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Ion traps —Precision measurements and more

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Abstract. Today ion traps are an important experimental tool. Applications range from high-precision measurements of masses and moments, realization of atomic clocks, to the study of ion chemical reactions. Ion traps have gained particular importance in the field of nuclear physics where they are used for the precise determination of nuclear binding energies, decay studies, and radioactive ion beam manipulation.

PACS. 21.10.Dr Binding energies and masses – 21.10.Ky Electromagnetic moments – 23.40.Bw Weak-interaction and lepton (including neutrino) aspects – 24.80.+y Nuclear tests of fundamental interactions and symmetries

1 Introduction

The wide-spread use of ion traps in fundamental and applied research is largely due to their ability to confine ions in small volumes in well-controlled fields. The confinement of particles for a long period of time is the key to high precision in all experiments where frequencies are measured. Traps can be highly sensitive devices since single ions can be stored and detected. Furthermore, stored ions can be manipulated in many ways. They can be cooled by laser light or buffer gas. The ions themselves, or their motion can be excited with radiofrequency and laser fields. They can undergo chemical and atomic reactions, or nuclear decay. Today, ion traps are utilized in analytical chemistry, trace analysis, molecular and cluster physics, physics of non-neutral plasmas, metrology, atomic spectroscopy, high-precision mass spectrometry on stable or unstable isotopes, and ion beam manipulation [1,2].

Two basic methods are most widely applied for the trapping of charged particles, the Paul trap and the Penning trap. In the case of the Paul, or radiofrequency quadrupole (RFQ) ion trap, an inhomogeneous radiofrequency field is employed for the ion confinement. This type of traps is well suited if ion storage is the only concern. In the case of the Penning trap a strong magnetic and a weak static electric field are used. The presence of the magnetic field allows Penning traps to be employed as mass spectrometers, which is their main use today. But a variety of other applications exists for both devices or even combinations of them.

This review will present some recent highlights achieved with ion traps with emphasis on mass measurements, ion beam manipulation and decay studies.

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2 Mass measurements

The basic principle of Penning-trap mass spectrometry is the determination of the ion's cyclotron frequency in a strong magnetic field. In the presence of this field and an axially symmetric electric quadrupole field the ion performs a characteristic motion, which is a superposition of three independent harmonic eigenmotions. They are an axial motion with frequency ν_z (parallel to the magnetic-field lines) and a radial motion. The radial motion itself is a superposition of a slow circular drift motion (magnetron motion) with frequency ν_- and a (reduced) cyclotron motion with the frequency $\nu_+ = \nu_c - \nu_-$, where

$$\nu_c = q/m \cdot B/(2\pi) \tag{1}$$

is the cyclotron frequency of an ion with a charge-to-mass ratio q/m confined in the magnetic field B.

Various destructive and non-destructive techniques have been developed for the determination of the eigenfrequencies or combinations for them. Of particular interest are the relations $\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$ [3] and $\nu_+ + \nu_- = \nu_c = q/m \cdot B/(2\pi)$ [4,5]. With these relations and (1), the mass m can be determined either by independent measurements of ν_+, ν_z, and ν_- or by a direct measurement of the sum frequency $\nu_+ + \nu_-$. Provided that the charge state of the ion is known, the magnetic-field strength B is still required for the mass determination. It can be obtained from the determination of the cyclotron frequency ν_c of an ion with a well-known mass (preferable ^{12}C or carbon cluster ions [6]).

The resolving power in Penning-trap mass spectrometry depends on the time of observation T_{obs} of the ion motion. The linewidth $\Delta\nu_c$(FWHM) with which the cyclotron frequency can be determined is approximately

given by $\Delta\nu_c \approx 1/T_{obs}$. For the resolving power one obtains

$$R = \frac{m}{\Delta m} = \frac{\nu_c}{\Delta\nu_c} \approx \nu_c \cdot T_{obs}\,. \quad (2)$$

For a singly charged ion with mass number 100 in a 6 T magnetic field the cyclotron frequency is about $\nu_c = 1$ MHz. A one-second observation time gives a resolving power of 1 million. Using ions with a charges state $Q = 10$ or extending the observation of the ion motion to ten seconds increases the resolving power by an order of magnitude.

