Preface

John Stewart Bell was without doubt one of the most influential scientists of the second half of the twentieth century. His scope of the research was very broad. Starting in accelerator physics in the 1950s at Harwell and Malvern, he soon turned to particle physics. In particular, after moving to CERN in 1960, he considered particle physics as a "job" he got paid for, but he certainly was enthusiastic about doing it. Parallel to his "job", he worked continuously on his "hobby", the foundations of quantum mechanics, the field he is most famous for, until his untimely death on 1 October 1990.

In all these areas, Bell made outstanding contributions. Let us mention just a few.

Already Bell's Ph.D. thesis included a fundamental paper "Time reversal in field theory". In that work, he proved independently from Gerhart Lüders and Wolfgang Pauli the celebrated CPT theorem, a basic symmetry of Nature that leaves a physical system unchanged under the joint action of charge conjugation C, parity inversion P and time reversal T.

Bell's most far-reaching contribution to particle physics, developed together with Roman Jackiw, was the discovery of the so-called Adler–Bell–Jackiw anomaly, which is responsible for the decay of the pion into two photons. It turned out to be the key to a deeper understanding of quantum field theory.

In accelerator physics, Bell wrote several papers, alone or in collaboration with William Walkinshaw at Harwell, mostly on how to focus a bunch of electrons or protons in a linear accelerator. At CERN, he collaborated with his wife Mary who was working in the Accelerator Research Group. Together they published several papers, for example on electron cooling in storage rings.

A particularly attractive work, in our opinion, was Bell's combination of the Unruh effect of quantum field theory with accelerator physics. The idea was to use the polarization of accelerated electrons as a thermometer that measures the temperature of the blackbody radiation experienced by the electrons. The results, small but measureable, were published together with Jon Leinaas.

Of course, John Bell is most famous for his contributions to the foundations of quantum mechanics. This topic attracted his interest already in the late 1940s while he was a student at Queen's University Belfast, got stimulated in the 1950s by Bohm's reinterpretation of quantum mechanics and culminated in 1964 when he was on sabbatical in the USA. There, he wrote his two seminal papers. The first one (but published secondly due to a delay in the publishing journal) was "*On the problem of hidden variables in quantum mechanics*", where he discovered that non-contextual hidden variable theories are in conflict with quantum mechanics. The second one, "*On the Einstein-Podolsky-Rosen paradox*", contained the celebrated Bell inequality, or what is called Bell's theorem, stating that any local realistic theory disagrees with quantum mechanics.

Thus, the year 2014 marked the 50th anniversary of Bell's theorem, one of the most significant developments in quantum theory. For us, it was immediately clear that we had to organize some kind of celebration. Discussing this idea with our colleagues, we received such a huge and enthusiastic response that our initial intention finally resulted in the conference "*Quantum [Un]Speakables II: Half a Century of Bell's Theorem*", which took place June 18th–22nd at the University of Vienna. About 400 scientists of the quantum foundations community attended. We were also very happy and felt privileged that Mary Bell took the effort to come as a *Guest of Honour* and to speak at the opening. The major part of the contributions to the conference is collected in this book.

As is well known by now, when John Bell started to work on the foundations of quantum mechanics, there was hardly any interest in such topics. Even worse, working on foundations was not considered to be a proper topic for a physicist. The first who had the courage to carry out an experiment on Bell inequalities was John Clauser in the 1970s; he had to struggle enormously to get the resources for doing the experiment. The situation began to change after the experiments of Aspect in the 1980s. Slowly, the community began to realize that there was something essential to Bell's theorem. The third generation of Bell experiments commenced in the 1990s and has extended into the twenty-first century. It has taken advantage of new technologies, such as spontaneous parametric downconversion, which is an effective way to create entangled photons. Also, more recently, it became possible to create entanglement in other systems, such as atoms or ions in traps or superconducting devices. In such experiments, the case against local realism, the viewpoint excluded by Bell's theorem, and for quantum mechanics became stronger and stronger, and more and more loopholes for the experiments were closed.

Also in the 1990s, the field of applications of entangled states and of Bell's theorem opened up. This was signified by experiments on quantum teleportation, quantum cryptography, long-distance quantum communication and the realization of some of the basic entanglement-based concepts in quantum computation.

Today, Bell's theorem and the underlying physics of entangled states have become cornerstones of the evolving technology of quantum information. Violation of Bell's inequality has become a litmus test for the realization of quantum entanglement in the laboratory. It has become part of the common understanding that a loophole-free Bell experiment is the final and definitive demonstration that quantum cryptography can be unconditionally secure. Also, entanglement swapping, the teleportation of an entangled state, is central for quantum repeaters, which are expected to be the backbone of a future worldwide quantum internet. Furthermore, Bell's theorem, as a fundamental contradiction between local realism and quantum mechanics, has been extended to higher dimensions and multiparticle systems.

The number of citations of Bell inequalities over the last decades is shown in Fig. 1.

