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Preface

Since its origins in the early 20th century mass spectrometry has developed into a diverse field with many important ramifications (see e.g. [1]). From the very beginning, it has made an enormous impact on the investigation of atomic nuclei, e.g. with respect to the existence of isotopes, followed soon by the "mass defect" as a quantitative manifestation of the strength of nuclear binding. Later on, the magic numbers revealed themselves in the mass landscape of known nuclei. Today, mass spectrometry is possible not only on stable or very long-lived nuclides, but also on nuclides very far away from the "valley of stability" where half-lives become as short as tens of milliseconds, and nuclides become increasingly more difficult to produce. The study of such nuclides helps to advance our understanding of nuclear structure, particularly in the case of extreme neutron-to-proton ratios, in finding exotic nuclear decay modes, in testing fundamental symmetries, and in improving the predictive power of mass models for masses of nuclei still further away from stability. Furthermore, mass values of very neutron and proton-rich nuclei are keys to a better understanding of how the elements in the universe have been formed [Schatz[1]].

A variety of mass spectrometers were built to determine masses of stable isotopes and the techniques were brought to perfection. Today some of them reach a precision that allows the study of atomic binding energies [Redshaw et al.[1], Fritioff et al.[1]]. In the case of short-lived isotopes it took many years before on-line mass measurements were performed, most notably by the pioneering work of Klapisch and collaborators at CERN [2,3] who used classical sector-field mass spectrometers. (In the meantime, the Orsay group has switched to a frequency-measurement based system too [Lunney et al.[1]].) Many of the early developments are touched upon in the article by Georges Audi in this special issue.[2] Prior to the seminal work of the Orsay group, energies measured in nuclear decays and reactions had been the only method of determining the masses of isotopes far from stability. And still, despite the tremendous progress of direct mass measurements on unstable isotopes, indirect mass measurements play an important role as discussed by Kavatsyuk et al.[1] and Hausladen et al.[1]

In the early eighties Jürgen Kluge at the University of Mainz considered mass measurements of trapped ions. Gernot Gräff, who worked at the same institute, had developed a time-of-flight technique for the determination of the electron–proton mass ratio from the respective cyclotron-resonance frequencies [4]. During this period the determination of the fundamental properties of the electron was of the highest interest. This included the measurement of the g-factor of the free electron, again with a Penning trap, for which Hans Dehmelt eventually won the Nobel Prize in physics. Jürgen decided to apply Gräff's method to the determination of masses of unstable nuclei. A setup was designed and built at Mainz, which comprised two Penning traps in a row. Following the idea of separation of functions, one trap served as the source of well-prepared ions for the actual mass measurement at the second trap. The operation of the setup thus included the ion transfer from one trap to the other. The first successful ion transfer was reported in 1986 [5]. A proposal to the scientific committee at CERN/Geneva for starting such an experimental program at ISOLDE, the on-line separator for short-lived nuclei at the synchrocyclotron of CERN, was accepted in 1985. Interestingly, at the same time Jerry Gabrielse proposed using a Penning trap mass spectrometer at CERN for the investigation of antiprotons, which turned out to become another very important and successful endeavour with ion traps [Gabrielse[1]].

At that time Jürgen acted as ISOLDE group leader. In the following years the tandem Penning trap setup was transferred from Mainz to ISOLDE and came to be known as ISOLTRAP [6]. It started the measurements of short-lived nuclides in the late eighties [7,8] and has been at the forefront of the field since then. For further details on recent developments in high-accuracy mass spectrometry of short-lived nuclei in general and for ISOLTRAP in particular see the reviews [9] and [10].

In its early phase ISOLTRAP used a stopping-reionization procedure in which the 60 keV ions, delivered from ISOLDE in a continuous beam, were implanted in a rhenium foil. This foil was then heated to release and surface-ionize the collected atoms. Thus, only surface-ionizable elements were accessible. This major limitation was overcome by the introduction of a third ion trap designed to accumulate the ions directly without any implantation, to cool them with buffer gas and to release them as low-energy ion bunches. The first system of this kind was a large Paul trap, developed in collaboration with Bob Moore at Montreal. Short-lived mercury isotopes were the first nuclides of non-surface-ionizable elements studied with ISOLTRAP [11].

[1] See contribution in this special issue.
[2] This article comprises a historical overview and introduction into the field of the masses of atomic nuclei and thus precedes the contributions of this issue.

