Landolt-Börnstein

Numerical Data and Functional Relationships in Science and Technology

Zahlenwerte und Funktionen aus Naturwissenschaften und Technik

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Group I

Volume 9

Elastic and Charge Exchange Scattering of Elementary Particles

Supplement to Volume I/7 and Extension to High Energies

Subvolume b: Pion Nucleon Scattering

Part 2: Methods and Results of Phenomenological Analyses

Springer-Verlag Berlin · Heidelberg · New York

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Editor in Chief: K.-H. Hellwege

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Band 9

Elastische und Ladungsaustausch-Streuung von Elementarteilchen

Ergänzung zu Band I/7 und Erweiterung für hohe Energien

Teilband b: Pion-Nukleon-Streuung

Teil 2: Methoden und Ergebnisse phänomenologischer Analysen

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Units for cross sections

$$\frac{d\sigma}{dt}\left[\frac{\text{mb}}{\text{GeV}^2}\right]=0.3894\frac{d\sigma}{dt}[\text{GeV}^{-4}]=1026.0\frac{d\sigma}{dt}[\text{n.u.}];$$

$$\frac{d\sigma}{d\Omega}\left[\frac{\text{mb}}{\text{sr}}\right]=0.3894\frac{d\sigma}{d\Omega}[\text{GeV}^{-2}]=19.99\frac{d\sigma}{d\Omega}[\text{n.u.}]=\frac{q^2[\text{GeV}^2]}{\pi}\frac{d\sigma}{dt}\left[\frac{\text{mb}}{\text{GeV}^2}\right]$$

$$1\,\text{mb}=10^3\,\mu\text{b}=10^6\,\text{nb}=10^{-27}\,\text{cm}^2.$$

Masses and derived quantities

Pion: $\mu=\mu_{\pm}=0.13957\,\text{GeV}$, $\mu_0=0.13496\,\text{GeV}$.
Nucleon: $m=m_p=0.93828\,\text{GeV}$, $m_n=0.93957\,\text{GeV}$.

$$1/\mu=7.1649\,\text{GeV}^{-1},\quad 1/\mu^2=51.336\,\text{GeV}^{-2},\quad m/\mu=6.7227,\quad m^2=45.195\,\mu^2.$$

Compton wavelength: $\lambda\!\!\!^{-}_{\pi}=\hbar c/\mu c^2=1.4138\,\text{fm}$, $\lambda\!\!\!^{-2}_{\pi}=19.989\,\text{mb}$, $\lambda\!\!\!^{-}_{\pi}/c=4.716\cdot10^{-24}\,\text{s}$.

We have always used the proton mass and the charged pion mass in kinematical calculations.

Pion-Nucleon coupling constant and other parameters

The pseudoscalar and pseudovector coupling constants g and f are related by $g^2/4\pi=(2m/\mu)^2f^2$. Taking $f^2=0.079$, we have $g^2/4\pi=14.28$, $g=13.40$, $g^2/m=26.70\,\mu^{-1}=191.3\,\text{GeV}^{-1}$, $g^2/2m^2=1.99\,\mu^{-2}$.

Pion decay constant: $f_\pi=(0.945\pm0.001)\mu=132\,\text{MeV}$. Axial vector coupling constant: $g_A=1.26\pm0.01$.

Isospin relations

Amplitudes for the reactions $\pi^{\pm}p\to\pi^{\pm}p$ and $\pi^-p\to\pi^0n$

$$A_+=A^{3/2}\qquad\qquad =A^+-A^-=\tfrac{1}{3}(2A^N+A^\Delta).$$

$$A_-=\tfrac{1}{3}(2A^{1/2}+A^{3/2})\qquad =A^++A^-=A^\Delta,$$

$$A_0=-\frac{\sqrt{2}}{3}(A^{1/2}-A^{3/2})=-\sqrt{2}A^-=\frac{\sqrt{2}}{3}(A^N-A^\Delta)=\frac{1}{\sqrt{2}}(A_+-A_-).$$

$I=1/2$ amplitude

$$A^{1/2}=\tfrac{1}{2}(3A_--A_+)=A^++2A^-.$$

Isospin even and odd combinations

$$A^+=\tfrac{1}{2}(A_-+A_+)=\tfrac{1}{3}(A^{1/2}+2A^{3/2});\quad A^-=\tfrac{1}{2}(A_--A_+)=-\frac{1}{\sqrt{2}}A_0=\tfrac{1}{3}(A^{1/2}-A^{3/2}).$$

Upper indices: 1/2 and 3/2 give the value of I. N and Δ belong to $I_u=1/2$ and 3/2, respectively.

