclear ground state has $I = \frac{1}{2}$ but the 250 keV $I = \frac{5}{2}$ state has a Q of 760 mb.[2,113] The value comes from a perturbed angular correlation measurement on solid Se and a band-structure q calculation.

Experimental evidence exists for a prolate shape of the first 2^+ state in ^{70}Se.[138]

Bromine. We choose for ^{79,80,81}Br the previous average values of 308.7(20), 182.6(12), and 257.9(17) mb, respectively from Stopkowicz *et al.*[139] These authors further confirmed the values from several halomethane molecules. They also closely agree with the earlier solid-state DFT results of Alonso *et al.*[140] Yakobi *et al.*[141] get $Q(^{79}\text{Br})$ = 302(5) mb.

A value of 1.197 0514(32) for the Q ratio 79/81 was obtained from BrF by Müller and Gerry.[142]

Krypton. The previous standard value of $Q(^{83}\text{Kr})$ of 259(1) mb was based on diatomic KrH^+ and a CCSD(T) DK calculation.[143] For the radioactive isotopes ^{81,85}Kr, +644(4) and +443(3) mb, respectively, was reported and for the 9.4 keV $I = \frac{7}{2}$ Mössbauer state of ^{83}Kr, 507(3) mb.[143]

Recent measurements on the Kr^+ ion have an adequate accuracy and could provide further confirmation.[144] For excited states of the neutral Kr atom, see Nomura[145] or Silwal and Brandenberger.[146]

Rubidium. The $Q(^{85}\text{Rb})$ of Kellö and Sadlej[147] is 276(1) mb. Combined with a solid-state 87/85 ratio of 0.4840 it would give a $Q(^{87}\text{Rb})$ of 133.5 mb, see Park *et al.*[148] They also get Q values in complete agreement with.[147] Note that Cederberg *et al.*[149] get from RbF molecules 0.4838301(18).

Already in 1973 Feiertag and zu Putlitz[150] obtained from Rb atoms $Q(^{85,87}\text{Rb})$ of 274(2) and 132(1) mb.

A precise atomic experiment for the $5P_{3/2}$ state of ^{85}Rb gives a B of 26.011(22) MHz.[151]

Strontium. Tang[73] uses the 5s 5p $^3P_{1,2}$ and 5s 4d $^1D_2$ states of Sr to derive an averaged $Q(^{87}\text{Sr})$ of 336(4) mb. This new Q is in excellent agreement with the molecular SrO and SrS value of 337(3) mb by Fabbro *et al.*,[152] which we recommend as the next standard value. Previously Lu *et al.*[153] obtained an atomic Q of 328(4) mb. Thus there are reasons to replace the previous standard value of 305(2) mb.[154] Chakraborty *et al.*[91] now obtain 310.2(19) mb. Note also the Sr^+ 4d-based 327(24) mb by Mårtensson-Pendrill.[155]

Yttrium. For $Q(^{90}\text{Y})$ the latest available value remains the atomic $4d5s^2\ ^2D$ one of −125(11) mb.[156]

Zirconium. The experiments on diatomic ZrO and ZrS by Beaton and Gerry[157] and the calculations by Kellö *et al.*[158] yield a $Q(^{91}\text{Zr})$ of −176(3) mb.

Niobium. The stable isotope has a $Q(^{93}\text{Nb})$ = −320(20) mb and $I = \frac{9}{2}$[159] according to a muonic experiment. Raghavan[19] also cites an atomic Q of −386(18) mb from Büttgenbach.[160]

Molybdenum. The current standard value, $Q(^{95}\text{Mo})$ = −22(1) mb is taken from Büttgenbach.[160] A ^{97}Mo/^{95}Mo ratio of −11.50(3) was obtained from non-spherical $4d^45s^2\ ^5D_{1,2}$ atomic states by Dubke *et al.*[161]

Technetium. The 'atomic' $Q(^{99}\text{Tc})$ of −129(6) mb comes from Büttgenbach.[160] Errico *et al.*[162] would accept the value but increase the error margin to (20) mb.

The NMR use of that I = 9/2, 212 kilo-year isotope was recently reviewed by Kuznetsov *et al.*[163]

Ruthenium. The previous $Q(^{99,101}\text{Ru})$ were 79(4) and 457(23) mb, respectively.[4] A new solid-state determination by Mishra[164] favors lower values, 73.4(17) and 431(14) mb, respectively. A lowering would also be favored by Holmes *et al.*[165] Gusmão *et al.*[166] used a RuC molecule to get 425(13) mb.

