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Discovery of the Chromium Isotopes

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Twentyseven chromium isotopes have so far been observed; the discovery of these isotopes is discussed. For each isotope a brief summary of the first refereed publication, including the production and identification method, is presented.

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CONTENTS

1. INTRODUCTION

The discovery of the chromium isotopes is discussed as part of the series of the discovery of isotopes which began with the cerium isotopes in 2009 [1]. The purpose of this series is to document and summarize the discovery of the isotopes. Guidelines for assigning credit for discovery are (1) clear identification, either through decay-curves and relationships to other known isotopes, particle or γ-ray spectra, or unique mass and Z-identification, and (2) publication of the discovery in a refereed journal. The authors and year of the first publication, the laboratory where the isotopes were produced as well as the production and identification methods are discussed. When appropriate, references to conference proceedings, internal reports, and theses are included. When a discovery includes a half-life measurement the measured value is compared to the currently adopted value taken from the NUBASE evaluation [2] which is based on the ENSDF database [3].

2. DISCOVERY OF $^{42-68}$CR

Twentyseven chromium isotopes from A = 42 – 68 have been discovered so far; these include 4 stable, 9 proton-rich and 14 neutron-rich isotopes. According to the HFB-14 model [4], ^{77}Cr should be the last odd-even particle stable neutron-rich nucleus while the even-even particle stable neutron-rich nuclei should continue through ^{84}Cr. At the proton dripline ^{40}Cr and ^{41}Cr should still be particle stable. Thus, about 15 isotopes have yet to be discovered corresponding to about 36% of all possible chromium isotopes.

Figure A summarizes the year of first discovery for all chromium isotopes identified by the method of discovery. The range of isotopes predicted to exist is indicated on the right side of the figure. The radioactive chromium isotopes were produced using deep-inelastic reactions (DI), light-particle reactions

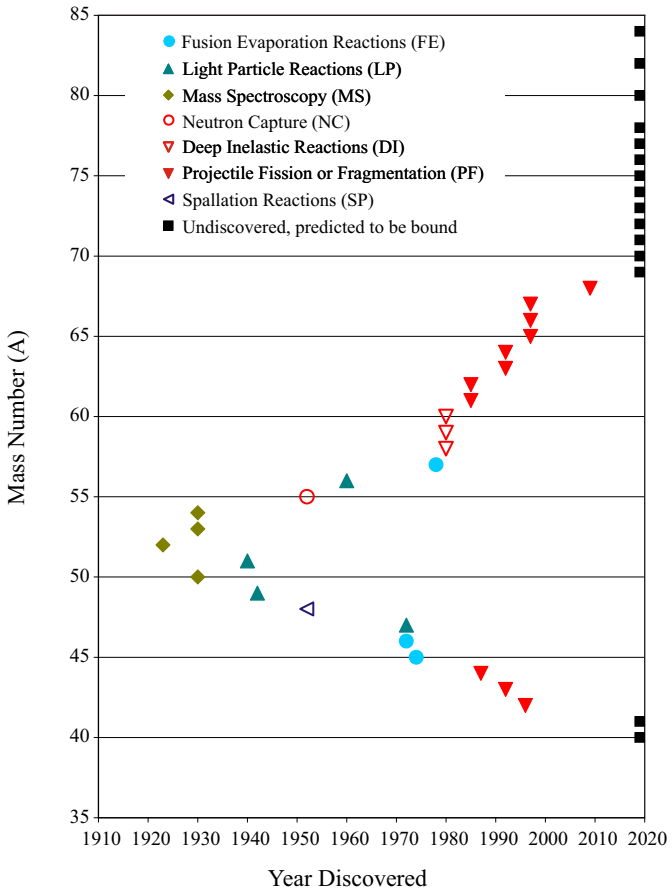

FIG. A. Chromium isotopes as a function of time when they were discovered. The different production methods are indicated. The solid black squares on the right hand side of the plot are isotopes predicted to be bound by the HFB-14 model.

(LP), neutron capture (NC), spallation (SP), heavy-ion fusion evaporation (FE) and projectile fragmentation of fission (PF). The stable isotopes were identified using mass spectroscopy (MS). Heavy ions are all nuclei with an atomic mass larger than A=4 [5]. Light particles also include neutrons produced by accelerators. In the following, the discovery of each chromium isotope is discussed in detail.