Parameters of meson resonances

	η	ϱ	ω	S*	φ	f	g
Mass [MeV]	548.8	769	782.6	975	1019.61	1273	1691
	±0.6	±3	±0.2	±4	±0.07	±5	±5
Full width [MeV]	$0.83\cdot10^{-3}$	154	9.9	33	4.21	179	200
	$\pm0.12\cdot10^{-3}$	±5	±0.3	±6	±0.13	±20	±20
$I^G(J^P)C_n$	$0^+(0^-)+$	$1^+(1^-)-$	$0^-(1^-)-$	$0^+(0^+)+$	$0^-(1^-)-$	$0^+(2^+)+$	$1^+(3^-)-$

I=isospin, G=G-parity, J=spin, P=space parity, C_n=charge-conjugation parity for the neutral member of the multiplet (Review of Particle Properties: 82 R Roos).

Conversion of units

Most of the equations contain only the physical quantities mass, energy, momentum, length and time (no electrical or magnetic quantities). In this case, the equations can be written in terms of only one natural unit, preferably an energy. If the rest mass μ of a particle is chosen, the units are shown in the first line of the following table; if 1 GeV is used as basic unit, the corresponding units are shown in the second line.

Basic unit	Energy	Mass	Momentum	Length	Time
μc^2	μc^2	μ	μc	$\lambda\!\!\!^{-} = \frac{\hbar}{\mu c}$	$\frac{\lambda\!\!\!^{-}}{c} = \frac{\hbar}{\mu c^2}$
1 GeV	GeV	GeV/c^2	GeV/c	GeV^{-1}	GeV^{-1}/c

Both these systems of units go usually under the expression $\hbar = c = 1$. In this volume the charged pion mass is used for μ (natural units, "n.u."). As an example the equation $E^2 = (pc)^2 + m^2c^4$ can be written as

$$(E/\mu c^2)^2 = (p/\mu c)^2 + (m/\mu)^2 \text{ or } (E/\text{GeV})^2 = (p/\text{GeV}/c)^2 + (mc^2/\text{GeV})^2$$

In the literature and also in this volume there is an inconsistency concerning the treatment of c in the dimension. In some cases, $c = 1$ is understood (for instance resonance masses are usually given in GeV) but in others, c is written in the dimension (momenta are given in GeV/c).

Length		fm	n.u.	GeV^{-1}	mb·GeV
1 fm = 10^{-13} cm	=	–	0.7073	5.068	1.9733
1 n.u. = $1\mu^{-1}$	=	1.414	–	7.165	2.7898
1 GeV^{-1}	=	0.1973	0.1396	–	0.3894
1 mb·GeV	=	0.5068	0.3585	2.568	–

Area		mb	n.u.	GeV^{-2}	$\text{mb}^{1/2}\,\text{GeV}^{-1}$
1 mb = 10^{-27} cm^2	=	–	0.05003	2.568	1.6025
1 n.u. = $1\mu^{-2}$	=	19.99	–	51.34	32.03
1 GeV^{-2}	=	0.3894	0.01948	–	0.6240
1 $\text{mb}^{1/2}\,\text{GeV}^{-1}$	=	0.6240	0.03122	1.6025	–

Units for amplitudes

Invariant amplitudes A, C and spin non-flip and flip amplitudes G, H:

$$A[\text{GeV}^{-1}] = \frac{A[\mu^{-1}]}{0.1396} = \frac{A[\text{fm}]}{0.1973} = \frac{A[\text{mb}\cdot\text{GeV}]}{0.3894} = \frac{A[\text{mb}^{1/2}]}{0.6240}$$

Invariant amplitude B and helicity amplitudes $F_{+\pm}, G_{+\pm}$:

$$B[\text{GeV}^{-2}] = \frac{B[\text{mb}]}{0.3894} = \frac{B[\text{mb}^{1/2}\text{GeV}^{-1}]}{0.6240} = 51.33\,B[\mu^{-2}].$$

Vorwort

Band I/9, der Daten über die Elastische und Ladungsaustausch-Streuung von Elementarteilchen enthält, besteht aus zwei Teilbänden a, b, von denen I/9a bereits 1980 erschienen ist.

