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Beta Beams: Neutrino Beams

贝塔束
——中微子束

（影印版）

〔瑞士〕林德罗斯（M. Lindroos）
〔意〕梅泽托（M. Mezzetto）
著

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序　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，“中外物理学精品书系”力图完整呈现近现代世界和中国物理

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科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

“中外物理学精品书系”另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，“中外物理学精品书系”还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套“中外物理学精品书系”的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

“中外物理学精品书系”编委会 主任

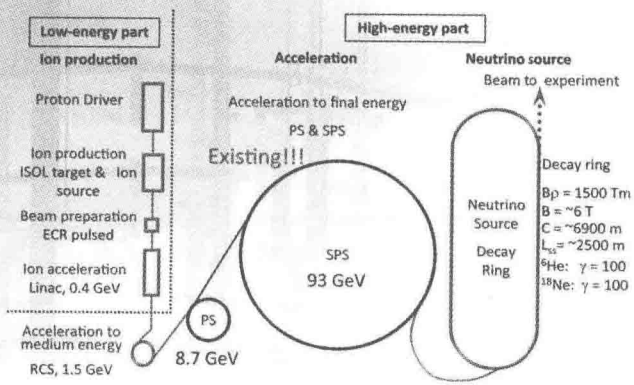
中国科学院院士，北京大学教授

王恩哥

2010 年 5 月于燕园

BETA BEAMS

Neutrino Beams



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With a Foreword by Piero Zucchelli and
a Contribution on Low Energy Beta Beams by Cristina Volpe

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To our families.
Without the support from our wives, Rebecca and Maria-Cristina,
this book would not have been possible and more importantly,
without them life would not be worth living.

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Foreword

Innovation can achieve its target by either an incremental or radical change in knowledge. Neutrino physics is an outstanding field in this respect since, in less than 100 years, three elusive fundamental particles have been postulated, searched for, discovered, and characterized by giant steps requiring radical innovations. In almost all cases, the innovation to be undertaken was inconceivable by the same scientific community just a few years before. Well-known are the words of W. Pauli, the neutrino inventor: "I have done a terrible thing. I have postulated a particle that cannot be detected." And less than ten years later, F. Reines and C. Cowan were able to detect it, apparently driven by the fact that everybody said it could not be done. Not surprisingly, as F. Reines admitted "Clyne (Cowan) knew as little about the neutrino as I did but he was a good experimentalist with a sense of derring-do. So we shook hands and got off to working on neutrinos."

The beta beam is no more than a recent invention in the neutrino physics history: invention is the first occurrence of an idea for a new product or process, while innovation is the first attempt to carry it out into practice (J.E. Faberger, 2004). However, it will become a true innovation if it benefits from the potential synergy among different scientific disciplines. If you are not an insider in neutrino physics, this is your book: you will learn about neutrino physics in the broadest sense, from theory to acceleration and detection techniques, and you will have a very different view of the challenges and applications that are critical to the expansion of the beta beams potential.

All elements are apparently present to motivate your active contribution to beta beams: just a few years ago, many scientists insisted that they are conceptually impossible (still today, all artificial neutrino beams are produced by meson decay, as pioneered by Lederman, Schwartz and

Steinberger in the 60s). Therefore, don't forget your sense of derring-do, still necessary to pioneers of any time: if there are roses, they will blossom and the next book on beta beams will include your contribution.

Piero Zucchelli

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Chapter 1

Introduction

1.1 Neutrino Oscillations

1.1.1 *Experiments*

The observation of neutrino oscillations has now established beyond doubt that neutrinos have mass and mix. This existence of neutrino masses is in fact the first solid experimental fact requiring physics beyond the Standard Model.

Since the early 1970s the chlorine solar neutrino experiment [1] provided evidence that electron neutrinos detected on earth were fewer than expected. In the 1980s this fact was confirmed by the water Čerenkov KamiokaNDE experiment [2] with a different detector threshold and the capability to demonstrate that the signals collected were indeed coming from the sun. A further experimental confirmation came in the early 1990s following two gallium experiments [3, 4] with very low detection thresholds. At the beginning of the 2000s, however, these experimental results were not considered evidence for neutrino oscillation, basically for two reasons: they were based on a comparison to theoretical predictions of the solar neutrino fluxes and multiple solutions could be found for the oscillation parameters, differing by several orders of magnitude to each other both in amplitude and in the neutrino mass difference squared.

This "solar neutrino puzzle" was closed in 2002 with the results from the SNO [5] and KamLAND [6] experiments. SNO, a heavy water Čerenkov solar neutrino detector, could simultaneously detect three solar neutrino processes: charged-current, elastic-scattering and neutral-currents, depending on different ratios of the ν_e and $\nu_\mu + \nu_\tau$ fluxes. In this way it was able to assess in a model-independent way that the total neutrino flux on earth ($\nu_e + \nu_\mu + \nu_\tau$) was as expected while the ν_e flux (the only neutrino flavor

generated on the sun) was indeed depleted, in a way compatible with the previous solar neutrino experiments. The KamLAND experiment provided at the same time a measurement of the disappearance of electron antineutrinos from nuclear fission reactors in Japan and Korea. This established, in combination with the solar neutrino results, large mixing-angle (LMA) MSW oscillations as the solution for the solar neutrino oscillations together with a precise determination of the relevant neutrino mixing angle and of the corresponding mass difference squared (see Table 1.1).

