ENGLISH-CHINESE LABORATORY EXPERIMENTS IN UNIVERSITY PHYSICS

英汉大学物理实验

史庆藩　王荣瑶　主编

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LABORATORY EXPERIMENTS IN UNIVERSITY PHYSICS

英汉大学物理实验

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内 容 简 介

本书是在北京理工大学物理实验中心多年来大学物理实验课建设和教学改革的成果基础上编写而成。全书总结了双语教学的实践经验，同时参照了教育部对于高等工业学校物理实验课程教学的基本要求。全书分为3大部分：第一部分阐述了误差理论以及利用EXCEL软件处理和分析数据的方法。第二部分为基础性实验，训练学生的基本操作技能。第三部为综合性、设计性实验，培养学生的创新思维能力。全书内容涉及力学、热学、电学、磁学、光学、原子与分子物理以及近代物理的部分内容。

本书可作为高等理工科院校各专业大学物理实验课双语教材或参考书，也可供专业英语爱好者参考之用。

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序

大学物理实验是理工科学生必修的一门独立的基础课程。通过学习这门课程，学生们不仅可以加深理解在物理学的理论课程中所学到的一些基本原理，更重要的是在这个学习过程中可以培养自己灵巧的动手与实践的能力、敏锐的观察现象与发现问题的思维能力、严谨的分析数据与发现科学规律的创新能力。因此，理工科的学生经过大学物理实验的训练必然会使自己的创造性思维能力和动手能力都得到极大的提升，对后续专业课程的学习以及对今后的工作都会有极大的帮助。

为适应当今激烈竞争时代的需要，为培养出具有更强的社会适应性和发展潜能的高素质人才，北京理工大学物理实验中心的教师们在多年实验教学经验的基础上，依据他们对教学规律的认识和国家对培养创新型人才的要求的理解，编写了这本具有鲜明时代特色的教材。

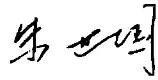
这本教材的内容以学生为本，把培养高素质学生作为教学指导思想，对实验项目进行了优化组合，使之形成一个由易到难、循序渐进的基础课程体系。按照数据处理与分析、基础性实验、综合设计性实验的次序使整个内容呈阶梯状的模块化结构。以 Excel 数据处理软件的训练掌握为先导，紧接着是测量误差的分析与处理为基础，这样的安排为后续的由简单到复杂的阶段式教学架构了良好开端。基础性实验阶段可以使学生掌握基本的实验方法和技能，初步具备严谨科学的实验习惯，为后续的实验课程以及专业课程的学习打下坚实基础。而综合设计性实验阶段则着重训练学生综合地运用多种知识和技能，提高分析问题和解决实际问题的能力。值得赞许的是，将 Excel 引入到处理实验数据的相关内容是这本教材的特色和亮点。因为 Excel、Origin 等是科学论文中数据处理的常用软件。学生们经过利用 Excel 来处理和分析实验数据的训练后将为以后从事研究活动和工程设计打下有益的基础。另外，这本教材在仪器使用和操作步骤的叙述上既有必要的说明，又给予了学生一定的自主发挥的空间，尽可能使学生通过独立的思考和操作后达到实验目的。这些做法有利于学生创造性思维能力的养成以及实验技能的提高。

这本教材以双语体系编写，符合教育部《关于加强高等学校本科教学工作提高教学质量的若干意见》所提出的使用英语等外语进行公共课和专业课教学的要求。北京理工大学物理实验中心的同志早在 2001 年就开始在部分班级进行了双语教学的实践探索。在教学过程中，使用了自编的英语教材，师生之间以英语为主交流，专业术语加日常用语，训练了学生用双语获取物理知识和实验技能的能力，提高了学生的科技英语水平，取得了良好的教学效果。显然，国际化视野下的大学物理实验课双语教学对于培养有创新能力的、在国际上有竞争力的一流人才具有重要意义。