The high resolving power is one ingredient for the high accuracy that can be achieved in Penning-trap mass spectrometry. Another ingredient is a high quality of the trapping fields. This is not too difficult to obtain, since the ions are usually confined in a very small volume of a few cubic millimeters or less.

2.1 Measurements on stable and long-lived isotopes

Masses and mass ratios of fundamental particles like electron and positron or proton and antiproton have been determined with Penning traps. However, for only about one decade Penning traps have been used for mass measurements of stable isotopes.

Penning-trap mass measurements of these kind are presently pursued at MIT [7,8] and with SMILETRAP at Stockholm [9]. Different approaches are followed at these places. At MIT, the measurements are carried out on single ions kept at a temperature of 4 K. The motion of the ion is observed by detecting the image signal induced in the trap electrodes. A highly tuned circuit connected to a SQUID detector is used. The low ion temperature is the key for the unprecedented precision that has been achieved of 0.2 ppb or better. In the MIT experiment the ions are created inside the trap, limiting somewhat the applicability of this approach. Nevertheless, an ultra-high-precision mass table covering light and heavy, stable isotopes has been established [7,8]. SMILETRAP [9] has been designed for mass measurements on highly charged ions. An advantage of using ions in high-charge states Q is the Q-fold increased cyclotron frequency, which allows higher resolving powers to be achieved for a given observation time. SMILETRAP receives its highly charged ions from an electron beam ion source. The ions are captured in a first Penning trap, which acts as a potential elevator, then they are captured in flight in the actual Penning-trap mass spectrometer. For the detection of the cyclotron resonance a destructive time-of-flight technique is used. The trap is operated at room temperature and the ions are not cooled. Instead, moderately cold ions are selected from a larger ion cloud. Despite the fact that no real cooling technique is used an accuracy of about 1 ppb is achieved. The advantage of the SMILETRAP approach is its wide applicability since ions from an external ion source are used.

The motivation behind measuring stable masses with very high precision is manifold. It ranges from establishing a reliable backbone of known masses along the line of beta-stability, providing masses important for metrology, or for measuring atomic binding energies in order to test atomic theory. Recent results from MIT and SMILETRAP on alkali isotopes may suffice to illustrate the potential of Penning-trap mass spectrometry.

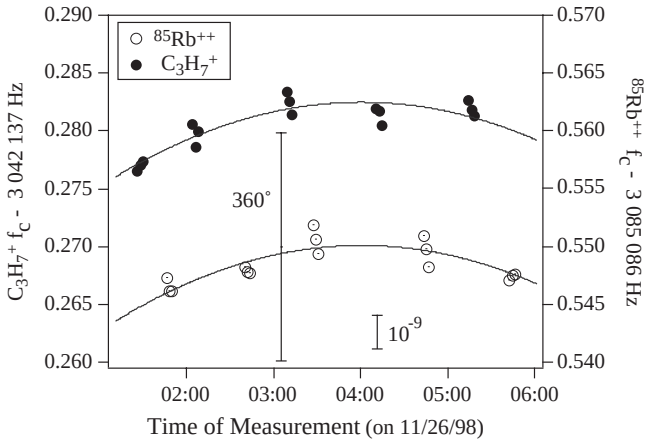

Fig. 1. Series of cyclotron frequency determinations performed at MIT on $^{85}Rb^{++}$ ions, alternated with measurements on $C_3H_7^+$ ions, which served for the calibration of the magnetic field. The solid lines correspond to a polynomial fit describing the magnetic field variation [10].