^{42}Cr

In the paper "First Observation of the $T_z = -7/2$ Nuclei ^{45}Fe and ^{49}Ni", Blank et al. reported the discovery of ^{42}Cr in 1996 at the Gesellschaft für Schwerionenforschung (GSI) in Germany [6]. A 600 A·MeV ^{58}Ni beam bombarded a beryllium target and isotopes were separated with the projectile-fragment separator FRS. ^{42}Ce was identified by time-of-flight, ΔE, and Bρ analysis. "We observed ten events of ^{42}Cr, three events of ^{45}Fe, and five events of ^{49}Ni. These three isotopes have been identified for the first time in the present experiment."

^{43}Cr

^{43}Cr was discovered by Borrel et al. at Grand Accelerateur National D'ions Lourds (GANIL) in France in 1992, as reported in the paper "The decay modes of proton drip-line nuclei with A between 42 and 47" [7]. A 69 A·MeV ^{58}Ni beam was incident on a natural nickel target and the projectile fragments were separated using the Ligne d'Ions Super Epluchés (LISE) spectrometer. The isotopes were identified by time of flight and energy loss measurements. "^{43}Cr is identified here for the first time, with 264 events recorded." The half-life of ^{43}Cr was determined via maximum-likelihood analysis of the time spectrum to be 21^{+4}_{-3}ms, which agrees with the presently accepted value of 21.6(7) ms.

^{44}Cr

The 1987 paper "Direct Observation of New Proton Rich Nuclei in the Region $23 \leq Z \leq 29$ Using A 55A.MeV ^{58}Ni Beam" reported the first observation of ^{44}Cr at GANIL by Pougheon et al. [8]. The fragmentation of a 55 A·MeV ^{58}Ni beam on a nickel target was used to produce proton-rich isotopes which were separated with the LISE spectrometer. Energy loss, time of flight, and magnetic rigidity measurements were recorded. "Here ^{44}Cr ($T_Z = -2$) is unambiguously identified with a statistics of 9 counts."

^{45}Cr

"A New Delayed Proton Precursor: Chromium-45" was published in 1974 by Jackson et al. reporting the discovery of ^{45}Cr [9]. The isotope was produced by the ^{32}S(^{16}O,3n) fusion evaporation reaction with ^{16}O beams of energies between 50 and 82 MeV from the Chalk River MP tandem accelerator. Spectra of β-delayed protons were measured with a surface barrier counter telescope. "The new $T_z = -3/2$ isotope, ^{45}Cr, has been produced by the ^{32}S(^{16}O,3n)^{45}Cr reaction. Its half-life was measured to be 50±6 ms." This half-life is consistent with the presently accepted value of 60.9(4) ms.

^{46}Cr

Zioni et al. published the first observation of ^{46}Cr in the paper "An Investigation of Proton-Rich Nuclei and Other Products from the Bombardment of ^{24}Mg, ^{28}Si and ^{32}S by ^{16}O Ions" in 1972 [10]. At the Jerusalem Racah institute a ^{16}O beam was accelerated to $22-33$ MeV with an EN tandem and ^{46}Cr was produced in the fusion-evaporation target ^{32}S(^{16}O,2n) reaction on a zinc sulphide target. Beta- and γ-ray spectra were recorded with a NE102 plastic scintillator and a Ge(Li) detector, respectively. "In particular the mass excess of the previously unobserved nucleus ^{46}Cr is found to be -29.46 ± 0.03 MeV; its half-life is 0.26±0.6 s." This half-life corresponds to the currently accepted value. A previously reported half-life of 1.1 s [11] could not be confirmed.

^{47}Cr

In the paper entitled "New Proton-Rich Nuclei in the $f_{7/2}$ Shell", Proctor et al. described the discovery of ^{47}Cr in 1972 [12]. The Michigan State University sector-focused cyclotron accelerated ^{3}He to 70.8 MeV and the reaction ^{50}Cr(^{3}He,^{6}He) was used to produce ^{47}Cr. The outgoing ^{6}He particles were detected in the focal plane of an Enge split-pole magnetic spectrograph. "The present measurements

represent the first observation of ^{47}Cr, ^{51}Fe, and ^{55}Ni." A measurement of a half-life of 430 ms [11] was assigned to either ^{47}Cr or ^{49}Mn. Similarly a 400 ms [11] was assigned to either ^{47}Cr or ^{46}V.

