

Jens-Volker Kratz, Karl Heinrich Lieser

Nuclear and Radiochemistry

Fundamentals and Applications

Volume 2

1																	18
H 1	2											13	14	15	16	17	2
Li 3	Be 4											5	6	7	8	9	10
Na 11	Mg 12	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	113	Fl 114	115	Lv 116	117	118
119	120	121	156	157	158	159	160	161	162	163	164						
165	166											167	168	169	170	171	172

Lanthanides

Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------

Actinides

Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103
----------	----------	---------	----------	----------	----------	----------	----------	----------	----------	-----------	-----------	-----------	-----------

Superactinides

122	123	124	125	126	127	128	129		151	152	153	154	155
-----	-----	-----	-----	-----	-----	-----	-----	--	-----	-----	-----	-----	-----

Stable elements

Natural radioisotopes

Natural radioelements

Artificial radioelements

Jens-Volker Kratz and Karl Heinrich Lieser

Nuclear and Radiochemistry

Fundamentals and Applications

Third, revised edition



WILEY-VCH
Verlag GmbH & Co. KGaA

The Author

Prof. Dr. Jens-Volker Kratz

Institut für Kernchemie
Universität Mainz
Fritz-Strassmann-Weg 2
55128 Mainz
Germany

All books published by **Wiley-VCH** are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2013 Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Composition Toppan Best-set Premedia Limited, Hong Kong

Printing and Binding Markono Print Media Pte Ltd, Singapore

Cover Design Schulz Grafik-Design, Fußgönheim

Print ISBN: 978-3-527-32901-4

ePDF ISBN: 978-3-527-65336-2

ePub ISBN: 978-3-527-65335-5

mobi ISBN: 978-3-527-65334-8

oBook ISBN: 978-3-527-65333-1

Printed in Singapore
Printed on acid-free paper

*Jens-Volker Kratz and
Karl Heinrich Lieser*

Nuclear and Radiochemistry

Related Titles

Vanhaecke, F.; Degryse, P. (eds.)

Isotopic Analysis

Fundamentals and Applications Using ICP-MS

2012

ISBN: 978-3-527-32896-3

Lehto, J., Hou, X.

Chemistry and Analysis of Radionuclides

Laboratory Techniques and Methodology

2011

ISBN: 978-3-527-32658-7

Atwood, D. (ed.)

Radionuclides in the Environment

2010

ISBN: 978-0-470-71434-8

Loveland, W. D., Morrissey, D., Seaborg, G. T.

Modern Nuclear Chemistry

2006

ISBN: 978-0-471-11532-8

Preface

This textbook aims at a complete and concise description of the present knowledge of nuclear and radiochemistry and applications in various fields of the natural sciences. It is based on teaching courses and research spanning several decades. The book is mainly addressed to advanced undergraduate students and to graduate students of chemistry. Students and scientists working in physics, geology, mineralogy, biology, medicine, and other fields will also find useful information about the principles and applications of nuclear and radiochemistry.

Traditionally, nuclear chemistry has been deeply tied to nuclear physics, cooperatively called nuclear science. At the same time, a wide field of applications of nuclear and radiochemistry in other sciences has developed. Therefore, it was considered important to bring together in one textbook a detailed presentation of the physical fundamentals as well as applied aspects of nuclear chemistry ranging from nuclear structure, nuclear masses, nuclear reactions, the production of radionuclides and labeled compounds, the chemistry of the radioelements, the study of radionuclides in the environment, all the way to the nuclear and radiochemistry needed in nuclear technology. Applications also include the use of radionuclides in analytical chemistry, in geo- and cosmochemistry, dating by nuclear methods, and the use of radionuclides in the life sciences and medicine.

For further reading, the relevant literature is listed abundantly at the end of each chapter. Generally, it is arranged in chronological order, beginning with the literature of historical relevance, followed by more recent work subdivided according to the subject matter into general and more specialized aspects.