A precise mass measurement of ^{133}Cs and other alkali isotopes may lead to an alternative and purely experimental determination of the fine-structure constant α. This is highly desirable since discrepancies exist between the most precise determinations of α that exist so far. The new path towards an experimental determination of the fine-structure constant is via a relationship between α and the molar Planck constant ($N_A\,h$), $\alpha^2 = \text{const}\cdot N_A h$, where const is the product of very well-known quantities. There is a good chance that the quantity $N_A h/M_{alkali}$ can be measured with very high precision via atom interferometry with laser-cooled alkali atoms. To make use of this measurement the mass M_{alkali} of the alkali atom needs to be known. Both the SMILETRAP and MIT groups accepted this challenge. SMILETRAP determined the mass of ^{133}Cs with an accuracy of about $2{\cdot}10^{-9}$ [11]. In the MIT experiment the masses of ^{133}Cs ^{85,87}Rb, and ^{23}Na were measured with an even higher accuracy of $2 \cdot 10^{-10}$ [8]. As an example for their results, fig. 1 shows a series of cyclotron frequency determinations on $^{85}Rb^{++}$ ions, alternated with measurements on $C_3H_7^+$ ions, which serve for the calibration of the magnetic field.

High-precision trap experiments on stable isotopes can also provide a stringent test of QED and atomic theory. This is the goal of HITRAP, a new project at GSI. HITRAP will combine both the MIT and the SMILETRAP approaches by capturing highly charged ions (possibly up to bare uranium nuclei) in a 4 Kelvin Penning-trap system. Both high-precision mass measurements of ions in different charge states and measurements of the g-factor of electrons bound by strong Coulomb fields are planned [12].

2.2 Nuclei far from stability

The development of new direct mass measurement techniques has provided tools for a detailed study of nuclear binding far from the valley of stability [13,14]. Employing these tools for a systematic exploration of masses allows us to directly observe nuclear-structure effects like the location of shell and subshell closures, pairing, or the onset of deformation. Masses play an important role in the understanding of nuclear astrophysical processes. However, many important nuclei in these processes are still not accessible in the lab and mass prediction by models and mass formula have to be employed [15–17]. It is clear that new and accurate mass data far from stability are the most stringent tests for the predictive power of these models. For these kind of studies a mass accuracy of about 10–100 keV is often more than sufficient. But there are special cases where the mass measurement accuracy must be even higher. This is for example the case for testing the standard model via a precise study of super-allowed β emitters. Mass measurements with an accuracy of 1 keV or less of the parent and daughter nuclides of such transitions give stringent β endpoint values and complement nuclear spectroscopy measurements.

Penning-trap mass spectrometers can achieve the accuracies mentioned above for even very short-lived isotopes. The statistical uncertainty $\delta m/m$ of a cyclotron frequency measurement is inversely proportional to both the resolving power R and to the square root of the number $N_{\rm ion}$ of detected ions. $(\delta m/m)_{\rm stat} \approx 1 \cdot R^{-1} \cdot N_{\rm ion}^{-1/2}$. The capability of Penning-trap mass measurements on unstable isotopes can easily be evaluated with this relation. A magnetic field of about 6 T, singly charged ions, and a maximum storage time of about twice the half-life of the investigated nuclide are assumed. For example, for a high-precision measurement ($< 1\,$keV) on ^{74}Rb ($T_{1/2} = 65$ ms), as required for a meaningful CVC test, a few hundred thousand detected ions are required. In the case of ^{11}Li ($T_{1/2} = 10$ ms), not more than 1000 ions need to be detected for a statistical uncertainty of a few keV. Of course, the total accuracy of the mass values has to include possible systematic errors. The design of present ion trap systems for nuclear-mass measurements is such that systematic errors due to field imperfections are typically below $\delta m/m < 1 \cdot 10^{-8}$. However, care has to be taken to avoid systematic errors due to Coulomb interaction between ions of different mass stored simultaneously [18]. Such effects can be avoided if the measurements are performed with only a single trapped ion at a time.

Presently there are two Penning-trap mass spectrometers operational for the study of short-lived nuclides. These are ISOLTRAP at ISOLDE/CERN and CPT at Argonne. The actual mass spectrometers are rather similar, the main difference is the type of radioactive ion beam sources used.