The ratio of the 89 keV state to the ground state, Q_1/Q_0 = 2.93(7) was measured by Kistner and Lumpkin.[167] Applying it to the Mishra value gives $Q(^{99}\text{Ru}\left(I = \frac{3}{2}\right))$ = 215 mb.

Rhodium. The $Q(^{100}\text{Rh})$ of 153 mb comes from PAC experiments and band-structure calculations for several solids.[113] It refers to the 75 keV, 215 ns I = 2+ nuclear state. The error limits are estimated by H. Haas (private communication to N. Stone, 2021).

Palladium. The present $Q(^{105}\text{Pd})$ of 660(11) mb is muonic.[168]

Silver. The stable silver isotopes ^{107,109}Ag have $I = \frac{1}{2}$ and hence no quadrupole moments. The radioactive isotopes $^{101-106,113-123}$Ag are being studied using the IGISOL machine[169] and nuclear DFT. The order of magnitude is 1 barn. New data for $Q(^{101-121}\text{Ag})$ are being provided by Skripnikov *et al.*[170]

Cadmium. A combination of atomic, molecular, and nuclear DFT theory gave for the $5/2^+$ state of ^{111}Cd a Q of 641(25) mb.[129] Later, perturbed angular correlation measurements on gaseous CdX_2, (X = Cl, Br, I) yielded a $Q(^{111m}\text{Cd})$ of +664(7) mb for the same $I = \frac{5}{2}$ state.[171]

The $Q(^{102,104,106}\text{Cd})$ were reported as −200(10), −230(10), and −280(80) mb by Ekström *et al.*[172]

The temperature dependence of q in solid Zn and Cd was analyzed by Haas.[173]

Indium. As explained in the previous review,[4] the $Q(^{113,115}\text{In})$ of 761(5), 772(5) mb came from the atomic calculations of Yakobi *et al.*[132] They closely agree with the diatomic molecular values 759(8), 770(8) mb, respectively, of van Stralen and Visscher.[174] Li and Tang[175] would favor a slightly smaller $Q(^{115}\text{In})$ of 758(12) mb.

The ratio $Q(^{115}\mathrm{In})/Q(^{113}\mathrm{In})$ was determined by Eck and Kusch[176] as 1.0138236(13) from the atoms.

For the Q values of the light In isotopes approaching the doubly magic $N = 50$ limit, see Karthein *et al.*[177] For the high-spin isomers of ^{127,129}In, see Vernon *et al.*[178]

A pseudoquadrupole effect would be a second-order M1 hyperfine effect, transforming like the first-order E2 one. Pyykkö[179] estimated that in metallic indium it could rise to about 1% of the total quadrupole-like effect.

Tin has a Z of 50, a nuclear magic number and therefore this neighborhood is of particular interest for nuclear studies.

In the previous review[4] we quoted the $Q(^{119}\mathrm{Sn})$ of −132(1) mb for the Mössbauer state of tin from Barone.[180] It was based on DFT calculations on 34 compounds but had no vibrational corrections. A different value of (−)104 mb would be obtained by Haas and Röder,[181] assuming that the underlying PAC measurement on β-Sn is correct. The minus sign was missing in their paper.

For the 18' isotope[109] Sn, three recent determinations by Elantkowska *et al.*,[182] Yordanov *et al.*,[183] and Papoulia *et al.*[184] give the converging results 220(8), 218(7)(15), and 219(7)(16) mb, respectively.

For the 2_1^+ state of[110] Sn, Park *et al.*[185] report a Q of +200(80) mb.

Antimony. The stable isotopes are ^{121,123}Sb. Their Q were reported by Dognon and Pyykkö[186] to be −541.7(8) and −690.6(8) mb, respectively, based on diatomic SbN, SbP, SbF, and SbCl. The earlier work is commented there. Worth mentioning are the $Q(^{121,123}\mathrm{Sb})$ of −543(11), −692(14) mb by Haiduke *et al.*,[187] based on the same molecules. Also the $Q(^{121}\mathrm{Sb})$ of −556(24) mb by Demović *et al.*[188] agrees within the error limits.

The isotopes $^{112-133}$Sb were discussed by Lechner *et al.*[189]

Tellurium seems to have few reliable Q data.[19]

Iodine. The stable isotope is ^{127}I with $I = \frac{5}{2}$. The atomic ground-state Q is −688.22 mb.[85]

The neutron-rich ^{131,132}I were found to have a Q of −300(10) and −250(20) mb, respectively.[190]

For the Mössbauer states of ^{127,129}I, see ref. 4.

Xenon. The older and newer $Q(^{131}\mathrm{Xe})$ of 114(1)[143] and 114.6(11) mb,[85] respectively, are close.