^{48}Cr

Rudstam et al. reported on the new discovery of ^{48}Cr in their 1952 publication "Nuclear Reactions of Iron with 340-Mev Protons" [13]. Protons were accelerated to 340 MeV by the Berkeley 184 inch cyclotron and ^{48}Cr was produced in spallation reactions on iron targets. Decay curves were measured with a chlorine-quenched Amperex Geiger-Müller tube following chemical separation. "In the chromium decay curves a new activity was found after subtraction of the activity due to 26.5-day Cr^{51}... The chromium isotope from these experiments can be assigned the mass number 48." In three different runs half-lives of 19, 24, and 25 h were measured which agree with the currently accepted value of 21.56(3) h.

^{49}Cr

"Artificial Radioactivity of ^{49}Cr", published in 1942 by O'Connor et al., announced the discovery of ^{49}Cr [14]. The bombardment of TiO_2 targets with 20 MeV alpha particles from the Ohio State cyclotron resulted in formation of ^{49}Cr by the reaction ^{46}Ti(α,n). A Wulf quartz fiber electrometer connected to a Freon filled ionization chamber was used to measure decay and absorption curves. "Since chemical separation shows that the 41.9-minute activity, produced by alpha-particle bombardment of titanium and by fast neutron bombardment of chromium is an isotope of chromium and since this period has not been found by proton bombardment of vanadium or deuteron bombardment of chromium, the activity must evidently be due to ^{49}Cr." This 41.9(3) min. half-life agrees with the accepted half-life measurement of 42.3(1) min.

^{50}Cr

The discovery of ^{50}Cr was reported in the 1930 paper "Constitution of Chromium" by Aston [15]. ^{50}Cr was observed with the Cavendish mass spectrometer using the volatile compound $Cr(CO)_6$. "The intensity of the beam of mass-rays has been so increased that not only has it has been possible, by the fine slits, to obtain a value for the packing fraction of Cr^{52} but also, by the use of coarse slits and long exposures, to reveal no less than three new isotopes, and to determine their relative abundances..." The three new isotopes were ^{50}Cr, ^{53}Cr and ^{54}Cr.

^{51}Cr

In the paper "K-Electron Capture and Internal Conversion in Cr^{51}", Walke et al. described their discovery of ^{51}Cr in 1940 [16]. At Berkeley a sample of metallic titanium was bombarded with 16-MeV alpha particles and ^{51}Cr was produced in the reaction ^{48}Ti(α,n). Electrons, X-rays and γ-rays were recorded. "As a result of these experiments we have failed to observe the 600-day vanadium activity which is consistent with the previous assignment to V^{47}. However, we have discovered another isotope which decays by K-electron capture, and we ascribe it to Cr^{51}." Its half life was measured to be 26.5(1) days, which is consistent with the accepted value of 27.7010(11) d.

^{52}Cr

Aston discovered ^{52}Cr in 1923 as reported in the paper "Further Determinations of the Constitution of the Elements by the Method of Accelerated Anode Rays" [17]. No details regarding the mass spectroscopic observation of cobalt is given. "Vanadium and chromium give single mass-lines at positions expected from their atomic weights 51 and 52."

^{53,54}Cr

The discovery of ^{53}Cr and ^{54}Cr was reported in the 1930 paper "Constitution of Chromium" by Aston [15]. ^{50}Cr was observed with the Cavendish mass spectrometer using the volatile compound $Cr(CO)_6$. "The intensity of the beam of mass-rays has been so increased that not only has it has been possible, by the fine slits, to obtain a value for the packing fraction of Cr^{52} but also, by the use of coarse slits and long exposures, to reveal no less than three new isotopes, and to determine their relative abundances..." The three new isotopes were ^{50}Cr, ^{53}Cr and ^{54}Cr.

^{55}Cr

In the 1952 publication "^{55}Cr, ein neues Chrom-Isotop mit T = 3,52 min Halbwertszeit" Flammersfeld and Herr reported the discovery of ^{55}Cr [18]. Slow neutrons produced in the reaction of deuterium on beryllium at Mainz University bombarded a pure chromium-oxide target and ^{55}Cr was produced by neutron capture on ^{54}Cr. Decay curves were measured following chemical separation. "Es lag nahe, die gemessene Aktivität auf ein durch unvermeidbare schnelle Neutronen aus dem Hauptisotop des Chroms nach ^{52}Cr(n,p) gebildetes ^{52}V (T = 3,77 min) zurückzuführen, um so mehr als Absorptionsversuche nahezu die gleiche β-Energie wie beim ^{52}V ergaben. Bestrahlungen mit und ohne Cadmium zeigten aber, daß die Aktivität aus dem Chrom hauptsächlich mit thermischen Neutronen entsteht, also ein (n,γ)-Prozeß vorliegen muß." [The measured activity could have been from the decay of ^{52}V (T = 3.77 min) produced in the reaction ^{52}Cr(n,p) due to the presence of fast neutrons, especially because absorption measurement resulted in β-decay energies similar to the decay of ^{52}V. However, irradiations with and without cadmium demonstrated that the activity was produced predominantly by thermal neutrons, thus it was due to the (n,γ) process.] The measured half-life of 3.52(3) min agrees with the currently accepted value of 3.497(3) min. Previously reported half-lives of 1.7 h [19], 2.27 h [20], 1.6 h [21], and 1.3 h [22] could not be confirmed.