ISOLTRAP [19] is installed at the ISOL facility ISOLDE at CERN, which delivers a 60 keV continuous ion beam. During the last years a number of new developments and improvements [20,21] have been implemented. As a result, ISOLTRAP is able to perform measurements on practically all beams available at ISOLDE and on isotopes with half-lives shorter than 100 ms. Figure 2 shows the present layout of the experimental set-up. The first component has the task to stop the 60 keV ISOLDE beam and to prepare it for efficient transfer into the cooler Penning trap. This beam manipulation (see subsect. 4.1) is achieved by a linear RFQ trap [21], which accumulates, cools, and bunches the ISOLDE ion beam. The second component is the cooler Penning trap [20]. It has the task to accumulate, cool, and in particular purify the ions delivered from the RFQ trap. A mass selective sideband cooling technique with buffer gas is used (see subsect. 4.2), which allows isobars to be separated. The purified ion cloud is delivered to the second Penning trap. This 6 T precision trap [19] is the actual mass spectrometer. Here the cyclotron frequency of the ions is determined with resolving powers of up to 10^7, sufficient to resolve isomer and ground states even in the case of low excitation energies.

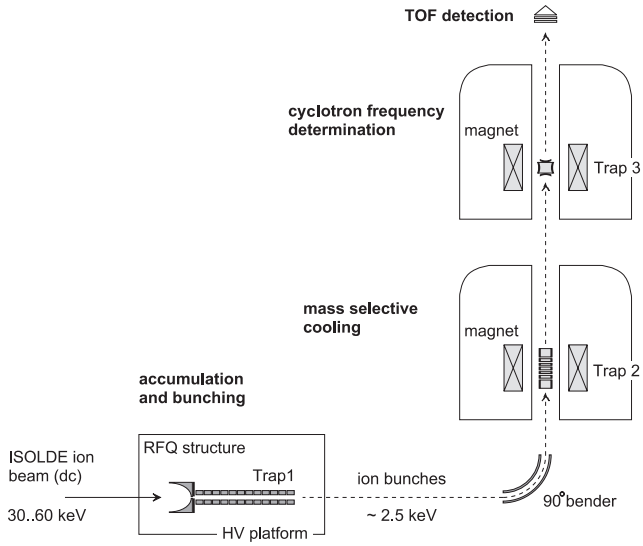

Fig. 2. Schematic view of the ISOLTRAP experimental set-up.

About 200 masses have been measured with ISOLTRAP so far [22–33]. Recent examples of a systematic study of binding energies far from stability are measurements carried out on rare earth isotopes [29,32] or on a long chain of neutron-deficient mercury isotopes [30]. In the case of ^{33}Ar a breakdown of the IMME mass equation was found [31] and with the investigation of ^{74}Rb [33] a first high-accuracy measurement of this important nucleus was performed. With $T_{1/2} = 65\,$ms is ^{74}Rb also the shortest-lived isotope ever investigated in an ion trap.

The CPT spectrometer at ANL [34] is the first Penning-trap project that includes stopping of energetic radioactive products from nuclear reactions in a gas cell. Stable beam from the ATLAS accelerator is sent to appropriate targets placed at the entrance of an Enge split-pole magnet. The reaction products are retarded and stopped in a high-pressure (about 100 mbar He) gas cell. Singly charged ions are extracted out of this cell and guided into a high vacuum region by employing multi-stage differential pumping and radiofrequency quadrupole systems which

act as ion guides. The last RFQ system is very similar to the ISOLTRAP accumulator and buncher mentioned above. It accumulates the radioactive ions and releases them as short ion bunches. These ion bunches are then trapped in a Paul trap for further cooling. Again a bunch is released and finally captured in a high-precision trap where the mass determination takes place. A measurement program has started recently and first results on neutron-deficient cesium [35] and germanium and arsenic isotopes [36] have been obtained.

3 Decay studies

Stored ions in traps are ideal sources for nuclear decay studies. Ions cooled to room temperature are confined in a volume of typically a few cubic millimeters. These sources are backing free which means that scattering in the target material is avoided. Open trap designs make efficient detection of the decay products possible. The magnetic field of Penning traps can be employed to guide charged decay products to outside detectors. A restriction is space charge, which limits the maximum number of ions that can be stored. In the case of Penning traps, for example, the so-called Brillouin density limit is approximately $10^9\,\mathrm{cm}^{-3}$ for singly charged ions with mass number 100 in a 6 T magnetic field.