The $Q(^{124,126,128,130}\mathrm{Xe})$ are compared by Clément *et al.*[191] for various states.

Cesium. The previous standard $Q(^{133}\mathrm{Cs})$ is −3.43(10) mb. It is based on a molecular beam experiment on CsF[192] and a coupled-cluster calculation by Pernpointner *et al.*[193] Gerginov *et al.*[194] obtained from the atomic 6p $^2P_{3/2}$ state a Q of −3.55(4) mb, which we regard as a confirmation of that molecular value.

Barium. Tang[73] uses the 6s 6p $^1P_1$, and 6s 5d $^1D_2$ or $^3D_{1,2,3}$ states of Ba to derive an averaged Q of 161(2) and 246(4) mb for^{135,137} Ba, respectively.

Slightly lower 'atomic' values are given by Sahoo[195] (153(2) and 236(3) mb, used as the Y-2017 standard values), and by Chakraborty *et al.*,[91] who obtained from 5d states of Ba^+ a $Q(^{137}\mathrm{Ba})$ of 234.4 (17) mb. Their calculation included virtual triple excitations. Further theoretical improvements may induce changes of a few percent.

Good B measurements on BaO exist[196] and calculations up to CCSD-T level were reported by Haiduke.[197] His final $Q(^{135,137}\mathrm{Ba})$ are 155(5) and 239(7) mb, respectively. These values support those of Tang.[73]

A good experimental B for the $v = 0$ state of diatomic BaF has just been published by Preston *et al.*[198] Their isotopic ^{137}Ba/^{135}Ba ratio was 1.5382, close to the solid-state magnetic resonance values of 1.543(3)[199] or 1.5385.[200]

Lanthanum. In ref. 4 we chose the atomic $Q(^{139}\mathrm{La})$ of Itkin[201] of 206(4) mb. It is supported by the diatomic LaX, X = F–I value of 200(6) mb.[202]

Cerium. The stable isotopes ^{136,138,140,142}Ce have all spin $I = 0$. For other isotopes, see Raghavan[19] or the IAEA tables.[23]

Praseodymium. The stable isotope is ^{141}Pr, $I = \frac{5}{2}$. An 'atomic' Q of −58.9(42) mb exists.[19]

Iimura *et al.*[203] report for the ^{143}Pr $\left(I = \frac{7}{2}\right)$ a Q of +770(160) mb.

For trivalent Pr^{3+} ions in a CaF_2 lattice, Macfarlane *et al.*[204] find electric quadrupole and magnetic pseudoquadrupole interactions of opposite sign but comparable magnitude.

Neodymium. The stable isotopes ^{143,145}Nd have both spin $\frac{7}{2}$. The latest Q are −610(21) and −314(12) mb, respectively.[205] The q values were deduced from M1 hfs or Hartree–Fock–Slater atomic calculations.

Letokhov *et al.*[206] report for ^{143}Nd an atomic beam Q of −590(27) mb.

Promethium. All isotopes of Pm are radioactive. Alkhazov *et al.*[207] report a $Q(^{147}\mathrm{Pr})$ of 0.66(15) b. The 1966 optical atomic value of Reader[208] was 0.74(20) b.

Samarium. ^{147}Sm has a muonic Q of −259(26) mb.[209] Atomic beam measurements give a ratio $Q(^{147}\mathrm{Sm})/Q(^{149}\mathrm{Sm})$ of −3.4601(3).[210]

Europium. ^{151,153}Eu have comparable abundancies. Both have $I = \frac{5}{2}$. There is a muonic determination of the two Q values as 0.903(10) and 2.412(21) b, respectively.[211]

Concerning the ratio $Q(^{151}\mathrm{Eu})/Q(^{153}\mathrm{Eu})$, Möller *et al.*[212] noticed that the atomic mean value of 0.39184(22) significantly deviated from the muonic value 0.903(10)/2.412(21) = 0.3744(53).

Gadolinium. The two stable quadrupolar isotopes ^{155,157}Gd have both $I = \frac{3}{2}$ and a muonic Q of 1.30(2) and 1.36(2) b, respectively.[213] These were basically confirmed as 1.27(3) and 1.35(3) b, respectively.[214]

An atomic beam measurement by Unsworth[215] gave the ratio $^{157}B/^{155}B = 1.06534(3)$. While Tanaka *et al.*[213] get 1.046, Laubacher *et al.*[214] get 1.063, which is closer. We therefore choose their values.

A particularity of nominally cubic ferromagnetic alloys of Eu(II) or Gd(III) is their quadrupolar broadening or splitting.[216] Both a SO-induced relativistic q from the half-filled $4f^7$ shell, and a pseudoquadrupole, second-order M1 hyperfine mechanism may contribute.