^{56}Cr

In 1960, Dropesky et al. published the discovery of ^{56}Cr in their paper "Note on the decay of the new nucleide Cr^{56}" [23]. Normal chromium metal was bombarded with 2.7−2.9 MeV tritons at Los Alamos National Laboratory, and ^{56}Cr was formed in the reaction ^{54}Cr(t,p). The emission of β- and γ-rays was measured following chemical separation. "First evidence for the presence of Cr^{56} in the purified Cr sample came from the growth of 2.6-h Mn^{56} activity as identified by the 0.845, 1.81, and 2.13 MeV photopeaks observed with a 3×3 NaI(Tl) scintillator." The half-life was measured to be 5.94(1) min., which is still the currently accepted half-life. Previous searches for ^{56}Cr which was predicted to have a substantially longer half-live were unsuccessful [24,25].

^{57}Cr

Davids et al. reported the discovery of ^{57}Cr in the 1978 paper entitled "Mass and β decay of the new isotope ^{57}Cr" [26]. A 21 MeV ^{11}B beam from the Argonne FN tandem accelerator bombarded an enriched ^{48}Ca target and ^{57}Cr was created with the fusion evaporation reaction ^{48}Ca(^{11}B,pn). An NE102-plastic scintillator was used to measure β-rays and γ-rays were detected with Ge(Li) detectors. " ^{57}Cr was identified by the observation of a decaying 205.8-keV γ ray in the singles spectra... The half-life of ^{57}Cr was obtained from the decay of the 205.8-keV γ ray, and is 21.1$\pm$1.0 s." This half-life is still the presently accepted value.

^{58,59}Cr

Guerreau et al. reported the discovery of ^{58}Cr, ^{59}Cr in the 1980 paper "Seven New Neutron Rich Nuclides Observed in Deep Inelastic Collisions of 340 MeV ^{40}Ar on ^{238}U" [27]. A 340 MeV ^{40}Ar beam accelerated by the Orsay ALICE accelerator facility bombarded a 1.2 mg/cm^2 thick UF_4 target supported by an aluminum foil. The isotopes were identified using two ΔE-E telescopes and two time of flight measurements. "The new nuclides ^{54}Ti, ^{56}V, $^{58-59}$Cr, ^{61}Mn, $^{63-64}$Fe, have been produced through ^{40}Ar + ^{238}U reactions." At least twenty counts were recorded for these isotopes.

^{60}Cr

^{60}Cr was discovered in 1980 by Breuer et. al., and the new isotope was reported in their paper "Production of neutron-excess nuclei in ^{56}Fe-induced reactions" [28]. A beam of ^{56}Fe ions with an energy of 8.3 MeV/u from the Berkeley SuperHILAC bombarded ^{209}Bi and ^{238}U targets and products of this reaction were identified with a ΔE-E time-of-flight detector placed 118 cm from the target. "In addition, tentative identification of six additional nuclides (^{56}Ti, $^{57-58}$V, ^{60}Cr, ^{61}Mn, and ^{63}Fe) is reported."

^{61,62}Cr

The 1985 paper "Production and Identification of New Neutron-Rich Fragments from 33 MeV/u ^{86}Kr Beam in the 18$\leq$Z$\leq$27 Region" by Guillemaud-Mueller et al. reported the first observation of ^{61}Cr and ^{62}Cr [29]. The 33 MeV/u ^{86}Kr beam bombarded tantalum targets and the fragments were separated with the GANIL triple-focusing analyser LISE. "Each particle is identified by an event-by-event analysis. The mass A is determined from the total energy and the time of flight, and Z by the ΔE and E measurements... In addition to that are identified the following new isotopes: ^{47}Ar, ^{57}Ti, ^{59,60}V, ^{61,62}Cr, ^{65,65}Mn, ^{66,67,68}Fe, ^{68,69,70}Co."