Presently a couple of decay experiments in ion traps are under preparation. Most of the experiments aim at precision decay studies as required for the search for scalar and tensor currents in weak interaction. One example is the WITCH spectrometer [37,38]. WITCH is being built at KU Leuven and will finally be installed at ISOLDE. It consists of a Penning-trap system for the accumulation of the ions of interest and a retardation spectrometer. After the decay, the energy of the recoiling nucleus is measured with this system. From a comparison of the recoil energy spectrum with that expected from theory, limits on scalar and tensor currents are determined. A similar goal is followed in an experiment under development at LPC/Caen [39]. Here a "transparent" Paul trap (see fig. 3) will be used to study the decay of ^{6}He for a search for tensor currents. The ring electrode of the Paul trap is made out of wires, which are arranged on a hyperboloid of revolution in order to generate the quadrupole field while allowing the decay radiation to escape out of the trap. With two position-sensitive detectors the correlation between the emitted beta-particle and the recoiling nucleus is observed directly.

Not only in these type of precision experiments do ion traps offer advantages. Penning traps can be particularly useful in the study of low-energy conversion electrons or the study of beta-delayed proton emitters. Gamma-ray spectroscopy has seen considerable progress during the last decades but conversion electron spectroscopy has hardly changed. The fundamental problem is the electron interaction in the source material rather than detector performance. Using sources of trapped ions resolves this problem. In the case of beta-delayed proton emitters summing

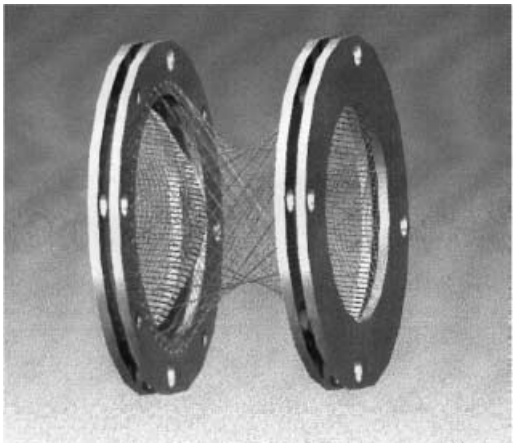

Fig. 3. Photograph of the transparent Paul trap developed at LPC/Caen for weak-interaction studies [40].

of electrons and proton signals can occur in the detectors. The magnetic field used in Penning traps and the different rigidity of protons and electrons make it possible to guide electrons and protons to different detectors or detector segments. First promising tests [41] of decay studies in Penning traps have been performed with REXTRAP [42] at ISOLDE.

4 Radioactive ion beam manipulation

The development of new techniques for the manipulation of radioactive ion beams is actively pursued by several groups worldwide. One of the main objectives is a better matching of the properties of the radioactive ions beams to specific requirements of the experiments. Ion trap techniques have started to play an increasingly important role, in particular for the accumulation, cooling, and bunching of these beams. Both Penning traps [43] and radiofrequency multipole ion traps [44] or guides can fulfil this task. In addition, Penning traps offer high-resolution mass separation and can be used for beam purification [20].

4.1 Isobar and isomer separation

ISOLTRAP has demonstrated that Penning traps can be used to separate isobars in radioactive ion beams with resolving powers up to 10^5 [20]. As already mentioned, for the isobar separation a mass selective cooling technique has been developed which is based on the simultaneous application of RF excitation and buffer gas cooling [4,5,45]. New Penning-trap projects that are going to employ this beam purification technique are JYFLTRAP at Jyväskylä [46] and SHIPTRAP at GSI [47]. While ISOLTRAP uses a separate magnet system for the purification trap, the new projects make the economic attempt to install both a measurement and a purification trap in one solenoid.

Fig. 4. Illustration of accumulation, cooling, and bunching in a buffer gas-filled ion trap.