After the passing of Professor Karl Heinrich Lieser, the younger author (JVK) was approached by the Lieser family and by the publisher and was motivated to prepare a generally updated third edition of this textbook. The concept and structure of the book remain largely unchanged; however, new developments and results have been incorporated, including the most recent references. These updates concern the physical properties of atomic nuclei, the nuclear force and nuclear structure, techniques in nuclear chemistry, nuclear reactions, statistical considerations in radioactivity measurements, the actinides and transactinides, radionuclide mass spectrometry, and modern methods of speciation of radionuclides in the environment. These have been

taken from teaching courses held at the Johannes Gutenberg University over the last 30 years.

It is my pleasure to thank Mrs. Petra Sach-Muth for help with the software “wiley-vch.dot” and Mr. Jürgen Hubrath for scanning and improving a large number of new figures.

Mainz, April 2012

Jens-Volker Kratz

Contents

Preface *XI*

Volume 1

- 1 Fundamental Concepts 1**
- 2 Radioactivity in Nature 23**
- 3 Radioelements and Radioisotopes and Their Atomic Masses 33**
- 4 Other Physical Properties of Nuclei 57**
- 5 The Nuclear Force and Nuclear Structure 73**
- 6 Decay Modes 119**
- 7 Radioactive Decay Kinetics 189**
- 8 Nuclear Radiation 205**
- 9 Measurement of Nuclear Radiation 235**
- 10 Statistical Considerations in Radioactivity Measurements 273**
- 11 Techniques in Nuclear Chemistry 289**

Volume 2

- 12 Nuclear Reactions 361**
- 12.1 Collision Kinematics 362
- 12.2 Coulomb Trajectories 364
- 12.3 Cross-sections 368
- 12.4 Elastic Scattering 372
- 12.5 Elastic Scattering and Reaction Cross-section 379

12.6	Optical Model	383
12.7	Nuclear Reactions and Models	385
12.7.1	Investigation of Nuclear Reactions	386
12.7.2	Compound-Nucleus Model	386
12.7.3	Precompound Decay	403
12.7.4	Direct Reactions	404
12.7.5	Photonuclear Reactions	407
12.7.6	Fission	407
12.7.7	High-Energy Reactions	418
12.8	Nuclear Reactions Revisited with Heavy Ions	422
12.8.1	Heavy-Ion Fusion Reactions	424
12.8.2	Quasi-fission	434
12.8.3	Deep Inelastic Collisions	440
12.8.4	Relativistic Heavy-Ion Collisions, the Phases of Nuclear Matter	457
	References	460
	Further Reading	462
13	Chemical Effects of Nuclear Transmutations	465
13.1	General Aspects	465
13.2	Recoil Effects	466
13.3	Excitation Effects	471
13.4	Gases and Liquids	476
13.5	Solids	479
13.6	Szilard–Chalmers Reactions	482
13.7	Recoil Labeling and Self-labeling	484
	References	485
	Further Reading	485
14	Influence of Chemical Bonding on Nuclear Properties	487
14.1	Survey	487
14.2	Dependence of Half-Lives on Chemical Bonding	488
14.3	Dependence of Radiation Emission on the Chemical Environment	490
14.4	Mössbauer Spectrometry	499
	References	504
	Further Reading	505
15	Nuclear Energy, Nuclear Reactors, Nuclear Fuel, and Fuel Cycles	507
15.1	Energy Production by Nuclear Fission	507
15.2	Nuclear Fuel and Fuel Cycles	512
15.3	Production of Uranium and Uranium Compounds	517
15.4	Fuel Elements	520
15.5	Nuclear Reactors, Moderators, and Coolants	524
15.6	The Chernobyl Accident	532
15.7	Reprocessing	537
15.8	Radioactive Waste	544