^{63,64}Cr

In their paper "New neutron-rich isotopes in the scandium-to-nickel region, produced by fragmentation of a 500 MeV/u ^{86}Kr beam", Weber et al. presented the first observation of ^{63}Cr and ^{64}Cr in 1992 [30]. The isotopes were produced in the fragmentation reaction of a 500 A·MeV ^{86}Kr beam from the heavy-ion synchroton SIS on a beryllium target and separated with the zero-degree spectrometer FRS at GSI. "The isotope identification was based on combining the values of Bρ, time of flight (TOF),

and energy loss ($\triangle$E) that were measured for each ion passing through the FRS and its associated detector array... The results shown in [the figure] represent unambigious evidence for the production of the very neutron-rich isotopes ^{58}Ti, ^{61}V, ^{63}Cr, ^{66}Mn, ^{69}Fe, and ^{71}Co, and yield indicative evidence for the production of ^{64}Cr, ^{72}Co, and ^{75}Ni." Thirty-five and three counts of ^{63}Cr and ^{64}Cr were recorded, respectively.

$^{65-67}$Cr

Bernas et al. observed ^{65}Cr, ^{66}Cr, and ^{67}Cr for the first time in 1997 as reported in their paper "Discovery and cross-section measurement of 58 new fission products in projectile-fission of 750·A MeV ^{238}U" [31]. Uranium ions were accelerated to 750 A·MeV by the GSI UNILAC/SIS accelerator facility and bombarded a beryllium target. The isotopes produced in the projectile-fission reaction were separated using the fragment separator FRS and the nuclear charge Z for each was determined by the energy loss measurement in an ionization chamber. "The mass identification was carried out by measuring the time of flight (TOF) and the magnetic rigidity Bρ with an accuracy of 10^{-4}." 82, 19, and 4 counts of ^{65}Cr, ^{66}Cr and ^{67}Cr were observed, respectively.

^{68}Cr

^{68}Cr was discovered by Tarasov et al. in 2009 and published in "Evidence for a change in the nuclear mass surface with the discovery of the most neutron-rich nuclei with $17 \leq Z \leq 25$" [32]. ^{9}Be targets were bombarded with 132 MeV/u ^{76}Ge ions accelerated by the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University. ^{68}Cr was produced in projectile fragmentation reactions and identified with a two-stage separator consisting of the A1900 fragment separator and the S800 analysis beam line. "The observed fragments include fifteen new isotopes that are the most neutron-rich nuclides of the elements chlorine to manganese (^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,58}Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn)."

3. SUMMARY

The discoveries of the known chromium isotopes have been compiled and the methods of their production discussed. With a few exceptions the discovery of the chromium isotopes was non-controversial. The half-life measurement of ^{46}Cr was initially incorrect and the half-life of ^{47}Cr did at first not have a firm element nor mass assignment. It took about 15 years following the first reports to determine and assign the correct half-life of ^{55}Cr. Searches for ^{56}Cr were initially unsuccessful.