ISOLTRAP has also shown that isomers can be resolved [18] even if the excitation energy is as low as 100 keV [30]. The possibility of isomer resolution in traps has not yet been employed for their separation, but it appears technically feasible in particular for excitation energies larger than a few hundred keV. Via mass selective dipole excitation at their reduced cyclotron frequency, ions in one state would be selectively removed from the trap. The remaining ions in the other state could then be ejected and delivered for experiments.

4.2 Beam cooling, accumulation, and bunching

The basic principle is illustrated in fig. 4. A continuous ion beam is allowed to overcome the potential hill at the entrance of an ion trap. Passing through the potential well of the trap, the ions lose kinetic energy due to collisions with buffer gas atoms. Finally, after the ions are accumulated in the potential minimum, they can be released by lowering the potential hill at the exit side of the trap. In addition to the depicted axial confinement, a transverse confinement is required. A new but already established approach is the employment of transverse focussing by inhomogeneous RF fields in linear RFQ ion traps. This type of system is for example used by CPT and ISOLTRAP for producing cooled ion bunches for Penning-trap mass measurements.

Beam improvement and manipulation is not only important for ion trap experiments. At Jyväskylä an ion beam cooler and buncher [48] was installed at the IGISOL on-line mass separator [49]. With this system the benefit of cooled bunched beams for collinear laser spectroscopy was demonstrated [50]. Figure 5 shows the result of a laser scan performed on ^{174}Hf, delivered by IGISOL with a beam current of about 1300 ions/s. Photons were detected as a function of the "scanning voltage" for the laser wavelength. Mainly background from scattered laser light is observed if singles are detected. Putting a gate on the ion pulse yields a practically background free resonance curve.

Penning traps can also be used as ion beam bunchers and accumulators, which was first demonstrated with the cooler Penning trap of ISOLTRAP (see fig. 2). Due to the usage of a buffer gas additional RF excitation is required to provide a transverse focussing force for the ions [4,5, 45]. The largest Penning-trap–based ion beam accumulator built so far is REXTRAP [42]. This system has become operational recently and has the task to accumulate and bunch the ISOLDE ion beam for post-acceleration within the REX-ISOLDE project [51].

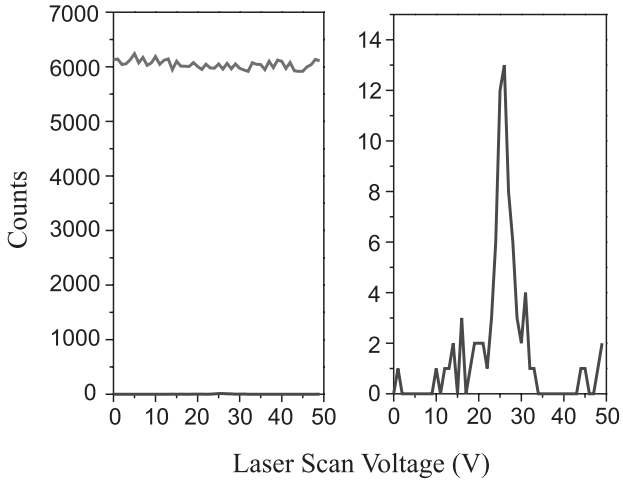

Fig. 5. Laser scan performed on ^{174}Hf. The detected photon signal is plotted as a function of the "scanning voltage" for the laser wavelength without (left) and with (right) gating on the ion bunch [52].

5 New ion trap projects at radioactive-beam facilities

A number of new projects for ion trap experiments at radioactive-beam facilities are coming into operation, are under construction or are planned. In addition to those already mentioned, SHIPTRAP at GSI, JYFLTRAP at JYFL, WITCH at ISOLDE, and the project at LPC Caen, there are ion trap projects on their way at RIKEN [53], KVI Groningen, at ISAC/TRIUMF, and at MAFF in Garching. The Low-Energy Beam and Ion Trap facility LEBIT is presently under construction at NSCL/MSU. A few of these projects will be briefly discussed.