Terbium. For the stable ^{159}Tb, $I = \frac{3}{2}$, Tanaka *et al.*[211] report a muonic Q of 1.432(8) b.

Dysprosium. For ^{163}Dy, Tanaka *et al.*[211] report a muonic Q of 2.648(21) b.

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Ferch *et al.*[217] report an experimental 163/161 ratio of 1.056148(8).

Lasner *et al.*[218] have measured accurate B for two states of diatomic DyO.

Holmium. For the $I = \frac{7}{2}$ ground state of[165] Ho, Olaniyi *et al.*[219] find a pionic Q of 3.58(2) b. Powers'[220] muonic $Q(^{165}\mathrm{Ho})$ is 3.49(3) b.

Terbium. For the stable ^{159}Tb, $I = \frac{3}{2}$, Tanaka *et al.*[211] report a muonic Q of 1.432(8) b.

Erbium. For ^{167}Er, Tanaka *et al.*[211] report a muonic Q of 3.565(29) b. Dzuba and Flambaum[221] used this value for a comparison between atomic Er and Fm.

Thulium. Cohen[222] estimated for the 8.4 keV Mössbauer state of ^{169}Tm a Q of −1.3 b. The nuclear ground state has $I = \frac{1}{2}$.

Ytterbium. The stable ^{173}Yb has $I = \frac{5}{2}$ and a muonic Q of +2.80(4) b.[223]

Jiang *et al.*[224] have measured for the $^2D_{3/2}$ state of $^{173}Yb^+$ a B of 963 609 800(570) Hz.

Lutetium. The 175/176 isotopic ratio from the Lu^{35} Cl(v = 0) NQCC was measured as 0.7088 by Cooke *et al.*[225] Exactly the same ratio was obtained from both atomic $^2D_{3/2,5/2}$ states of the neutral Lu atom by Brenner *et al.*[226] Haiduke *et al.*[227] used molecular data on LuF and LuCl to get a $Q(^{175,176}\mathrm{Lu})$ of 3.415(34) and 4.818(48) b, respectively. We take these as the next recommended values.

For ^{175,176}Lu, the pionic Q of Olaniyi *et al.*[219] are 3.62(9) and 5.07(7) b, respectively. The ratio is 0.714. An earlier muonic measurement gave a $Q(^{175}\mathrm{Lu})$ of +3.49(2) b.[228] For^{175} Lu, Lu and Chang[229] report an atomic Lu^+ Q 3.53(17) b. Their isotopic ratio is 0.72.

Flanagan *et al.*[230] settled at $Q(^{175,177}\mathrm{Lu})$ of 3.52(5) and 4.03(6) b, respectively.

Jin *et al.*[231] obtained from atomic spectra an average ratio $B(177)/B(179)$ of 0.884925.

Hafnium. For ^{177,179}Hf, Tanaka *et al.*[211] report muonic Q of 3.365(29) and 3.793(33) b, respectively. As noted in ref. 4, the latter value can be compared with Haiduke's molecular HfO and HfS based value of 3.750(37) b, which is in good agreement. Olaniyi *et al.*[219] have a $Q(^{179}\mathrm{Hf})$ of 3.93(5) b.

Tantalum. Olaniyi[219] report a pionic $Q(^{181}\mathrm{Ta})$ of 3.17(2) b.

Tungsten. The stable isotopes ^{180,182,183,184,186}W have all zero or $I = \frac{1}{2}$ spin in their ground states. Q data for excited states of ^{182,183}W exist.[23,232]

Rhenium. The latest, muonic, $Q(^{185,187}\mathrm{Re})$ of Antognini *et al.*[233] are 2.07(5) and 1.94(5) b, respectively. A number of small corrections were introduced. The previous ones of 2.180(20) and 2.070(20) b, respectively, were pionic.[234]

The isotopic ratio $B(185)/B(187)$ = 1.056709(17) was determined by Segel[235] in a number of compounds at various temperatures.

Osmium. The $Q(^{189}\mathrm{Os})$ of +856(28) mb is taken from Raghavan.[19]

Iridium. For ^{191,193}Ir Tanaka *et al.*[211] report muonic Q of 816(9) and 751(9) mb, respectively.

Platinum. The stable isotopes are not quadrupolar.

Gold. The $Q(^{197}\mathrm{Au})$ of 547(16) mb was muonic.[236] As discussed in the previous review,[4] both atomic and molecular work may suggest somewhat lower values.