Acknowledgments

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REFERENCES

1. J.Q. Ginepro, J. Snyder, and M. Thoennessen, At. Data Nucl. Data Tables **95**, 905 (2009)
2. G. Audi, O. Bersillon, J. Blachot, and A.H. Wapstra, Nucl. Phys. A **729**, 3 (2003)
3. ENSDF, Evaluated Nuclear Structure Data File, mainted by the National Nuclear Data Center at Brookhaven National Laboratory, published in Nuclear Data Sheets (Academic Press, Elsevier Science).
4. S. Goriely, M. Samyn, and J.M. Pearson, Phys. Rev. C **75**, 64312 (2007)
5. H.A. Grunder and F.B. Selph, Annu. Rev. Nucl. Sci. **27**, 353 (1977)
6. B. Blank, S. Czajkowski, F. Davi, R. Del Moral, J.P. Dufour, A. Fleury, C. Marchand, M.S. Pravikoff, J. Benlliure, F. Boué, R. Collatz, A. Heinz, M. Hellström, Z. Hu, E. Roeckl, M. Shibata, K. Sümmerer, Z. Janas, M. Karny, M. Pfützner, and M. Lewitowicz, Phys. Rev. Lett. **77**, 2893 (1996)
7. V. Borrel, R. Anne, D. Bazin, C. Borcea, G.G. Chubarian, R. Del Moral, C. Detraz, S. Dogny, J.P. Dufour, L. Faux, A. Fleury, L.K. Fifield, D. Guillemaud-Mueller, F. Hubert, E. Kashy, M. Lewitowicz, C. Marchand, A.C. Mueller, F. Pougheon, M.S. Pravikoff, M.G. Saint-Laurent, and O. Sorlin, Z. Phys. A **344**, 135 (1992)
8. F. Pougheon, J.C. Jacmart, E. Quiniou, R. Anne, D. Bazin, V. Borrel, J. Galin, D. Guerreau, D. Guillemaud-Mueller, A.C. Mueller, E. Roeckl, M.G. Saint-Laurent, and C. Detraz, Z. Phys. A **327**, 17 (1987)
9. K.P. Jackson, J.C. Hardy, H. Schmeing, R.L. Graham, J.S. Geiger, and K.W. Allen, Phys. Lett. B **49**, 341 (1974)
10. J. Zioni, A.A. Jaffe, E. Friedman, N. Haik, R. Schectman, and D. Nir, Nucl. Phys. A **181**, 465 (1972)
11. H. Tyren and P.-A. Tove, Phys. Rev. **96**, 773 (1954)
12. I.D. Proctor, W. Benenson, J. Dreisbach, E. Kashy, G.F. Trentelman, and B.M. Preedom, Phys. Rev. Lett. **29**, 434 (1972)
13. G. Rudstam, P.C. Stevenson, and R.L. Folger, Phys. Rev. **87**, 358 (1952)
14. J.J. O'Connor, M.L. Pool, and J.D. Kurbatov, Phys. Rev. **62**, 413 (1942)
15. F.W. Aston, Nature **126**, 200 (1930)
16. H. Walke, F.C. Thompson, and J. Holt, Phys. Rev. **57**, 171 (1940)
17. F.W. Aston, Nature **112**, 449 (1923)
18. A. Flammersfeld, W. Herr, Z. Naturforsch. **7a**, 649 (1952)
19. M.L. Pool, J.M. Cork, and R.L. Thornton, Phys. Rev. **52**, 239 (1937)
20. G. Dickson, P.W. McDaniel, and E.J. Konoki, Phys. Rev. **57**, 351 (1937)
21. T. Amaki, T. Jumori, and A. Sugimoto, Phys. Rev. **57**, 751 (1940)
22. L. Seren, H.N. Friedlander, and S.H. Turkel, Phys. Rev. **72**, 888 (1947)
23. B.J. Dropesky, A.W. Schardt, and T.T. Schull, Nucl. Phys. **16**, 357 (1960)

24. J.W. Jones, U.S. Atomic Energy Commission Report, NYO-6627 (unpublished)

25. L.P. Roy, and L. Yaffe, Can. J. Chem. **35**, 176 (1957)

26. C.N. Davids, D.F. Geesaman, S.L. Tabor, M.J. Murphy, E.B. Norman, and R.C. Pardo, Phys. Rev. C **17**, 1815 (1978)

27. D. Guerreau, J. Galin, B. Gatty, and X. Tarrago, Z. Phys. A **295**, 105 (1980)

28. H. Breuer, K.L. Wolf, B.G. Glagola, K.K. Kwiatkowski, A.C. Mignerey, V.E. Viola, W.W. Wilcke, W.U. Schroder, J.R. Huizenga, D. Hilscher, and J. Birkelund, Phys. Rev. C **2**, 2454 (1980)

29. D. Guillemaud-Mueller, A.C. Mueller, D. Guerreau, F. Pougheon, R. Anne, M. Bernas, J. Galin, J.C. Jacmart, M. Langevin, F. Naulin, E. Quiniou, and C. Detraz, Z. Phys. A **322**, 415 (1985)

30. M. Weber, C. Donzaud, J.P. Dufour, H. Geissel, A. Grewe, D. Guillemaud-Mueller, H. Keller, M. Lewitowicz, A. Magel, A.C. Mueller, G. Münzenberg, F. Nickel, M. Pfützner, A. Piechaczek, M. Pravikoff, E. Roeckl, K. Rykaczewski, M.G. Saint-Laurent, I. Schall, C. Stéphan, K. Sümmerer, L. Tassan-Got, D.J. Vieira, and B. Voss, Z. Phys. A **343**, 67 (1992)

31. M. Bernas, C. Engelmann, P. Armbruster, S. Czajkowski, F. Ameil, C. Böcksteigel, Ph. Dessagne, C. Donzaud, H. Geissel, A. Heinz, Z. Janas, C. Kozhuharov, Ch. Miehé, G. Münzenberg, M. Pfützner, W. Schwab, C. Stéphan, K. Sümmerer, L. Tassan-Got, B. Voss, Phys. Lett. B **415**, 111 (1997)