SHIPTRAP [47] at GSI is a system dedicated to the study of isotopes of transactinide and superheavy elements. In addition to mass measurements this may include at a later stage decay studies, laser spectroscopy and ion chemistry studies. The ion source is the velocity filter SHIP. Separated reaction products (typical energy several MeV/u) will be converted into a low-energy high-quality pulsed beam via a concept very similar to the one used in the CPT project at Argonne. The separated reaction products will be stopped in a gas cell. RFQ ion guides will be used to guide, cool and bunch the ion beam before the ions are sent into a tandem Penning-trap mass spectrometer. The construction phase of SHIPTRAP is largely completed and tests have started.

At the cyclotron laboratory in Jyväskylä the IGISOL technique [49] has been providing low-energy ion beams for a rich physics programme since several years. A recent step for improving the IGISOL beams was the installation of an ion beam cooler and buncher [48], as already discussed above. A second important step will be the installation of a tandem Penning-trap system, which will be used as an isobar separator and for in-trap decay studies and precision mass measurements.

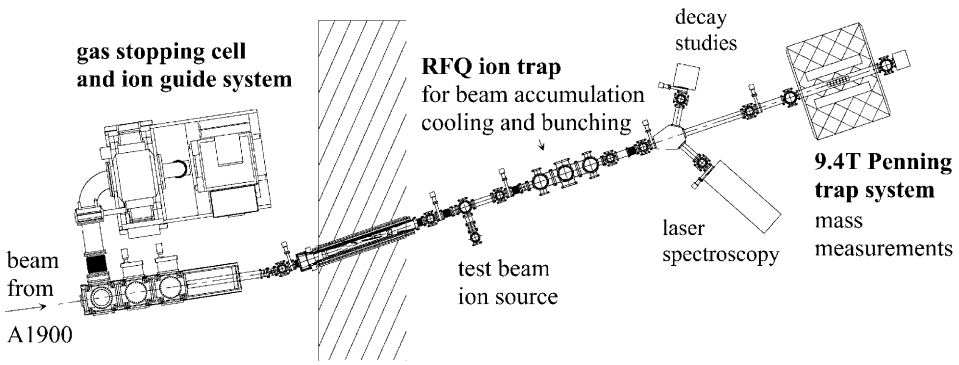

Fig. 6. The Low-Energy Beam and Ion Trap Project (LEBIT) at NSCL/MSU.

LEBIT [54], the first project towards high-precision mass measurements on short-lived isotopes produced by projectile fragmentation, is under construction at NSCL/MSU (see fig. 6). The goal is to extend the use of the new intense exotic beams available at the upgraded cyclotron facility [55] by adding the capability for low-energy beam experiments. For this purpose the high-energy radioactive beam (typically 100 MeV/u) delivered by the A1900 fragment separator is brought to rest by letting it pass through an appropriate solid degrader (with the option to employ energy bunching) and by finally stopping it in a gas cell operated at a pressure of about 1 bar helium. The stopped ions are then guided by electrostatic fields to a supersonic nozzle through which they leave the gas cell. Radiofrequency ion guides transport the ions into subsequent sections with improved vacuum. Then the low-energy ion beam is sent into a low-temperature (80 K) RFQ ion beam accumulator and buncher. Cooled ion bunches pass a pulsed drift-tube for obtaining final ion beam energies of 5–60 keV. An electrostatic switchyard distributes the bunched beam into different beam lines. At one of these beam lines a Penning-trap mass spectrometer will be installed. In the design of this system special emphasize has been put on the study of very short-lived isotopes ($T_{1/2} >$ a few ms). This is one of the reasons why a magnet system has been selected with a field strength of 9.4 T. The mass measurement program foresees a precise study of light and medium-heavy neutron-rich isotopes including drip line nuclei, as well as a study of proton-rich nuclei in the vicinity of the $N = Z$ line. At a later stage, LEBIT will open the possibility for other experiments like decay studies or laser spectroscopy. The project is planned to become operational in 2002.

6 Conclusions and outlook

Ion traps have found a wide field of applications. In nuclear physics they have become important for the improvement of radioactive ion beams. Their employment as mass spectrometers for very exotic nuclides has turned out to be very successful and they promise to be beneficial for precision decay studies.

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