15.9	The Natural Reactors at Oklo	551
15.10	Controlled Thermonuclear Reactors	552
15.11	Nuclear Explosives	554
	References	555
	Further Reading	555
16	Sources of Nuclear Bombarding Particles	559
16.1	Neutron Sources	559
16.2	Neutron Generators	560
16.3	Research Reactors	561
16.4	Charged-Particle Accelerators	565
16.4.1	Direct Voltage Accelerators	565
16.4.2	Linear Accelerators	568
16.4.3	Cyclotrons	570
16.4.4	Synchrocyclotrons, Synchrotrons	574
16.4.5	Radioactive Ion Beams	576
16.4.6	Photon Sources	577
	References	578
	Further Reading	579
17	Radioelements	581
17.1	Natural and Artificial Radioelements	581
17.2	Technetium and Promethium	585
17.3	Production of Transuranic Elements	588
17.3.1	Hot-Fusion Reactions	594
17.3.2	Cold-Fusion Reactions	598
17.3.3	^{48}Ca -Induced Fusion Reactions	604
17.4	Cross-sections	606
17.5	Nuclear Structure of Superheavy Elements	610
17.6	Spectroscopy of Actinides and Transactinides	615
17.7	Properties of the Actinides	618
17.8	Chemical Properties of the Transactinides	629
17.8.1	Prediction of Electron Configurations and the Architecture of the Periodic Table of the Elements	630
17.8.2	Methods to Investigate the Chemistry of the Transactinides	632
17.8.3	Selected Experimental Results	653
	References	668
	Further Reading	671
18	Radionuclides in Geo- and Cosmochemistry	677
18.1	Natural Abundances of the Elements and Isotope Variations	677
18.2	General Aspects of Cosmochemistry	680
18.3	Early Stages of the Universe	681
18.4	Synthesis of the Elements in the Stars	683
18.4.1	Evolution of Stars	684
18.4.2	Evolution of the Earth	686

18.4.3	Thermonuclear Reaction Rates	687
18.4.4	Hydrogen Burning	688
18.4.5	Helium Burning	690
18.4.6	Synthesis of Nuclei with $A < 60$	690
18.4.7	Synthesis of Nuclei with $A > 60$	691
18.5	The Solar Neutrino Problem	696
18.6	Interstellar Matter and Cosmic Radiation	704
18.6.1	Interstellar Matter	704
18.6.2	Cosmic Radiation	705
18.6.3	Radionuclides from Cosmic Rays	706
18.6.4	Cosmic-Ray Effects in Meteorites	706
18.6.5	Abundance of Li, Be, and B	707
	References	708
	Further Reading	708
19	Dating by Nuclear Methods	711
19.1	General Aspect	711
19.2	Cosmogenic Radionuclides	712
19.3	Terrestrial Mother/Daughter Nuclide Pairs	717
19.4	Natural Decay Series	720
19.5	Ratios of Stable Isotopes	723
19.6	Radioactive Disequilibria	724
19.7	Fission Tracks	725
	References	726
	Further Reading	727
20	Radioanalysis	729
20.1	General Aspects	729
20.2	Analysis on the Basis of Inherent Radioactivity	730
20.3	Neutron Activation Analysis (NAA)	732
20.4	Activation by Charged Particles	736
20.5	Activation by Photons	738
20.6	Special Features of Activation Analysis	739
20.7	Isotope Dilution Analysis	741
20.8	Radiometric Methods	743
20.9	Other Analytical Applications of Radiotracers	745
20.10	Absorption and Scattering of Radiation	745
20.11	Radionuclides as Radiation Sources in X-ray Fluorescence Analysis (XFA)	746
20.12	Analysis with Ion Beams	748
20.13	Radioisotope Mass Spectrometry	752
20.13.1	Resonance Ionization Mass Spectrometry (RIMS)	752
20.13.2	Accelerator Mass Spectrometry (AMS)	757
	References	761
	Further Reading	763