Nowadays, physicists agree that John Bell would have definitely received the Nobel Prize for his outstanding contributions to the foundations of quantum mechanics if he had lived longer. This was, for instance, expressed explicitly by Daniel Greenberger in an interview given at the conference *Quantum [Un]Speakables II* in Vienna:

> Of course, people more and more appreciate John Bell's beautiful work. He was essentially starting the field, his work was totally seminal, and if he were alive he certainly would have won the Nobel Prize!

We also want to mention that Bell was not only an outstanding scientist with a sharp and clear view of Nature, but also a man of honest character and high morals. The late Abner Shimony expressed his appreciation for Bell, which we fully share, in the following way:

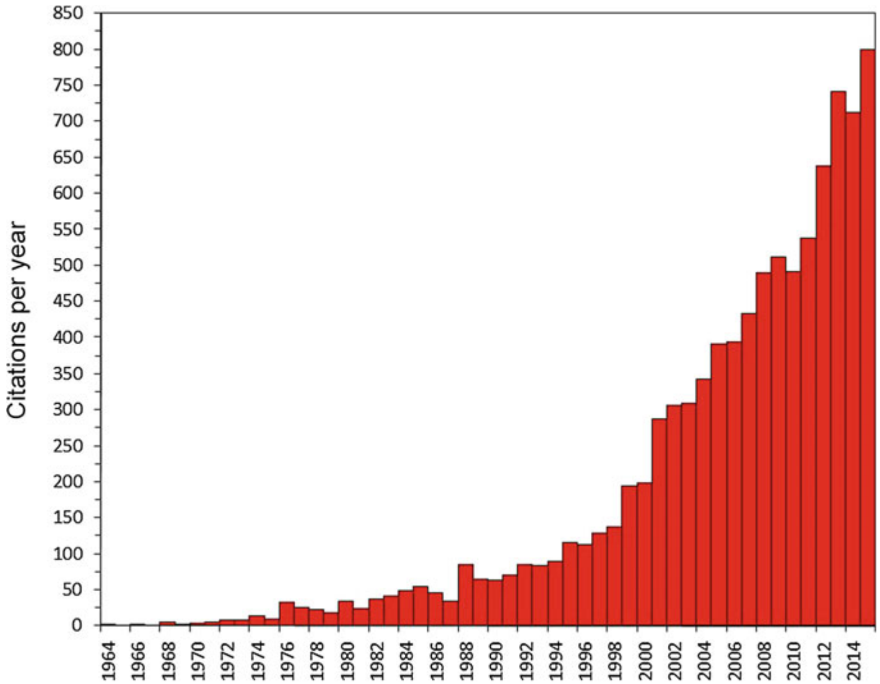

Fig. 1 Number of citations of Bell's paper according to Google Scholar (February 2016)

Fig. 2 The Belfast City Council named a street "*Bells Theorem Crescent*" in the Titanic Quarter of Belfast to honour its eminent scientist John Stewart Bell. *Photo* Joan Whitaker

> His [Bell's] passion for understanding, uncompromising honesty, simplicity of lifestyle and demeanour, dignity, courtesy, generosity to other scientists, and passion for social justice were combined into a character that was inspiring to all who had the privilege to be acquainted with him.

In 2014, the city of Belfast honoured John Bell as "*one of Northern Ireland's most eminent scientists*". The City Council named a street after his theorem "*Bells Theorem Crescent*" in the Titanic Quarter of Belfast, bending their rule of avoiding streets being named after individuals (see Fig. 2). Today, the Technical College, renamed Belfast Metropolitan College, that Bell attended is situated in that location. Furthermore, the Naughton Gallery at Queen's University Belfast organized the exhibition "*Action at a distance: The life and legacy of John Stewart Bell*" combined with lectures about Bell at the university.

Finally, we would like to mention that the late Walter Thirring, Austria's most prominent theoretical physicist, who was a member of the International Advisory Board of our conference series, in his last years developed a deep interest in Bell's theorem and published several papers about it together with Heide Narnhofer and one of the editors (R.A.B.). When working on Bell's ideas, Thirring said:

> I have to apologize to John Bell that I recognized the significance of Bell's theorem only so late.

Thirring's original German phrasing was:

> Ich muss John Bell Abbitte leisten, dass ich erst so spät die Bedeutung von Bell's Theorem erkannt habe.

This collection of articles is based to some extent on presentations made at the conference "Quantum [Un]Speakables II" in Vienna. However, where possible, contributors have made an effort to write at a level accessible to non-specialists and have also updated and expanded their texts as necessary. We are confident that the result will be of interest to graduate students and researchers in quantum theory, specifically in the conceptual foundations of quantum mechanics. But it will be also of value to philosophers and historians of science working in this field, as well as providing stimulating reading for many scientifically literate persons from other fields.

The current volume would not exist without our editor at Springer, Angela Lahee. Her unequivocal support right from the beginning and her continuing feedback and guidance were invaluable for the making of this book.

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