In Teilband I/9b sind die Daten über die π-N Streuung zusammengestellt. Da dieser Prozess über viele Jahrzehnte das besondere Interesse sowohl der Experimentalphysiker wie der Theoretiker fand, wurde es nötig, den Teilband noch einmal zu unterteilen. Teil I/9b1 (erschienen Ende 1981) enthält die experimentellen Daten. Die π-N Streuung ist einer der wenigen Prozesse, bei denen es gelingt, aus den Experimenten Streuamplituden abzuleiten. Die Zusammenstellung dieser Streuamplituden ist der wesentliche Inhalt dieses (letzten) Teiles I/9b2.

Da die Berechnung der Streuamplituden aus den experimentellen Daten nicht ganz einfach ist und gewisse Annahmen erfordert, hat sich um diesen Problemkreis eine reiche Literatur entwickelt. Im ersten Kapitel wird eine kritische Übersicht über die verschiedenen Methoden der Partialwellenanalyse und der Bestimmung der Streuamplituden gegeben.

Da die Streuamplituden Mittelwerte über die einzelnen Experimente darstellen, sind sie zuverlässiger als die ursprünglichen Daten. Es ist daher für manche Zwecke sinnvoll, die aus den Streuamplituden zurückberechneten meßbaren Größen zu verwenden. Diese Größen sind in einem weiteren Kapitel zusammengestellt. Weiterhin werden Anwendungen der Streuamplituden auf eine Reihe von speziellen Problemen diskutiert.

Sehr nützlich sollte auch die Formelzusammenstellung im Anhang sein, insbesondere bei der Lektüre von Originalarbeiten mit ihren sehr uneinheitlichen Bezeichnungsweisen.

Die kritische und umfassende Zusammenstellung der Ergebnisse und Methoden der π-N Streuung dürfte einmalig sein. Sie wurde nur möglich durch die große Kompetenz und Mühe des Autors, der diesen Problemen einen großen Teil seiner wissenschaftlichen Aktivität gewidmet hat. Alle bei der Fertigstellung des Bandes aufgetretenen technischen und administrativen Schwierigkeiten wurden in der üblichen souveränen Weise durch den Gesamtherausgeber, die Redaktion, besonders Herrn Dr. W. Polzin und Frau D. Dolle, und den Verlag überwunden. Ihnen allen gebührt besonderer Dank. Dieser Bandteil wurde, wie alle Bände des Landolt-Börnstein, ohne finanzielle Unterstützung von anderer Seite veröffentlicht.

Genf, Oktober 1982

Der Herausgeber

Preface

Volume I/9 containing data on Elastic and Charge Exchange Scattering of Elementary Particles, consists of two subvolumes a, b, the first of which, I/9a, is already available since 1980.

In subvolume I/9b the data of the π-N scattering have been compiled. Since this process has attracted the special interest of both experimentalists and theorists during many decades, it became necessary to subdivide this subvolume into two parts. Part I/9b1 (published late 1981) contains the experimental data. π-N scattering is one of the few processes for which it is possible to derive scattering amplitudes from the experiments. The compilation of these scattering amplitudes is the essential content of part I/9b2.

Since the derivation of the scattering amplitudes from the experimental data is not simple and requires certain assumptions, a comprehensive literature developed around this field of problems. Hence a critical review of the various methods of partial wave analysis and the determination of scattering amplitudes is presented in the first chapter.