Mercury. An atomic $Q(^{201}\mathrm{Hg})$ of 387(6) mb was obtained by Bieroń *et al.*[237]

Perturbed angular correlation measurements on gaseous $HgCl_2$ and HgI_2 yielded a $Q(^{199m}\mathrm{Hg})$ of 674(17) mb for the $I = \frac{5^-}{2}$ state.[171] Møller Jessen *et al.*[238] looked at the vibrational corrections, as opposed to taking B (R_e) by comparing the B ratios between these two molecules, thereby eliminating the actual value of Q.

Shell model calculations for $^{193-200}$Hg were published by Sahoo *et al.*[239]

Thallium. The stable isotopes ^{203,205}Tl have $I = \frac{1}{2}$. For the radioactive isotopes, see the reviews.[19,23]

Lead. The atomic $Q(^{209}\mathrm{Pb})$ of −269(165) mb comes from Anselment *et al.*[240] Values for several radioactive nuclides $^{196-214}$Pb were also given. For DFT nuclear calculations of Q in Eu to Pb, see Bonnard.[241]

Bismuth. The previous standard value of $Q(^{209}\mathrm{Bi})$ was −516(15) mb[242] and came from an atomic ground-state calculation, involving 20 131 relativistic configurations, thought at the time to be adequate. By now this value is replaced by later work.

The recent 'molecular' values are −420(8), −415.1, and −422(3) mb by Teodoro and Haiduke,[243] Shee *et al.*,[244] or Dognon and Pyykkö,[186] respectively. An atomic value of −422(22) mb is obtained by Li *et al.*[245] and −418(6) mb by Skripnikov *et al.*[246] A 'World average' $Q(^{209}\mathrm{Bi})$ of −420(17) mb is supported by Barzakh *et al.*[247]

Thus there is ample evidence for convergence to about −0.42 b and we pick the molecular value with the narrowest error margin, or −422(3) mb.[186]

The old low-temperature specific-heat determination of B in solid Bi yielded −380(40) mb, see.[36] Nuclear theory by Karayonchev *et al.*[248] yields −428 mb. Both agree with the present value.

See Barzakh *et al.* for the isotopes $^{187-191}$Bi[247] and $^{214-218}$Bi.[249]

We finally remind that already in 1936 Schüler and Schmidt[250] had a $Q(^{209}\mathrm{Bi})$ of −0.4 b.

Polonium. Skripnikov and Barzakh[251] used CCSDT(Q)-level calculations and available atomic experiments on the $6p^4\ ^3P_2$ states of the neutral Po atoms to deduce a $Q(^{205,207}\mathrm{Po})$ of 172.2(41) and 285.9(34) mb, respectively. Most of the estimated error was expected to be experimental. Both Breit and QED corrections were applied. Other isotopes were discussed.

Astatine. For $Q(^{195-211}\mathrm{At})$, see Cubiss *et al.*[252]

Radon. The $Q(^{209}\mathrm{Rn})$ of +311(31) mb was taken by Raghavan[19] from an unpublished CERN report.

Francium. The $Q(^{211}\mathrm{Fr})$ of −210(20) mb comes from Sahoo.[253] Most of the uncertainty is expected to be experimental. For ^{203,207}Fr, Wilkins *et al.*[254] obtain a Q of −0.47(2) and −0.24(2) b, respectively. Both isotopes have $I = \frac{9}{2}$.

Radium. The $Q(^{209,211,221,223}\mathrm{Ra})$ were obtained by Li *et al.*[255] The ^{221,223}Ra values of 1.978(106) and 1.248(22) b, respectively,

are coherent with the semiempirical analysis of Neu *et al.*[256] The $Q(^{211}\mathrm{Ra})$ of 0.33(2) b deviated from earlier results. The $Q(^{209}\mathrm{Ra})$ was 0.337(123)(6) b. Both $7p_{3/2}$ and $6d_{3/2}$ states of Ra^+ were employed. The calculations were at CCSD level.

Measurements on neutron-rich isotopes, up to ^{233}Ra, were reported by Lynch *et al.*[257]

Actinium. The neutron-rich isotopes ^{225,226,228,229}Ac were considered by Li *et al.*[258] The Q were 2.1093(7), 1.1013(12), 5.0434(40), and 2.4789(54) b, respectively. As said under their Table 2, to these statistical errors one should add 10% from the atomic theoretical calculations. The reference value 1.7 b for $Q(^{227}\mathrm{Ac})$ comes from Fred *et al.*[259]

Thorium. Li *et al.*[260] used 5f and 6d states of $^{229}Th^{3+}$ and CCSD calculations to get an averaged Q of 2.95(7) b. The measurements were made by Campbell,[261] who reported at the time a Q of 3.11(16) b. Combined with Safronova's calculation,[262] the result was narrowed to 3.11(6) b. The measurement has later been improved by Zitzer *et al.*[263] Their Q is 3.11(5) and 3.10(4) b from the $5F_{5/2}$ AND $6D_{5/2}$ states, respectively.