21	Radiotracers in Chemistry	765
21.1	General Aspects	765
21.2	Chemical Equilibria and Chemical Bonding	765
21.3	Reaction Mechanisms in Homogeneous Systems	767
21.4	Reaction Mechanisms in Heterogeneous Systems	772
21.5	Diffusion and Transport Processes	776
21.6	Emanation Techniques	778
	References	781
	Further Reading	781
22	Radionuclides in the Life Sciences	783
22.1	Survey	783
22.2	Application in Ecological Studies	784
22.3	Radioanalysis in the Life Sciences	784
22.4	Application in Physiological and Metabolic Studies	786
22.5	Radionuclides Used in Nuclear Medicine	787
22.6	Single-Photon Emission Computed Tomography (SPECT)	789
22.7	Positron Emission Tomography (PET)	790
22.8	Labeled Compounds	790
	References	797
	Further Reading	797
23	Technical and Industrial Applications of Radionuclides and Nuclear Radiation	801
23.1	Radiotracer Techniques	801
23.2	Absorption and Scattering of Radiation	803
23.3	Radiation-induced Reactions	805
23.4	Energy Production by Nuclear Radiation	807
	Further Reading	810
24	Radionuclides in the Geosphere and the Biosphere	813
24.1	Sources of Radioactivity	813
24.2	Mobility of Radionuclides in the Geosphere	816
24.3	Reactions of Radionuclides with the Components of Natural Waters	818
24.4	Interactions of Radionuclides with Solid Components of the Geosphere	823
24.5	Radionuclides in the Biosphere	826
24.6	Speciation Techniques with Relevance for Nuclear Safeguards, Verification, and Applications	832
24.6.1	Redox Reactions, Hydrolysis, and Colloid Formation of Pu(IV)	837
24.6.2	Investigation of the Homologs Th(IV) and Zr(IV)	842
24.6.3	Time-resolved Laser-induced Fluorescence	850
24.6.4	Conclusions	854

References 854

Further Reading 855

25 Dosimetry and Radiation Protection 861

25.1 Dosimetry 861

25.2 External Radiation Sources 864

25.3 Internal Radiation Sources 865

25.4 Radiation Effects in Cell 867

25.5 Radiation Effects in Humans, Animals, and Plants 868

25.6 Non-occupational Radiation Exposure 872

25.7 Safety Recommendations 872

25.8 Safety Regulations 875

25.9 Monitoring of the Environment 879

References 880

Further Reading 880

Appendix 883

Glossary 883

Physical Constants 887

Conversion Factors 889

Relevant Journals 889

Web References 890

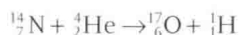
Index 891

12

Nuclear Reactions

A nuclear reaction is a process in which a nucleus reacts with a proton or another nucleus, an elementary particle, or a photon to produce one or more other nuclei and possibly other particles. The nuclear states that can be investigated in the decay of radioactive isotopes as discussed in Section 11.9 are limited to a relatively low energy range. A much larger energy range is accessible through nuclear reactions. It is of great principle and practical importance to understand the various reaction mechanisms that occur in nuclear collisions.

The phenomenon of nuclear reactions was discovered by Rutherford in 1919 when he observed that, in the bombardment of nitrogen with the 6.69 MeV α particles of ^{214}Po , scintillation of a zinc sulfide screen persisted even when enough material to absorb all the α particles was interposed between the nitrogen and the screen. Further experiments showed that the long-range particles causing the scintillation were protons and Rutherford's first reaction may be written



with the shorthand notation $^{14}\text{N}(\alpha, \text{p})^{17}\text{O}$ where, as indicated here, atomic numbers are commonly omitted. Most nuclear reactions are studied by inducing a collision between two nuclei where one of the nuclei is at rest, the target nucleus, and the other nucleus, the projectile, is in motion. In a nuclear reaction, there is conservation of the total number of nucleons A , charge, energy, momentum, angular momentum, statistics, and parity. Nuclear reactions, like chemical reactions, are always accompanied by a release or absorption of energy, and this is expressed by adding the term to the right hand side of the equation. Thus, a more complete statement of Rutherford's first reaction is