Since the scattering amplitudes represent average values over individual experiments, they are more reliable than the original data. For certain purposes it seems useful therefore to utilize measurable quantities reconstructed from the scattering amplitudes. These quantities are compiled in another chapter. In addition, applications of the scattering amplitudes to a number of special problems are discussed.

The compilation of formulae in the Appendix should turn out to be very useful, in particular facilitating the reading of original papers with their rather non-uniform notation.

The critical and comprehensive review of the results and methods of π-N scattering should be regarded as unique. It became possible only by the remarkable competence and efforts of the author who has dedicated a large part of his scientific activity to these problems. All technical and administrative difficulties which arose during the production of this volume were mastered in the usual expert way by the editor in chief, the editorial office, especially Dr. W. Polzin and Frau D. Dolle, and the publisher. Special thanks are due to all of them. This part of the volume, like all other volumes of Landolt-Börnstein, has been published without financial support from any outside source.

Geneva, October 1982

The Editor

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Subvolume b1: Tables of data

2 Methods and results of phenomenological analyses

2.0 Introduction

Volumes I/7 and I/9b1 contain tables of the experimental data on elastic and charge-exchange pion-nucleon scattering. The present volume deals with the determination of scattering amplitudes from these data and applications within the framework of phenomenological theories.

The methods for partial wave and amplitude analysis are treated in Sect. 2.1 and results for various scattering amplitudes and for measurable quantities reconstructed from them are presented in Sects. 2.2 and 2.3, respectively. These tables give a condensed version of the experimental information.

Scattering amplitudes can be determined from data only if one uses in addition a theoretical input. Besides general theoretical principles (Lorentz invariance, *T*, *C*, and *P*-invariance, unitarity, fixed-*t* analyticity) one employs Mandelstam analyticity, which has the status of a working hypothesis, and isospin invariance, which is thought to be a good approximation for the strong interaction amplitudes.

Thus one could argue that the theoretical input leads to a model dependence of the result, which is due for instance to the necessary assumptions on the high energy behaviour and on the smoothing procedure in applications of the analyticity constraint. The magnitude of the resulting uncertainty can be estimated by repeating the analysis with reasonable modifications of these assumptions. It turns out to be much less serious than the model dependence in those cases, for which the analysis is based on a parametrization derived from a specific phenomenological model.

For a comparison with theoretical predictions, it is not sufficient to have long tables of four complex-valued amplitudes, which depend on two variables. One needs in addition a description of the amplitudes in certain kinematical regions in terms of a relatively small number of parameters, which have a direct physical interpretation and can be compared with the values calculated from models.

The most important parameters of the pion-nucleon system are those of the poles and zeros of the scattering amplitudes. The pole parameters are listed and discussed in Sects. 2.4.1 and 2.4.2. They are the "experimental" quantities, which are used in tests of various quark models of the nucleon. The properties of the zero trajectories (Sect. 2.4.3) show a remarkable similarity to the prediction from Veneziano-type dual models.

Section 2.4.4 deals with the saturation of isospin bounds. Kinematical regions in which these saturations occur are of interest in connection with the search for small violations of isospin invariance.

Analytic continuations of scattering amplitudes into unphysical regions have to be performed for several reasons, for instance for the determination of $\pi\pi N\bar{N}$ amplitudes, for the test of predictions derived from Current Algebra and PCAC and for the study of zero trajectories. A brief treatment of $\pi\pi$-scattering at low energies is included, because $\pi\pi$-phase shifts are needed as part of the input (Sects. 2.4.5 and 2.4.6). The result is given not only in the form of tables (Tables 2.2.3.2 and 2.4.6.1) but also by the coefficients of the subthreshold expansion (Sect. 2.4.7). The coefficients of the effective range expansion at threshold are in practice also determined by a continuation, because it is not possible to obtain accurate values of the strong interaction amplitudes from πN scattering experiments at very low energies (Sect. 2.4.7).

Three applications of the continued amplitudes are treated in Sect. 2.5:

i) Many authors have proposed models for the πN system at low energies, which incorporate the predictions derived from Current Algebra and PCAC. These models have to be compared with amplitudes in the threshold and subthreshold regions (Sect. 2.5.1). One of the reasons why these models are studied is the possibility to calculate off-shell extrapolations of πN scattering amplitudes, which are needed in nuclear physics.