Porsev *et al.*[264] used the RCCSDT method to calculate on Th^{3+}, obtaining a Q of 3.11(2) b.

Notice that these values agree well with the Coulomb excitation value of 3.15(3) b of Bemis.[265] Chakraborty and Sahoo[266] land at the lower Q of 2.91(3) b using RCCSDT.

Protactinium. The $Q(^{231}\mathrm{Pa})$ of −1.72(5) b is estimated from Coulomb excitation.[267]

Uranium. The $Q(^{233}\mathrm{U})$ of 3.663(8) b is muonic.[268] So is the $Q(^{235}\mathrm{U})$ of 4.936(6) b. The dominant isotope ^{238}U has $I = 0$.

Neptunium. The $Q(^{237}\mathrm{Np})$ of +3.886(6) b is both muonic and pionic.[269] For the short-lived isotope ^{239}Np a Q of +4.05(8) b has been measured.[270]

Plutonium. For ^{241}Pu, a Q of +5.6(20) b is available from $5f^6 7s\ ^8F_{3/2}$ Pu II.[271]

Americium. The $Q(^{241,243}\mathrm{Am})$ of 3.8(1.2) and 4.21 b come from Dembczynski *et al.*[272] The q was deduced from the M1 hyperfine interaction. The Coulomb excitation $Q(^{243}\mathrm{Am})$ is 4.29(3) b.[273] Another measurement of the ^{241,243}Am B was published by Izosimov *et al.*[274]

Curium. Apparently no data.

Berkelium. Apparently no data.

Californium. Weber *et al.*[275] combined laser spectroscopy and atomic calculations to obtain $Q(^{249,253}\mathrm{Cf})$ of 6.27(33) and 5.53(51) b, respectively.

Einsteinium. A very precise B of −4316.254(76) MHz was published for ^{253}Es by Goodman *et al.*[276] The Q was deduced from the M1 hfs as 6.7(8) b.

Nothhelfer *et al.*[277] cite for $Q(^{254,255}\mathrm{Es})$ 9.6(1.2) and 5.1(1.7) b, respectively.

Fermium. Urquiza-González *et al.*[278] obtain from atomic laser spectroscopy and MCDHF calculations a large $Q(^{255}\mathrm{Fm})$ of +5.84(13) b. The spin $I = \frac{7}{2}$.

Nobelium. Raeder *et al.*[279] obtain from optical spectroscopy and MCDF atomic calculations a $Q(^{253}\mathrm{No})$ of +5.9(1.4)(0.9) b. Kumar *et al.*[280] refined this at Fock space CCSD level to 6.232 b, after correcting by a factor of 2. Thanks to referee 2.

4. Discussion

4.1. The Year-2026 recommended Q

The current recommendations are given in Tables 1–3. The changed values are indicated by •. Methods: a = atomic, m = molecular, s = solid, C = nuclear Coulomb excitation, M = Mössbauer state, T = nuclear theory.

4.2. Relation to nuclear theory

Gordy[283] pointed out that the small values near the magic nucleon numbers provide direct support to Maria Goeppert Mayer's nuclear shell theory.[284] Somà discusses how these magic numbers 2, 8, 20,