《英汉大学物理实验》双语教材是理工科大学物理实验教学改革的一种新尝试。我们期

待它在培养学生的动手技能、创新思维、科学素质等综合能力方面发挥重要的作用，并在使用过程中得到不断精练和完善，成为一本师生们爱用的新教材。

四川大学物理学院

 **教授**

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前　言

现代教育要求全面推行素质教育和创新能力培养。大学物理实验课是理工科学生重要的必修基础实验课程，是一门以本科学生为主体的独立设课的综合性实践课程。它不仅是传授知识和训练才能相结合的过程，同时也应当是一门培养学生创造性思维能力和全面提升学生科学素质的课程。当前，国际竞争日趋激烈，对当今的中国学校教育提出了新的挑战。为了培养有创新能力的、与国际接轨、在国际上有竞争力的一流人才，我们对大学物理实验进行了双语教学的改革。双语教学与传统意义上纯粹的物理实验和英语教学不同，它用外语作为沟通媒介，训练学生用双语思维能力获取物理实验知识，有利于提高学生的科技英语水平，同时也有助于培养学生的创新意识和创新能力。

本书按照教育部对高等工业学校物理实验课程教学的基本要求，采取实验数据处理的基本理论与技术、基本实验、综合性设计性实验的教学模式编写，内容涉及力学、热学、电学、磁学、光学、原子与分子物理以及近代物理的部分内容。

本书分为三大部分：第一部分阐述了误差理论和数据处理的基本知识以及利用 Excel 软件处理和分析数据的方法。数据处理的训练水平，直接关系到科学与工程论文的质量与发表的水平，是培养高素质学生不可缺少的环节。具体训练内容包括表格、计算、作图、标准偏差、标准误差、误差的传播、曲线拟合以及其他的统计技术。经过计算机数据处理训练后的学生所写的实验报告将能够达到科技论文发表所要求的数据处理格式。第二部分则通过 14 个基础性的实验，训练学生的各种基本操作技能，培养学生的动手能力。第三部分围绕如何培养综合素质高、创新能力强的开拓性人才，撰写了 12 个综合性、设计性实验。通过这些实验可使学生由被动学习的方式转变为主动学习方式，强化了学生独立思考、独立动手和创新思维的训练。

本书的成书是在物理实验中心大学物理实验双语教学的实践基础上进行的。董建平副教授于 2001 年开始在部分班级进行了大学物理实验双语教学的实践。在教学过程中使用了自编教材“Experiments in Physics for Students”。在教学方法上也进行了有益的探索，如学生用双语分组讨论，师生互动等。此次出版由万葆红撰写了第 1 章及实验 3、8、14，王荣瑶撰写了第 2 章，史庆藩撰写了实验 7、15、26，陈新撰写了实验 2、6、13、17、18、23，李龙海撰写了实验 16，李维晖撰写了实验 9、10、25，张宏撰写了实验 19，张瑞撰写了实验 1，李林撰写了实验 5、21，范朝霞撰写了实验 11、20、22，鲁长宏撰写了实验 4、12、24。英国兰开夏大学（University of Central Lancashire）的 Alan Christy 博士检查了全书的英文表述，史庆藩和王荣瑶策划并统筹了全书的内容及英文翻译。另外，需要特别说明的是：本书的某些章节或语句并没有采取完全英汉对照的格式，这是考虑到目前本科生们已普遍具备良好的

英文阅读能力。

本书是北京市教育委员会共建项目建设计划支持项目之一。项目名称：改革大学物理实验教学，培养学生综合素质和创新能力。本书自始至终得到了北京理工大学教务处、实验室设备处的大力支持，作者在此表示衷心的感谢。在本书的成书过程中，还得到了研究生杨雷、张宇、苟铭江、于广泽、R. Abdul，D. Ntirikwendera 及其他本科生的大力支持和帮助，在此一并致谢。

我们期待本教材的出版不仅有助于培养学生的动手能力、分析解决问题的能力、数据分析处理的能力、创新能力等综合素质，也能大幅度提高实验教师队伍自身的业务能力。由于作者水平所限，书中不足之处在所难免，恳请读者提出宝贵的批评意见和建议。

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Part 1
Processing and Analysis of Data

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Chapter 1 Experimental errors and data analysis

1.1 Basic Concept of Error

1. Absolute error

It is defined as the difference between the measured value and the true value of the measured quantity, given by:

$$\Delta x = x - x_0$$

Here, x is the measured value, and x_0 is the true value.

2. Relative error (or Fractional Error)

It is defined as the ratio of the absolute error to the true value

$$N = \frac{\Delta x}{|x_0|}$$

The true value of a measured quantity is actually unknown. The theoretical value or the accepted value (e. g. from the measurements by other people) is generally used as the true value. The typical examples are the velocity of light $2.998 \times 10^8 \mathrm{m/s}$, the Avogadro's constant $6.023 \times 10^{23}/\mathrm{mol}$. If there is no theoretical or accepted value available, the mean value from a series of repeated measurements can be taken as the best estimate of the true value.