Another problem of current interest is a test of the prediction for the πN sigma term from quantum chromodynamics.

ii) Important properties of the electromagnetic nucleon form factors can be determined only if one applies the dispersion approach and includes the $I=J=1$ $\pi\pi N\bar{N}$ partial waves of Sect. 2.4.6 as part of the input (Sect. 2.5.2). Since the pion form factor is also needed, we have added a summary on recent experimental results and investigations of its dispersion relation.

iii) Originally, simple one-boson-exchange models were used for the description of two-pion-exchange in nucleon-nucleon scattering. The results for the $\pi\pi N\bar{N}$ partial waves are the basic input for a quantitative treatment (Sect. 2.5.3).

Since the physical range $t>4m^2$ occurs in dispersion analyses of $\pi\pi N\bar{N}$-amplitudes, we have added in Sect. 2.5.4 a short summary of the $\bar{N}N\leftrightarrow\pi\pi$ experiments available in this region, mentioning the first attempts to determine the partial wave amplitudes.

Section 2.6 is devoted to the analysis of πN scattering data at high energies. It can be expected that, in the coming years, a considerable part of the experimental and theoretical activity in pion-nucleon physics will concentrate in this field. Therefore, I have summarized the most popular models. pp-scattering is included because of the close similarity of the diffraction phenomena.

The last section contains a list of references for books and reviews (Sect. 3.1), original papers and recent preprints (Sect. 3.2), and papers on pion-nucleon scattering experiments (Sect. 3.3, see also Table 1.2.1 in Volume I/9b1).

A collection of pion-nucleon scattering formulas has been added in an Appendix, because it is my experience that one can lose considerable time on more or less trivial but tedious calculations, if it is necessary to work with formulas taken from various books, reviews and original papers. The reason is that the authors employ different conventions and notations, which are not always explained in full detail, or at a place where the definition is not easily found. Furthermore, the number of misprints is far from negligible.

To my knowledge, there exists no single book which covers all topics treated in the Appendix. Of course, printing and other errors cannot be avoided, but the present volume has a useful redundancy: it contains many numerical tables and figures, which have been calculated from the formulas of the Appendix. Furthermore, a shorter version of the collection of formulas has been used in our group for many years.

A reader who is interested in the derivation of a formula can find the reference in Sect. A.12.

The present volume has been written for physicists who are familiar with the main experimental facts and at least with the elementary parts of the theoretical formalism, which is described in several excellent textbooks and monographs. It will be useful for experimentalists who are studying possible interpretations of their results or planning new experiments, and also for theorists who want to test phenomenological models or rigorous predictions.

Part of the contents will be of interest to physicists who are working in other fields, where πN or $\pi\pi N\bar{N}$-amplitudes are needed, for instance in nuclear physics or in investigations of pionic atoms or of nucleon form factors.

The chapters on pion-nucleon scattering in the existing textbooks and monographs were written about 10 years ago or even earlier. Therefore, this book will be valuable for graduate students who want to become acquainted with the more recent developments.

Volume I/9b1 includes the results of all experimental investigations on pion-nucleon scattering which have been performed since the publication of Volume I/7. Because of the very large number of phenomenological and theoretical papers in this field, only a small fraction could be taken into account in Volume I/9b2. My choice was to give a fairly complete treatment of the phenomenological analysis of the experimental data, which leads to results for the scattering amplitudes and for various parameters of the pion-nucleon system. Special attention has been paid to applications of dispersion relations as constraints and for analytic continuations.

Since the work done in the fifties and sixties has been described in several excellent books and in many reviews and summer school lectures, I have concentrated on the progress made during the last decade.

It would have been unsatisfactory to present the amplitudes and the parameters without explaining why such a great effort has been made for their determination. Therefore, I have also discussed the present status of various models which have had some success in explaining properties of the pion-nucleon system, and a few applications of πN and $\pi\pi N\bar{N}$-amplitudes in other fields. The choice of topics reflects my own interests and limitations.