Table 1 '2026' Quadrupole moments, Z = 1–36. I gives both spin and parity

Nucleus	Z	A	I	Q/mb	Ref.	Meth	New
H	1	2	1+	2.85699(15)(18)	34	m	•
Li	3	6	1+	−0.7787	*t*	m	•
		7	3/2−	−38.624(292)	6	m	•
				−38.6(5)	41	a	
Be	4	9	3/2−	53.50(14)	47	a	•
B	5	10	3+	84.59(24)	52	a, m	
		11	3/2−	40.65(26)	52	a	
C	6	11	3/2−	33.36(19)(2)	56 *t*		•
N	7	14	1+	20.44(3)	59	a	
O	8	17	5/2+	−25.58(22)	57	a	
F	9	19	5/2+	−94.2(9)	64	m[t]	
Ne	10	20	2+	−220(20)	67	C	•
		21	3/2+	101.55(75)	57	a	
Na	11	23	3/2+	104(1)	69	m	
Mg	12	25	5/2+	203(2)	73	a	•
Al	13	27	5/2+	146.598(1)	40	m	•
S	16	33	3/2+	−69.4(4)	82	m	
		35	3/2+	47.1(9)	82	m	
Cl	17	35	3/2+	−81.12	85	a	
		37	3/2+	−63.93	4	am	
Ar	18	37	3/2+	76(3)	86	a	
		39	7/2−	−116(2)	86	a	
K	19	39	3/2+	60.3(6)	87	m	
		40	4−	−75.0(8)	87	m	
		41	3/2+	73.4(7)	87	m	
Ca	20	41	7/2−	−78.1(10)		a[t]	•
		43	7/2−	−47.9(6)	89	a	•
Sc	21	45	7/2−	−223(3)	94	m	•
Ti	22	47	5/2−	302(13)	99	a[t]	
		49	7/2−	247(11)	99	a	
V	23	50	6+	210(40)	103	a	
		51	7/2−	−52(10)	101	a	
Cr	24	53	3/2−	−150(50)	108	a	
Mn	25	55	5/2−	330(10)	110	a	
Fe	26	57	3/2−	150(20)	114	s[M]	•
Co	27	59	7/2−	410(10)	119	a	
Ni	28	61	3/2−	162(15)	122	a	
Cu	29	63	3/2−	−220(10)	126	m	
Zn	30	67	5/2−	122(10)	128	a	
Ga	31	69	3/2−	171(2)	79	m	
		71	3/2−	108(1)		m[t]	
Ge	32	69	5/2−	114(8)	134,281	a	•
		73	9/2+	−196(1)	133	m	
As	33	75	3/2−	311(2)	136	m	
Se	34	77	5/2	760	113	s[t]	
Br	35	79	3/2−	308.7(20)	139	m	
		80	1+	182.6(12)	139	m	
		81	3/2−	257.9(17)	139	m	
Kr	36	83	9/2+	259(1)	143	m	
		83	7/2	507(3)	143	m,[M]	

[t]See text.

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Table 2 '2026' Quadrupole moments. Z= 37–71

Nucl	Z	A	I	Q/mb	Ref.	Meth	New
Rb	37	85	5/2−	276(1)	147	m	
		87	3/2−	133.5	147	m	
Sr	38	87	9/2+	337(3)	152	m	•
Y	39	90	2−	−125(11)	156	a	
Zr	40	91	5/2+	−176(3)	158	m	
Nb	41	93	9/2+	−320(20)	159	μ	
Mo	42	95	5/2+	−22(1)	160	a	
Tc	43	99	9/2+	−129(20)	160,162	a[t]	
Ru	44	99	5/2+	73.4(17)	164	s	•
		101	5/2+	431(14)	164	s	•
Rh	45	100	2+	153(18)	113	s	
Ag	47					t	
Cd	48	111	5/2+	664(7)	171	m[t]	•
Cd	48	111	5/2+	641(25)	129	m, s	
In	49	113	9/2+	761(5)	132	a	
		115	9/2+	772(5)	132	a	
Sn	50	119	11/2−	−132(1)	180	s[M,t]	
Sb	51	121	5/2+	−541.7(8)	186	m	•
		123	7/2+	−690.6(8)	186	m	•
I	53	127	5/2+	−688.22	85	a	
Xe	54	131	3/2+	114.6(11)	282	m	
Cs	55	133	7/2+	−3.43(10)	193	m	
Ba	56	135	3/2+	161(2)	73	a	•
		137	3/2+	246(4)	73	a	•
La	57	139	7/2+	206(4)	201	a[t]	
Ce	58					t	
Pr	59	141	5/2+	−58.9(42)	19	a	
		143	7/2+	770(160)	203	a	
Nd	60	143	7/2−	−610(21)	205	a	
		145	7/2−	−314(12)	205	a	
Pm	61	147	7/2+	660(150)	207	a	
Sm	62	147	7/2−	−259(26)	209	μ	
Eu	63	151	5/2+	903(10)	211	μ	
		153	5/2+	2412(21)	211	μ	
Gd	64	155	3/2−	1270(30)	214	μ	
		157	3/2−	1350(30)	214	μ	
Tb	65	159	3/2+	1432(8)	211	μ	
Dy	66	163	5/2−	2648(21)	211	μ	
Ho	67	165	7/2−	3580(20)	219	π	
Er	68	167	7/2+	3565(29)	211	μ	
Tm	69	169	3/2+	−1300	222	M	
Yb	70	173	5/2−	2800(40)	223	μ	
Lu	71	175	7/2+	3415(34)	227	m	
		176	7−	4818(48)	227	m	

[t]See text.