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The Paul trap was later replaced by a linear RFQ trap system [12] which offers advantages in terms of capture efficiency and provides ion pulses with properties better suited for subsequent capture in a Penning trap. Similar systems are now in use at many radioactive-beam facilities. In any case, ISOLTRAP proved to be very successful and moved with ISOLDE, when the on-line separator was relocated to CERN's proton synchrotron booster in 1992 [13]. The in-flight stopping of ions in traps and ion guides, as well as their manipulation e.g. by sympathetic cooling or rf fields, remain topics of continuing interest [Bussmann et al.[1] and Moore et al.[1]].

In the early years of ISOLTRAP the ring electrode of the trap was segmented into just two halves. However, it was soon realized [14] that the ring was to be split into four segments for an efficient quadrupolar excitation and conversion of the ion's magnetron motion into the cyclotron motion. This conversion is the basis of the direct determination of the ion's "true" cyclotron frequency, $\omega_c = qB/m$ (for charge q, mass m and magnetic field B), i.e. the (angular) cyclotron frequency in the absence of an additional electric field. Today all Penning trap mass spectrometers for radioactive isotopes employ this technique. At the same time it was also realized, and experimentally confirmed, that the additional application of a buffer gas leads to cooling and mass-selective centering of the ion motion. The method was studied in detail [15] and the first Penning trap used in ISOLTRAP was reconstructed and optimized for efficient accumulation, cooling, and ion beam purification via isobar separation [16]. Now implemented in many mass spectrometer systems for the study of exotic nuclei, this technique is also used in the first stage of a post-accelerator system at ISOLDE/CERN [17]. The method was also rapidly adopted in analytical chemistry [18,19]. Here the questions of interest are, in general, very different from those of high-accuracy mass determinations of ions of single atoms as typically investigated in the case of short-lived nuclei, although questions of accuracy can also be of high importance in this field [Marshall et al.[1]].

Not only the methods were spreading out, but also the instruments: when the use of ion traps for the study of unstable isotopes and antiprotons was originally proposed, Ingmar Bergström, former director of the Manne Siegbahn Institute at Stockholm, was a member of the Scientific Policy Committee at CERN. He became very interested in the new technique and asked for his own trap. A system was built and tested at Mainz and then transferred to Stockholm: The Stockholm-Mainz Ion LEvitation trap (SMILETRAP) has specialized in highly charged ions and thus achieves high resolving powers at the corresponding cyclotron frequencies [Fritjoff et al.[1]]. Thus, the ToF detection of ion cyclotron resonances joined other methods of highest accuracy as applied to stable species [Van Dyck et al.[1], Redshaw et al.[1]]. Guy Savard, who learnt the ion-trap business during a postdoctoral stay at ISOLTRAP, later went on and built the "Canadian Penning trap" (CPT) now hosted at the Argonne National Laboratory [Savard et al.[1]]. Similarly, one of the editors (G.B.), who had been in charge of ISOLTRAP for more than a decade, has recently built up a new ion-trap system at the National Superconducting Cyclotron Laboratory at Michigan State University. LEBIT, the Low-Energy Beam and Ion Trap Facility, is the first system of its kind allowing high-precision mass measurements to be performed on short-lived isotopes produced by fast-beam fragmentation and delivered at half the speed of light [Ringle et al.[1]].

Jürgen Kluge has always been open for any kind of collaboration. As coordinator of European networks he promoted the idea of trap-based nuclear-physics research. Further projects that took advantage of the know-how exchange are JYVLTRAP at Jyväskylä [Jokinen et al.[1]] WITCH at CERN (Kozlov et al.[1]], and TITAN at TRIUMF/Vancouver [Dilling et al.[1]]. Jürgen also included the theoretical aspects of the various nuclear and atomic physics research into the networks, bilateral collaborations, and close contacts [Stoitsov et al.[1]].

Not being content with ISOLTRAP and its on-going success [Herlert et al.[1]], Jürgen himself started two new trap projects, SHIPTRAP and HITRAP [Block et al.[1] and Herfurth et al.[1]] after his change from the University of Mainz to GSI at Darmstadt as the atomic physics group leader. He also realized the great possibilities of storage-ring based mass spectrometry and supported the very successful efforts at GSI [Bosch et al.[1]].