The quantity Q is the energy of the reaction or simply the reaction Q value. Other than in chemistry, the convention is to assign positive Q values to energy-releasing reactions (exoergic reactions) and negative Q values to energy absorption (endoergic reactions). Another important difference between chemical reactions and nuclear reactions must be pointed out. In chemical reactions, macroscopic amounts of material undergo transmutation and heats of reaction are given per mole of the reactants. In nuclear reactions, single processes are considered and

the Q values are therefore given per nucleus transformed. For example, the reaction $^{14}\text{N}(\alpha, p)^{17}\text{O}$ has a Q value of -1.190 MeV or $-1.19066 \cdot 10^{-6}$ ergs or $-4.56 \cdot 10^{-14}$ calories per ^{14}N atom transformed. To convert 1 mole of ^{14}N to ^{17}O would require an energy of $6.022 \cdot 10^{23} \cdot 4.56 \cdot 10^{-14} \text{ cal} = 2.75 \cdot 10^{10} \text{ cal}$. This is five orders of magnitude larger than the largest values observed for heats of chemical reactions. The Q value is calculated with tabulated mass excesses, see Eq. (3.5), as $Q = \Delta(^{14}\text{N}) + \Delta(^4\text{He}) - (\Delta(^{17}\text{O}) + \Delta(^1\text{H})) = 2.863 + 2.425 - (-0.811 + 7.28903) \text{ MeV} = -1.190 \text{ MeV}$. Does that mean that the reaction can actually be produced by α particles whose kinetic energies are just over 1.19 MeV? The answer is no for two reasons. Firstly, in the collision conservation of momentum requires that at least 4/18 of the kinetic energy of the α particle must be retained by the products as kinetic energy. Thus only 14/18 of the α particle's kinetic energy is available for the reaction. The threshold energy of α particles for the $^{14}\text{N}(\alpha, p)^{17}\text{O}$ reaction is $18/14 \times 1.19 \text{ MeV} = 1.53 \text{ MeV}$. The second reason why the α particles must have higher energies than the Q value is the Coulomb repulsion between the α particle and the ^{14}N nucleus, Eq. (1.15),

$$V_C = 1.44 \frac{Z_1 Z_2}{R_1 + R_2} \text{ MeV}$$

Setting $R = 1.5A^{1/3} \text{ fm}$, we get a value of about 3.4 MeV for the Coulomb barrier between the α particle and the ^{14}N nucleus. Thus, classically, an α particle must have $18/14 \times 3.4 = 4.4 \text{ MeV}$ kinetic energy for the (α, p) reaction to occur even though the energetic threshold for the reaction is only 1.53 MeV. In the quantum-mechanical treatment of the problem, there exists a finite probability for barrier penetration, but the probability is extremely small as we saw in the discussion of α decay in Section 6.2.

12.1

Collision Kinematics

Generalizing the above discussion, and using the notation $A_1 + A_2 \rightarrow A_3 + A_4$, we can describe the situation before the collision in the laboratory system by

$$E_{\text{lab}} = \frac{m}{2} A_1 v_{\infty}^2 \quad (12.1)$$

$$P_{\text{lab}} = m A_1 v_{\infty} \quad (12.2)$$

where m is the nucleon mass, A_1 is the mass number of the projectile, and v_{∞} is the velocity at infinite distance with

$$v_{\infty} = \sqrt{\frac{2E_{\text{lab}}}{mA_1}} = 1.389 \sqrt{\frac{E_{\text{lab}}}{A_1}} \text{ cm ns}^{-1} \quad (12.3)$$

In the center-of-mass system, Figure 12.1, before the collision, both ions move toward the center of mass, S , with

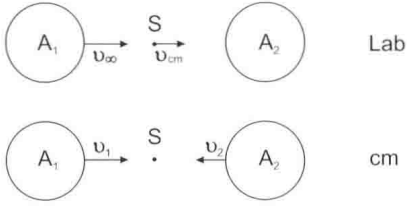


Figure 12.1 Laboratory and center-of-mass system before the collision.

$$\begin{aligned} v_1 &= \frac{A_2}{A_1 + A_2} v_{\infty} \\ v_2 &= \frac{A_1}{A_1 + A_2} v_{\infty} \end{aligned} \quad (12.4)$$