3. Classification of experimental errors

In general, experimental errors fall into two categories: systematic and random errors. The characteristics of these two types of experimental errors are described as follows.

(1) Systematic error

This type of error occurred in a measurement has multiple sources, including the measuring instruments, the experimental methods, and the mistakes by experimentalist. More important, systematic errors often dominate other types of errors. Offset error is one of the most important systematic errors associated with the instruments. It can be identified by using a stardard, i. e. the calibration by checking the values indicated by the instruments against 'known standards'. Once the offset error has been quantified, the measured values can be corrected accordingly.

(2) Random error

In repeated measurements, random errors produce a scatter of measured values around the true value. Environmental factors, for instance, the electrical interference in a sensitive voltage measurement, can introduce random scatter in the observed data. Although it is not possible to reduce the ramdom error completely, the variability in values can often be dealt with some statistical techniques.

Here we consider the spread of data in repeated measurements of a quantity obeys the normal distribution only. As is shown in Figure 1 - 1, for a continuous variable, x, the probability density function of normal distribution is given by

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-m)^2/2\sigma^2}$$

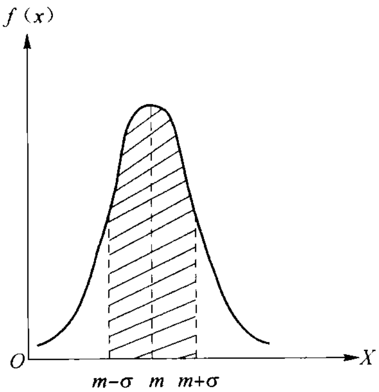

Figure 1 - 1 Normal Distribution Curve

m is the mean value of a series of measured values x_i, defined as

$$m = \lim_{n\to\infty} \frac{\sum_{i=1}^{n} x_i}{n}$$

where n is the number of repeated measurements.

Another important parameter to measure the values spread from the mean is the standard deviation σ, which is defined as

$$\sigma = \lim_{n\to\infty} \sqrt{\frac{\sum_{i=1}^{n} (x_i - m)^2}{n}}$$

The properties of the normal probability distribution are

(1) The bell-shaped curve shows a single maximum at the mean value. A large proportion of the measured values lie close to the mean.

(2) The spread/distribution of measured values is symmetrical about the interval containing the mean.

(3) Less probability for the values that lie far away from the mean.

(4) The true value could be obtained by performing infinite number of repeated measurements. But this way to eliminate random errors in an experiment is little practical.

The confidence interval and confidence probability of the normal distribution should also be considered. The area of the space between the normal distribution and the x-axis can be used to express the probability of the measured value in a certain range; this range is called the confidence interval. According to the normalized condition of the probability density function $\int_{-\infty}^{+\infty} f(x)\,dx = 1$, during the interval $(-\infty, +\infty)$, the area between the normal distribution curve and the x-axis equals 1, which means that the probability of the measured value appearing in the interval $(-\infty, +\infty)$ is 100%. The standard deviation σ is the characteristic width of the normal distribution. The probability of finding a result x_i falling in the interval $(m-\sigma, m+\sigma)$ is 68.27%, in the interval $(m-2\sigma, m+2\sigma)$ is 95.45%, and in the interval $(m-3\sigma, m+3\sigma)$ is 99.73%, etc.

For a sufficient large number of repeated measurements, the mean value is taken as the best estimated true value, while the standard deviation S is taken as a measure of spread.

$$S_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (1-1)$$

The above is called the Bessel formula. The standard error of the mean is given by

$$S_{\bar{x}} = \frac{S_x}{\sqrt{n}}$$

4. precision and accuracy

(1) Precision

Precision describes the effect of random errors on repeated measurements. When we say a measurement is precise, it means that the spread of measured data around the mean value (S_x) is small. But it does not imply the mean value is close to the true value.

(2) Accuracy

Accuracy describes how a measured quantity is close to the true value. But it does not necessarily mean that the spread of data is small. It reflects, to some extent, the effects of the systematic errors in a measurement.