32. O.B. Tarasov, D.J. Morrissey, A.M. Amthor, T. Baumann, D. Bazin, A. Gade, T.N. Ginter, M. Hausmann, N. Inabe, T. Kubo, A. Nettleton, J. Pereira, M. Portillo, B.M. Sherrill, A. Stolz, and M. Thoennessen, Phys. Rev. Lett. **102**, 142501 (2009)

EXPLANATION OF TABLE

TABLE I. Discovery of chromium isotopes

Isotope	Chromium isotope
Author	First author
Journal	Journal of publication
Ref.	Reference
Method	Production method used in the discovery: FE: fusion evaporation LP: light-particle reactions (including neutrons) MS: mass spectroscopy NC: neutron capture reactions DI: deep-inelastic reactions PF: projectile fragmentation or fission SP: spallation reactions
Laboratory	Laboratory where the experiment was performed
Country	Country of laboratory
Year	Year of discovery

TABLE I. Discovery of Chromium Isotopes

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Isotope	Author	Journal	Ref.	Method	Laboratory	Country	Year
^{42}Cr	B. Blank	Phys. Rev. Lett.	Bla96	PF	Darmstadt	Germany	1996
^{43}Cr	V. Borrel	Z. Phys. A	Bor92	PF	GANIL	France	1992
^{44}Cr	F. Pougheon	Z. Phys. A	Pou87	PF	GANIL	France	1987
^{45}Cr	K.P. Jackson	Phys. Lett. B	Jac74	FE	Chalk River	Canada	1974
^{46}Cr	J. Zioni	Nucl. Phys. A	Zio72	FE	Jerusalem	Israel	1972
^{47}Cr	I.D. Proctor	Phys. Rev. Lett.	Pro72	LP	Michigan State	USA	1972
^{48}Cr	G. Rudstam	Phys. Rev.	Rud52	SP	Berkeley	USA	1952
^{49}Cr	J.J. O'Connor	Phys. Rev.	OCo42	LP	Ohio State	USA	1942
^{50}Cr	F.W. Aston	Nature	Ast30	MS	Cambridge	UK	1930
^{51}Cr	H. Walke	Phys. Rev.	Wal40	LP	Berkeley	USA	1940
^{52}Cr	F.W. Aston	Nature	Ast23	MS	Cambridge	UK	1923
^{53}Cr	F.W. Aston	Nature	Ast30	MS	Cambridge	UK	1930
^{54}Cr	F.W. Aston	Nature	Ast30	MS	Cambridge	UK	1930
^{55}Cr	A. Flammersfeld	Z. Naturforsch.	Fla52	NC	Mainz	Germany	1952
^{56}Cr	B.J. Dropesky	Nucl. Phys.	Dro60	LP	Los Alamos	USA	1960
^{57}Cr	C.N. Davids	Phys. Rev. C	Dav78	FE	Argonne	USA	1978
^{58}Cr	D. Guerreau	Z. Phys. A	Gue80	DI	Orsay	France	1980
^{59}Cr	D. Guerreau	Z. Phys. A	Gue80	DI	Orsay	France	1980
^{60}Cr	H. Breuer	Phys. Rev. C	Bre80	DI	Berkeley	USA	1980
^{61}Cr	D. Guillemaud-Mueller	Z. Phys. A	Gui85	PF	GANIL	France	1985
^{62}Cr	D. Guillemaud-Mueller	Z. Phys. A	Gui85	PF	GANIL	France	1985
^{63}Cr	M. Weber	Z. Phys. A	Web92	PF	Darmstadt	Germany	1992
^{64}Cr	M. Weber	Z. Phys. A	Web92	PF	Darmstadt	Germany	1992
^{65}Cr	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{66}Cr	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{67}Cr	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{68}Cr	O.B. Tarasov	Phys. Rev. Lett.	Tar09	PF	Michigan State	USA	2009

REFERENCES FOR TABLE

Ast23 F.W. Aston, Nature **112**, 449 (1923)

Ast30 F.W. Aston, Nature **126**, 200 (1930)

Ber97 M. Bernas, C. Engelmann, P. Armbruster, S. Czajkowski, F. Ameil, C. Böckstiegel, Ph. Dessagne, C. Donzaud, H. Geissel, A. Heinz, Z. Janas, C. Kozhuharov, Ch. Miehé, G. Münzenberg, M. Pfützner, W. Schwab, C. Stéphan, K. Sümmerer, L. Tassan-Got, and B. Voss, Phys. Lett. B **415**, 111 (1997)