Table 3 '2026' Quadrupole moments. Z = 72–102

Nucl	Z	A	I	Q/mb	Ref.	Meth	New
Hf	72	177	7/2−	3365(29)	211	μ	
		179	9/2+	3793(33)	211	μ	
Ta	73	181	7/2+	3170(20)	219	π	
Re	75	185	5/2+	2070(50)	233	μ	
		187	5/2+	1940(50)	233	μ	
Os	76	189	3/2+	856(28)	19	t	
Ir	77	191	3/2−	816(9)	211	μ	
		193	3/2+	751(9)	211	μ	
Au	79	197	3/2+	547(16)	236	μ	
Hg	80	199	5/2−	674(17)	171	m[t]	•
		201	3/2−	387(6)	237	a	
Pb	82	209	9/2+	−269(165)	240	a	
Bi	83	209	9/2−	−422(3)	186	m	•
Po	84	205	5/2−	172.2(41)	251	a	•
		207	5/2−	285.9(34)	251	a	•
At	85					t	
Rn	86	209	5/2−	311(31)	19		
Fr	87	211	9/2−	−210(20)	253	a	
Ra	88	209	5/2−	337(123)	255	a	
		211	5/2−	333((19)(6)	255	a	
		221	5/2−	1968(7)(34)	255	a	
		223	3/2+	1248(3)(22)	255	a	
Ac	89	225	3/2−	2100(210)	258	a	•
		226	(1)	1100(110)	258	a	•
		227	3/2−	1700(200)	19,259	a	
		228	3+	5040(500)	258	a	•
		229	(3/2+)	2480(250)	258	a	•
Th	90	229	5/2+	3110(60)	262	a t	
Pa	91	231	3/2−	−1720(50)	267	s	
U	92	233	5/2+	3663(8)	268	μ	
		235	7/2−	4936(6)	268	μ	
Np	93	237	5/2+	3886(6)	269	μ, π	
		239	5/2+	4050(80)	270	a, μ	•
Pu	94	241	5/2+	5600(200)	271	a	
Am	95	241	5/2−	3800(120)	272	a	
		243	5/2−	4210	272	a	
Cf	98	249	9/2−	6270(330)	275	a	•
		253	7/2+	5530(510)	275	a	•
Es	99	253	7/2+	6700(800)	276	a	
		254	(7+)	9600(1200)	277	a	•
		255	(7/2+)	5100(1700)	277	a	•
Fm	100	255	7/2+	5840(130)	278	a	•
No	102	253	(9/2−)	6232	280	a, t	•

[t]See text.

28, 50, 82 and 126 survive in microscopic nuclear theory in his minireview[285] on the work of Ding *et al.*[286]

Q values for nuclei from $_{64}$Gd to $_{76}$Os were calculated using nuclear DFT by Dobaczewski *et al.*[287] An adequate correlation is presented in their Fig. 20.

X.-J. Sun *et al.*[288] proposed a general formula for predicting Q for nuclear ground states and report values for Z = 11–96.

De Rydt *et al.*[289] reviewed the ground-state Q of the π (sd) nuclei.

Armat and Nejad[290] calculated Q for odd-neutron nuclei using a relativistic approach.

Correlations between quadrupole and hexadecapole deformations were discussed by Tang *et al.*[291] Rodríguez-Guzmán and Robledo[292] discuss the same issue beyond mean field correlations.

Rathi *et al.*[293] propose a new muonic method for muonic atoms in the range Z = 23–30, based on cryogenic microcalorimetry.

For a discussion on the E3 moments of pear-shaped nuclei, see Butler[294] or Kanerva and Kortelainen.[295] A further exotic shape for nuclei is the tetrahedral one found for $^{80}_{40}$Zr by Xu and Zhao[296] in a relativistic fully numerical calculation, and attributed to proton-neutron correlation effects.

4.3. Pseudoquadrupole effects

Ramsey[297] pointed out that 2nd-order M1 hyperfine effects can lead to quadrupole-like effects. He estimated the order-of-magnitude for HD. Later rough calculations were made for LiF and LiBr molecules[298] and for metals.[179]

Another example are the q which can arise in spherical or high-symmetry systems due to higher-order mechanisms. A first example is the small B of 1.27(10) Hz observed by Ramsey's group in the N atom $2p^3\ ^4S$ ground state.[299,300] In this particular case the reason was found to be the Breit interaction.[301]

In heavier, nd^5 (ref. 302) or nf^7 (ref. 216 and 301) systems, higher order spin–orbit and spin–spin terms are found to be

the dominant reason behind this q. At non-relativistic level such q vanish.

The quadrupole shifts due to electron penetration into the nucleus were analysed in Cottenier's group.[303,304]

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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