The first evidence of neutrino oscillation came from atmospheric neutrinos. Since the late 80s there have been indications from atmospheric neutrino experiments that muon neutrinos disappear when going through the earth. This was finally unambiguously demonstrated by the Super-Kamiokande experiment in 1998 [7], a result well supported by the Soudan2 [8] and MACRO [9] experiments. This disappearance takes place at a much shorter wavelength than for solar neutrinos (L/E$\sim$ 500 km/GeV) [10]; it is not seen for electron neutrinos, a fact that has been best established by the CHOOZ reactor experiment [11]. This disappearance has been confirmed by two long-baseline experiments: the K2K experiment in Japan [12] and MINOS in USA [13] (see Section 1.3.2).

A further, much more controversial, indication of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations with a Δm^2 of 0.3 - 20 eV^2 came from the beam dump LSND experiment detecting a $\sim 4\sigma$ excess of $\overline{\nu}_e$ interactions in a neutrino beam produced by π^+ decays at rest where the $\overline{\nu}_e$ component was highly suppressed ($\sim 7.8{\cdot}10^{-4}$) [14]. The KARMEN experiment [15], using a very similar technique but with a lower sensitivity (a factor 10 less for the lower Δm^2), and the NOMAD experiment at WANF of CERN SPS [16], for $\Delta m^2 > 10$ eV^2, did not confirm the result, excluding a large part of the allowed region of the oscillation parameters. The results of the MiniBooNE experiment [17] again did not confirm the LSND result, even though some non-standard explanations, for instance sterile neutrinos [18] or ν_e disappearance [19], have not been fully excluded.

1.1.2 *Phenomenology*

The above experimental observations are consistently described by three families ν_1, ν_2, ν_3 with mass values m_1, m_2 and m_3 that are connected to the flavor eigenstates ν_e, $\nu_\mu$and ν_τ by a mixing matrix U, usually parameterized

as

$$U(\theta_{12},\theta_{23},\theta_{13},\delta_{\rm CP}) = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{\rm CP}} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta_{\rm CP}} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta_{\rm CP}} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta_{\rm CP}} & c_{13}c_{13} \end{pmatrix} \quad (1.1)$$

where the short-form notation $s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$ is used. As a result, the neutrino oscillation probability depends on three mixing angles, $\theta_{12},\theta_{23},\theta_{13}$, two mass differences, $\Delta m^2_{12} = m^2_2 - m^2_1$, $\Delta m^2_{23} = m^2_3 - m^2_2$, and a CP phase $\delta_{\rm CP}$. Additional phases are present in case neutrinos are Majorana particles, but they do not influence neutrino flavor oscillations at all. Furthermore, the neutrino mass hierarchy, the order by which mass eigenstates are coupled to flavor eigenstates, can be fixed by measuring the sign of Δm^2_{23}. In vacuum the oscillation probability between two neutrino flavors α, β is:

$$P(\nu_\alpha \to \nu_\beta) = -4\sum_{k>j} Re[W^{jk}_{\alpha\beta}]\sin^2\frac{\Delta m^2_{jk}L}{4E_\nu} \pm 2\sum_{k>j} Im[W^{jk}_{\alpha\beta}]\sin^2\frac{\Delta m^2_{jk}L}{2E_\nu}, \quad (1.2)$$

where $\alpha = e,\mu,\tau$, $j = 1,2,3$, $W^{jk}_{\alpha\beta} = U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}$. In the case of only two neutrino flavor oscillations it can be written as:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \cdot \sin^2\frac{1.27\,\Delta m^2(eV^2)\cdot L(km)}{E_\nu(GeV)}. \quad (1.3)$$

When neutrinos pass through matter, the oscillation probability is perturbed [20] (see Eq. 1.5 in the following section). Two independent mass splittings characterize the system, since oscillations only depend on the difference of squared masses. Although no formally agreed definition exists, the usage is that the mass eigenstates are classified by decreasing electron-neutrino content $|<\nu_e|\nu_1>|^2$, $|<\nu_\mu|\nu_2>|^2$, $|<\nu_\tau|\nu_3>|^2$. With this definition, the mass of ν_1 is not necessarily smaller than that of ν_2.

Since two-family neutrino oscillations in vacuum (Eq. 1.3) depend on the mass difference as $\sin^2(1.27\Delta m^2 L/E)$, one cannot determine the sign of Δm^2 unless the oscillation interferes with another process; in the case of electron neutrinos, this is offered by coherent scattering on electrons in matter, a.k.a. matter effects.

The best-fit values and allowed range of values of the oscillation parameters at different CL obtained in [22] are shown in Table 1.1.

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