Bla96 B. Blank, S. Czajkowski, F. Davi, R. Del Moral, J.P. Dufour, A. Fleury, C. Marchand, M.S. Pravikoff, J. Benlliure, F. Boué, R. Collatz, A. Heinz, M. Hellström, Z. Hu, E. Roeckl, M. Shibata, K. Sümmerer, Z. Janas, M. Karny, M. Pfützner, and M. Lewitowicz, Phys. Rev. Lett. **77**, 2893 (1996)

Bor92 V. Borrel, R. Anne, D. Bazin, C. Borcea, G.G. Chubarian, R. Del Moral, C. Detraz, S. Dogny, J.P. Dufour, L. Faux, A. Fleury, L.K. Fifield, D. Guillemaud-Mueller, F. Hubert, E. Kashy, M. Lewitowicz, C. Marchand, A.C. Mueller, F. Pougheon, M.S. Pravikoff, M.G. Saint-Laurent, and O. Sorlin, Z. Phys. A **344**, 135 (1992)

Bre80 H. Breuer, K.L. Wolf, B.G. Glagola, K.K. Kwiatkowski, A.C. Mignerey, V.E. Viola, W.W. Wilcke, W.U. Schröder, J.R. Huizenga, D. Hilscher and J. Birkelund, Phys. Rev. C **22**, 2454 (1980)

Dav78 C.N. Davids, D.F. Geesaman, S.L. Tabor, M.J. Murphy, E.B. Norman, and R.C. Pardo, Phys. Rev. C **17**, 1815 (1978)

Dro60 B.J. Dropesky, A.W. Schardt, and T.T. Schull, Nucl. Phys. **16**, 357 (1960)

Fla52 A. Flammersfeld, W. Herr, Z. Naturforsch. **7a**, 649 (1952)

Gue80 D. Guerreau, J. Galin, B. Gatty, and X. Tarrago, Z. Phys. A **295**, 105 (1980)

Gui85 D. Guillemaud-Mueller, A.C. Mueller, D. Guerreau, F. Pougheon, R. Anne, M. Bernas, J. Galin, J.C. Jacmart, M. Langevin, F. Naulin, E. Quiniou, and C. Detraz, Z. Phys. A **322**, 415 (1985)

Jac74 K.P. Jackson, J.C. Hardy, H. Schmeing, R.L. Graham, J.S. Geiger, and K.W. Allen, Phys. Lett. B **49**, 341 (1974)

OCo42 J.J. O'Connor, M.L. Pool, and J.D. Kurbatov, Phys. Rev. **62**, 413 (1942)

Pro72 I.D. Proctor, W. Benenson, J. Dreisbach, E. Kashy, G.F. Trentelman, and B.M. Preedom, Phys. Rev. Lett. **29**, 434 (1972)

Pou87 F. Pougheon, J.C. Jacmart, E. Quiniou, R. Anne, D. Bazin, V. Borrel, J. Galin, D. Guerreau, D. Guillemaud-Mueller, A.C. Mueller, E. Roeckl, M.G. Saint-Laurent, and C. Detraz, Z. Phys. A **327**, 17 (1987)

Rud52 G. Rudstam, P.C. Stevenson, and R.L. Folger, Phys. Rev. **87**, 358 (1952)

Tar09 O.B. Tarasov, D.J. Morrissey, A.M. Amthor, T. Baumann, D. Bazin, A. Gade, T.N. Ginter, M. Hausmann, N. Inabe, T. Kubo, A. Nettleton, J. Pereira, M. Portillo, B.M. Sherrill, A. Stolz, and M. Thoennessen, Phys. Rev. Lett. **102**, 142501 (2009)

Wal40 H. Walke, F.C. Thompson, and J. Holt, Phys. Rev. **57**, 171 (1940)

Web92 M. Weber, C. Donzaud, J.P. Dufour, H. Geissel, A. Grewe, D. Guillemaud-Mueller, H. Keller, M. Lewitowicz, A. Magel, A.C. Mueller, G. Münzenberg, F. Nickel, M. Pfützner, A. Piechaczek, M. Pravikoff, E. Roeckl, K. Rykaczewski, M.G. Saint-Laurent, I. Schall, C. Stéphan, K. Sümmerer, L. Tassan-Got, D.J. Vieira, and B. Voss, Z. Phys. A **343**, 67 (1992)

Zio72 J. Zioni, A.A. Jaffe, E. Friedman, N. Haik, R. Schectman, and D. Nir, Nucl. Phys. A **181**, 465 (1972)