One of my aims was to present a "guide to the literature" in the following sense. In Sects. 2 and A.12, I have not only mentioned the publications actually used in writing this book but also many others, which would have to be discussed in a more detailed review. In particular, I have added references of the most recent papers, even if I have not been able to give a comment, because my manuscript had already been submitted. Furthermore, Sect. 3.1 contains a fairly complete list of books and reviews, which are related to the topics treated in this volume.

A well-known difficulty of books of this type is that parts will be outdated after a period which is appreciably smaller than the time interval between two editions. One can extend the space of time during which the book fulfills its purpose and is actually used by physicists working in this field by producing an informal "Supplement", which contains updated versions of the main tables and lists, corrections of misprints and short remarks on errors or omissions, which have been brought to the attention of the author. Updated versions of the tables will be prepared in any case for the continuation of the work of our group and we are willing to distribute copies on request.

In the fifties and sixties, pion-nucleon scattering was one of the main topics at international conferences on high energy physics. Later, many physicists left this field and started to work on other problems which seemed to be more promising.

Nowadays, interest is increasing again because of first attempts to calculate parameters of the pion-nucleon system using methods based on quantum chromodynamics, which is believed to have a good chance to be the correct theory of strong interactions. At present, the best evidence in favour of this theory comes from reactions other than hadron-hadron scattering, e.g. electron-positron interactions. However, as soon as the serious difficulties in deriving quantitative predictions for the interactions between hadrons have been overcome, pion-nucleon scattering amplitudes will play an important role for a critical test. They are known with a higher accuracy than other strong scattering amplitudes and furthermore, they contain the experimental information on the excited states of the nucleon. A calculation of these states is one of the fundamental problems in a theory of strong interactions.

Acknowledgements

Our group has been working on pion-nucleon scattering and related topics for two decades. During this period I have had several generations of coworkers who investigated very actively various problems in this field. Among them are: J. Baacke, E. Borie, K. Dietz, G. Ebel, J. Engels, G. von Gehlen, W. Grein, M. Hutt, H.P. Jakob, F. Kaiser, R. Koch, P. Kroll, E. Pietarinen, I. Sabba-Stefanescu, W. Schmidt, F. Steiner, and R. Strauss. I wish to express my gratitude for many discussions, which helped to clarify the ideas presented in this book.

The treatment of partial wave analysis and of analytic continuations was strongly influenced by the work of E. Pietarinen. When he left Karlsruhe and changed his field, the analysis was continued by R. Koch and the study of related mathematical problems by I. Sabba-Stefanescu.

I am grateful to J. Hamilton for a stimulating exchange of ideas on dispersion methods over a long period and to R.E. Cutkosky and R. Kelly for valuable discussions on partial wave analysis as well as for sending us tables of their amplitudes and amalgamated data on magnetic tapes.

It is a great pleasure to thank all those physicists who sent us their unpublished results and contributed to my understanding of special questions. I can only mention a few: D. Atkinson, D. Chew, T. Ekelöf, J. Fischer, J. Gasser, A. Hendry, P. Koehler, P. Kroll, C.B. Lang, G.C. Oades, K.P. Pretzl, M. Scadron, and B. and F. Schrempp.

The writing of this book would have been much more difficult without the untiring help of my coworkers M. Hutt, F. Kaiser, R. Koch, and I. Sabba-Stefanescu, who have read part of the manuscript, contributed figures and tables and noticed a number of misprints and errors in the collection of formulas. I was very glad to have had the possibility to discuss various questions with my colleagues E. Borie, H. Genz, H. Pilkuhn, and H.M. Staudenmaier. Furthermore, I also wish to thank S. Kunze for her assistance with the preparation of the list of references on a microcomputer as well as J.G. Otto and J. Stahov for supplying some figures and tables.

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The search for references was simplified by using the High Energy Physics Index compiled at DESY.

I am deeply indebted to the editor, H. Schopper, for supporting my proposal to include a treatment of the phenomenological analysis and for his advice and encouragement during the long time it took to complete this project.

This book is dedicated to my wife Hildegard and I wish to thank her for her patience.

G. H.