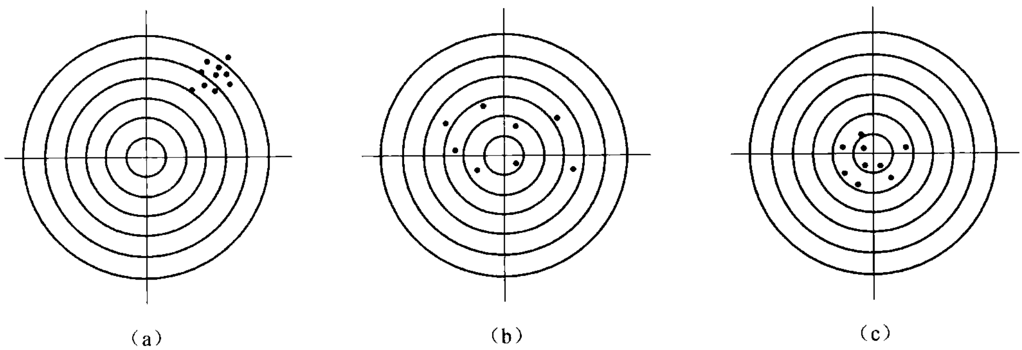

Figure 1 - 2 Scheme to Show the Difference Between Precision and Accuracy

In Figure 1 - 2, the difference between accuracy and precision is illustrated.

Fig. 1 - 2a: Precision, the hit points are concentrated, but far away from the centre of the bull's-eye (true value).

Fig. 1 - 2b: Accuracy, the average position of the hit points is close to the bull's-eye, but these points disperse from each others in a relatively large region.

Fig. 1 - 2c: Both precise and accurate, the hit points are concentrated and lie close to the bull's-eye. It means that both the random and the systematic errors are small.

1.2 Uncertainty and Methods of Evaluation

Instead of experiemental error, experimental uncertainty is nowadays a more commonly used term to quantify in a clear way the amount of variation of a measured value in experimental work. We must acknowledge that the realibility of our experiment is judged based on the quantification of the viaration, which may strongly affect the conclusions drawn from the experimental results.

1. Two kinds of evaluation methods for experimental uncertainty

The uncertainty can be divided into standard uncertainty and extended uncertainty. In this book, it just refers to the former.

(1) A-type standard uncertainty

The A-type standard uncertainty is for repeated measurements, and is obtained by using a statistical evaluation method.

With repeated measurements under equal precision condition, the measured value x is observed independently n times. The observed data are denoted as x_i $(i = 1, 2, 3, \ldots, n)$. The mean value is given by

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (1-2)$$

The A-type uncertainty of any measured value is given by the Bessel formula:

$$u_A = S_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \qquad (1-3)$$

The A-type uncertainty of the mean value is:

$$u_A(\bar{x}) = S_{\bar{x}} = \frac{S_x}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n(n-1)}} \qquad (1-4)$$

The larger the number of measurements, n, the more reliable the evaluation of the A-type uncertainty is. Commonly, the number of measurements n must be larger than 5.

(2) B-type standard uncertainty

The B-type standard uncertainty is generally related to the resolution limit of an instrument and/or the calibration of an instrument provided by manufacturer or 'bureau of standards'. It can be obtained by evaluating previous measurements, manufacturer's data sheets and other standard sources. Here only the resolution limit of apparatus Δ_{ins} is consided, the B-type uncertainty can be written as:

$$u_B = \frac{\Delta_{ins}}{k}$$

where k is called the coverage factor and is a constant for an assumed probability distribution of the measured values and the assumed confidence probability.

For a uniform distribution and the confidence probability of 100%, $k = \sqrt{3}$. Thus the B-type standard uncertainty is:

$$u_B = \frac{\Delta_{ins}}{k} = \frac{\Delta_{ins}}{\sqrt{3}} \qquad (1-5)$$

where Δ_{ins} is the resolution limit of the apparatus which can be found in the manufacturers' technical manuals or data sheets. If the above information is unknown, Δ_{ins} can be estimated as half of the smallest division on the scale of the apparatus.

Example Calculate the B-type standard uncertainty of an analogue ammeter:

$$\Delta_{ins} = \frac{A}{100} \times R$$

where A is the grade of the analogue ammeter, R is the full scale range used in the measurement. Both are the apparatus specifications provided by manufacturers. Thus we have:

$$u = \frac{1}{\sqrt{3}} \times \frac{A}{100} \times R$$

(3) Combination of A-type and B-type standard uncertainties

The combined standard uncertainty includes both A-type and B-type standard uncertainties.