As described, Jürgen is probably best known for the development of ion-storage devices and methods for accurate measurements of nuclear masses. Thus, this topic has been taken up for the present special issue. However, in more general terms he has been a key player in pioneering the application of methods of atomic physics at accelerators [20]. Starting with the work on his doctoral thesis at Heidelberg he applied refined techniques from optical spectroscopy at ISOLDE, first to mercury and then later on, under his direction, to platinum and gold isotopes. These investigations were in the tradition of the "EXAKT" the former Mainz group lead by Ernst Otten, Jürgen's Ph.D. adviser. Interestingly, Otten later started a very successful research project on the mass [!] of the electron neutrino with techniques not too far from those of the ones mentioned above and described by Otten et al.[1]. For other contributions in the present special issue with regard to fundamental symmetries and interactions see Gabrielse[1], Jentschura et al.[1], Shabaev et al.[1], Becker et al.[1], Werth et al.[1], Hardy et al.[1], and Kozlov et al.[1]. Jürgen's laser spectroscopy work revealed a new region of the nuclear chart characterized by strong co-existing shape instabilities and demonstrated how a few but accurate and model-free numbers – spin, parity, nuclear moments, charge radii – could put our assumptions about nuclear structure to test. This, of course, has become today's accepted paradigm for radioactive-beam research, and nuclear masses have to be added to the list at a prominent position.

While developing new methods for basic research on short-lived nuclei Jürgen also adapted these methods to other fields. In particular, the application of laser spectroscopy combined with mass spectrometry (short RIMS for resonance ionization mass spectroscopy) applied for trace analysis of elements and particular nuclides should be mentioned [21]. Jürgen was also a driving force behind the development of laser-ion sources for the efficient and selective ionization of radioactive atoms [22,23]. This technique is one of the most-important developments in recent years for the production of radioactive ion beams. To mention just one further field of activities, Jürgen also initiated

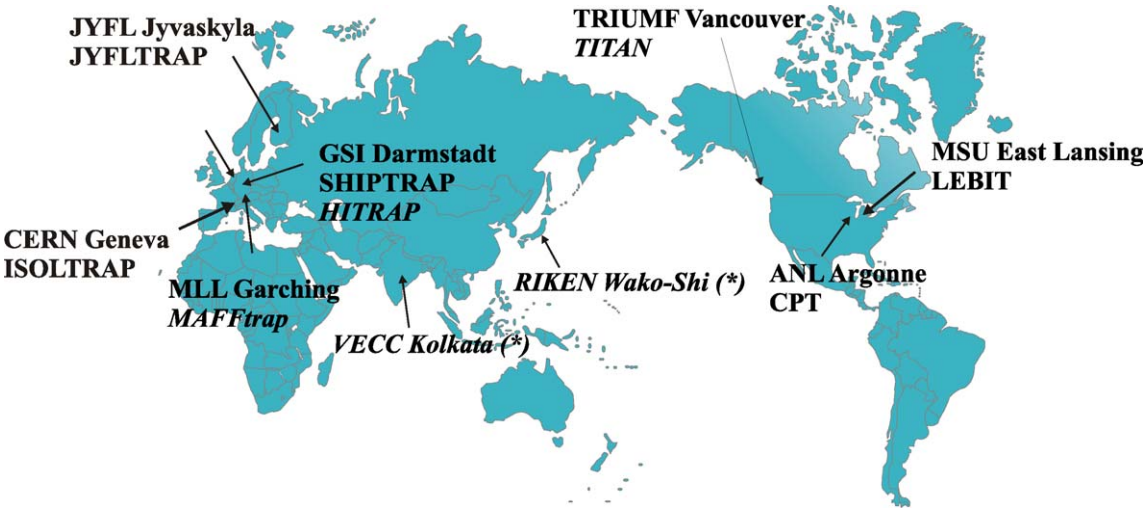

Fig. 1. Ten years ago ISOLTRAP was the only operational Penning trap mass spectrometer for short-lived isotopes. This has changed: the world-map shows operational facilities, further ones under construction (in italic) and accelerator laboratories with similar plans (marked with an asterix).

the application of a Penning trap for metal cluster research [24], which has been followed up by one of the editors of this special issue [25–27]. Recently, the connection to atomic clusters has paid off as carbon cluster ions are the ideal species for mass calibration. Furthermore, they have proved valuable in exploring the limits of the experimental accuracy of ISOLTRAP [28] and may be used for mass calibration in general [29].

Returning to Penning traps we will finally have a quick look at the future: Figure 1 shows a map where trap facilities for mass measurements of short-lived nuclei are indicated, as established instruments or having started operation recently, as under construction and as planned. Obviously, the field has just started to grow from its infancy. Similarly, a look at Jürgen's publications (see the list in this special issue) shows that of the almost 300 entries (as of the end of 2005) more than a hundred are due to just the last 5 years.

Jürgen, we wish you as much success in the coming years!

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East Lansing Georg Bollen
Greifswald Lutz Schweikhard

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