The kinetic energy and momentum in the center-of-mass system are

$$E_{\text{cm}} = \frac{m}{2} (A_1 v_1^2 + A_2 v_2^2) = \frac{\mu}{2} v_{\infty}^2 \quad (12.5)$$

$$P_{\text{cm}} = m(A_1 v_1 + A_2 v_2) = \mu v_{\infty}$$

where μ , the reduced mass, equals

$$m \frac{A_1 A_2}{A_1 + A_2} = m A_{12}$$

Only the center-of-mass energy E_{cm} and the relative momentum P_{cm} are available for the reaction. The remainder is translational energy (recoil energy) of the total system

$$E_{\text{trans}} = \frac{A_1}{A_1 + A_2} E_{\text{lab}} \quad (12.6)$$

and

$$E_{\text{cm}} = E_{\text{lab}} - E_{\text{trans}} \quad (12.7)$$

The translational velocity of the center of mass relative to the laboratory system is

$$v_{\text{cm}} = \frac{A_1}{A_1 + A_2} v_{\infty} = v_2 = \sqrt{\frac{2E_{\text{trans}}}{m(A_1 + A_2)}} = 1.389 \sqrt{\frac{E_{\text{trans}}}{A_1 + A_2}} \text{ cm ns}^{-1} \quad (12.8)$$

Another useful energy variable is the laboratory energy per nucleon

$$\varepsilon = \frac{E_{\text{lab}}}{A_1} = \frac{E_{\text{cm}}}{A_{12}} = \frac{m}{2} v_{\infty}^2 \quad (12.9)$$

After the collision, the situation is as depicted in Figure 12.2. In the center-of-mass system the product A_3 is emitted with velocity v_3 under the center-of-mass angle Θ . It is common to look explicitly at the projectile-like product A_3 ; for the target-like fragment, the corresponding variables result from trivial transformation.

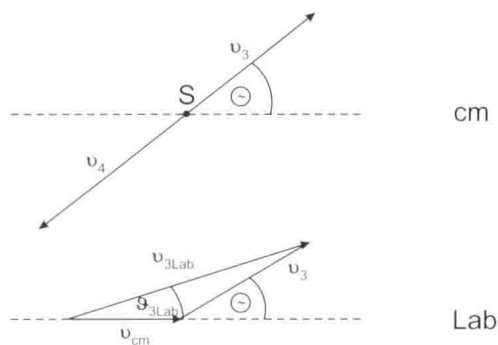


Figure 12.2 Center-of-mass and laboratory system after the collision.

Figure 12.2 also shows the situation in the laboratory system: vector addition of v_3 and v_{cm} yields v_{3lab} under laboratory angle ϑ_{3lab} . The connection between ϑ_{3lab} and Θ_{cm} is

$$\tan \vartheta_{3lab} = \frac{v_3 \sin \Theta}{v_3 \cos \Theta + v_{cm}} = \frac{\sin \Theta}{\cos \Theta + \frac{v_{cm}}{v_3}} \quad (12.10)$$

and vice versa

$$\Theta = \vartheta_{3lab} + \arcsin \frac{v_{cm} \sin \vartheta_{3lab}}{v_3}$$

It is customary to introduce the kinematic variable $\gamma_3 = v_{cm}/v_3$. For elastic scattering $v_3 = v_1$ and $\gamma_3 = A_1/A_2$. For two colliding ions of equal mass, $\gamma_3 = 1$ and $\vartheta_{3lab} = \Theta/2$. In the general case of a two-body reaction, the quantity γ_3 is given by

$$\gamma_3 = \left(\frac{A_1 A_3}{A_2 A_4} \frac{E_{cm}}{E_{cm} + Q} \right)^{1/2} \quad (12.11)$$

where the Q value can also be determined as the difference of the kinetic energies after and before the reaction as $Q = E_f^{\infty} - E_i^{\infty}$ equal to the total kinetic energy loss $\text{TKEL} = \text{TKE}_i - \text{TKE}_f = -Q$. The ∞ sign indicates that the particles need to be separated far enough from each other so that the interaction potential is no longer acting. Because of the conservation of the total energy, the Q value at the same time corresponds to the difference of the rest masses of the initial and final state (Eq. (3.5)).

12.2

Coulomb Trajectories

Figure 12.3 shows the classical trajectories of two colliding ions in the center-of-mass system. The distance of closest approach between the two centers of gravity, D , and the scattering angle Θ are related by