For a measurement having several independent uncertainty quantity u_i (u_i can be A-type or B-type), the combined standard uncertainty is:

$$u_C = \sqrt{\sum_i (u_{A_i}^2 + u_{B_i}^2)} \qquad (1-6)$$

1.3 Expression of the Results of a Measurement

When giving the result of a measurement, the best estimate, the uncertainty and units should be given. There are different formats to express the measurement result; but the following format is recommended in this book.

$$X = \bar{x}(u_C) \qquad (\text{Unit})$$

Here, X is the quantity measured, $\bar{x}$ is the best estimate of X, u_C is the value of the combined standard uncertainty.

Example Given a certain length with the best estimate value $L = 31.42$ mm, and the combined standard uncertainty $u_C = 0.05$ mm, the final result should be quoted as:

$$L = 31.42(0.05)\text{mm}$$

1. Expression of the direct measurement result

(1) Expression of a single measurement result

The result should be given as:

$$X = x(u_B) \qquad (\text{Unit})$$

Here, x is the single measurement value; u_B is the B-type uncertainty.

(2) Expression of the result of repeated measurements

The result should be given as:

$$X = \bar{x}(u_C) \qquad (\text{Unit})$$

Here, $\bar{x}$ is the mean value of the repeated measurements, and u_C is the combined standard uncertainty.

Example Measure the diameter D of a steel ball for 7 times with a micrometer caliper. The measured values d_i are (6.995, 6.998, 6.997, 6.994, 5.995, 6.993, 6.994) mm. The zero-offset is -0.003 mm, and the resolution limit of the micrometer caliper is $\Delta_{ins} = 0.004$mm. Give the final result of measurement in the correct format.

Solution:

(1) The fifth datum 5.995 mm is obviously spurious; it must be rejected.

(2) Find the mean value of the rest of 6 data points:

$$\overline{d'} = \frac{1}{6}\sum_{i=1}^{6} d_i = 6.99517\text{mm}$$

(3) Correct the mean value by eliminating the zero-offset error:

$$\bar{d} = \overline{d'} - (-0.003) = 6.99817\text{mm}$$

(4) Use the Bessel formula to calculate the standard deviation:

$$S_{d_i} = \sqrt{\frac{\sum_{i=1}^{6}(d_i - \bar{d})^2}{n-1}} = 0.0019\text{mm}$$

(5) Calculate the standard error of the mean:

$$S_{\bar{d}} = \frac{S_{d_i}}{\sqrt{n}} = 0.00078\text{mm}$$

(6) The A-type standard uncertainty:

$$u_A = S_{\bar{d}} = 0.00078\text{mm}$$

(7) Calculate the B-type standard uncertainty:

$$u_B = \frac{\Delta_{ins}}{K} = \frac{0.004}{\sqrt{3}} = 0.0023\text{mm}$$

(8) Calculate the combined standard uncertainty:

$$u_C = \sqrt{u_A^2 + u_B^2} = 0.00243\text{mm}$$

(9) Quote the final result of the measurement:

$$D = 6.9982(0.0024)\text{mm}$$

2. Expression of the indirect measurement result

Assume a quantity Φ is a function of the independent direct measured quantities $(x_1, x_2, x_3, \cdots, x_N)$:

$$\Phi = F(x_1, x_2, x_3, \cdots, x_N)$$

Here, x_i is the i^{th} direct measured quantity. The formula for propagating the standard uncertainty is given by:

$$u_C(\Phi) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial\Phi}{\partial x_i}\right)^2 u_C^2(x_i)} \qquad (1-7)$$

Here, $u_C(x_i)$ is the standard uncertainty of x_i. So that, the final result of the indirect measurement is:

$$\Phi = \phi[u_C(\Phi)] \qquad \text{(Unit)}$$

EXAMPLE There are three resistors in series, $R_1 = 40.5\ (0.3)\ \Omega$, $R_2 = 120.0\ (0.3)\ \Omega$, $R_3 = 160.2\ (0.3)\ \Omega$. Calculate the total resistance R in series, and the uncertainty in R, u_C.

Solution:

(1) Calculate the total resistance R:

$$R = R_1 + R_2 + R_3 = 320.7\Omega$$

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