Aspects of Cooling at the TRIμP Facility

L. Willmann, G.P. Berg, U. Dammalapati, S. De, P. Dendooven, O. Dermois, K. Jungmann, A. Mol, C.J.G. Onderwater, A. Rogachevskiy, M. Sohani, E. Traykov, and H.W. Wilschut

Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen, Zernikelaan 25, NL 9747 AA Groningen, The Netherlands

Abstract. The TriμP facility at KVI is dedicated to provide short lived radioactive isotopes at low kinetic energies to users. It comprised different cooling schemes for a variety of energy ranges, from GeV down to the neV scale. The isotopes are produced using beam of the AGOR cyclotron at KVI. They are separated from the primary beam by a magnetic separator. A crucial part of such a facility is the ability to stop and extract isotopes into a low energy beamline which guides them to the experiment. In particular we are investigating stopping in matter and buffer gases. After the extraction the isotopes can be stored in neutral atoms or ion traps for experiments. Our research includes precision studies of nuclear β-decay through β-ν momentum correlations as well as searches for permanent electric dipole moments in heavy atomic systems like radium. Such experiments offer a large potential for discovering new physics.

Short lived radioactive isotopes are interesting for several promising lines of research and currently a number of facilities to provide the isotopes are planned or are being set up. The research topics cover a wide range in atomic, nuclear and particle physics [1]. At the Kernfysisch Versneller Instituut (KVI), Groningen, The Netherlands, we are commissioning the TRIμP Facility (Trapped Radioactive Isotopes: μicrolaboratories for fundamental Physics) [2], which is open to outside users.

The physics interest of the TRIμP group are tests of discrete fundamental symmetries, i.e. charge conjugation (C), space inversion (P), and time reversal (T). In standard theory the structure of weak interactions is V-A, which means that vector (V) and axial vector (A) currents with opposite relative sign causing a left handed structure and thus parity violation [3]. Other possible currents like scalar, pseudo-scalar or tensor like are signs for new physics. They can be tested by searching for β-ν correlations in weak interactions [4]. In order to determine the neutrino momentum, the recoil to the nucleus needs to be measured. Since the recoil energy is on the order of 100 eV, a precision measurement of the recoil momentum can only performed when the nuclei are suspended in a very shallow potential, which can be provided by confining atoms by light forces [5]. Particularly good candidates are 20,21Na and 18,19Ne.

Another research direction is searching for permanent electric dipole moments (edm), which violated C and P simultaneously [6]. Any observation of an edm would be an indication of physics beyond the standard model. Currently the most sensitive experiment on a nuclear edm, was performed with 199Hg [7], which gives a limit of $2.1 \times 10^{-28}$ ecm. Recently Flambaum and collaborators pointed out that radium offers a large sensitivity to edm’s due to its nuclear as well as atomic level structure [8]. Currently we are inves-
tigating the feasibility of a search for an edm using radium. Both experiments require

to produce the isotopes and to store them subsequently in a neutral atom traps. We will
describe the setup of the facility.

Isotopes of interest are produced in fragmentation or fusion-evaporation reactions
utilizing heavy ion beams from the AGOR cyclotron on fixed targets, which are chosen
for optimum production rates. The production mechanism favors proton rich isotopes.
The goal is to provide a clean beam of the requested isotopes with very low background
radiations. This requires dedicated separation and isotopes selective extraction stages.
The primary heavy ion beam is separated from the reactions product in a magnetic
device, which is designed to cover a wide range from light to heavy isotopes. Through
unique magnet design we achieved a compact device. This magnetic separator has been
successfully commissioned in the fall of 2004 [9]. After the separator the reaction
products are stopped in matter, which will be discussed in below. The extraction time
from the stopping device sets the lower limit for the lifetime of the isotopes which can be
provided by the facility. We are aiming at times shorter than 1 s. After the extraction from
the stopping device the isotopes are cooled and trapped in an radio frequency buncher
cooler (RFQ-cooler). From the buncher they are transported to the experiment in an
electrostatic beamline. After neutralisation the atoms can be stored in neutral atom traps
by laser cooling and trapping methods.

A central role in the design of a facility for radioactive beams takes the cooling
from the energies of several MeV/u at the productions to the eV range. For short lived
isotopes the stopping and extraction should be minimal. Reaction products stopped in
matter will be spread over a distance given by the range straggling and initial momentum
uncertainty. There are two options.

• Stopping ions in a buffer gas, preferentially helium. The main common argument is
that the ionization potential for helium (24.5eV) is much larger than for any other
elements. Thus the neutralization of the incoming ion is energetically forbidden,

at least at low enough energies. The ionic isotope can be extracted from the buffer
gas by electrostatic guiding fields. A technical aspect is that the helium gas has to
be extremely clean. A main question is the survival of ions in a buffer gas while

they are cooled by collisions especially at high rates of incoming ions [10, 11]. This

approach is followed by groups at several accelerators because it is less dependent

on the specific element.

• Implanting in a solid which can be heated to a high temperature at which the

isotopes diffuse out of the material [12]. At high temperature the diffusion and
effusion time can be less than 1s if the stopping foils are sufficiently thin (≈ 1µm).
Such a thermoionizer could provide high efficiencies of order 1 for alkaline and
alkaline earth metals.

We have investigated the possibility of using a gas cell. While an ion traverses through
the buffer gas it changes its charge state very rapidly as it undergoes many neutralization-
reionization cycles. The neutralization has a kinematic cutoff because all isotopes have
a lower ionization potential then helium. The neutralization cross section for a singly
charged ion is maximal around an energy of about 25 keV/nucleon (Fig. 1). Below

that energy the cross section drops rapidly. The fraction of charged isotopes at thermal
energies is expected to be determined by the ratio of the ionization to neutralization cross section. These charge exchange cross sections at low energies are important input for the development of devices like radio frequency coolers as well as gas catcher cells for stopping high energetic ions.

We have measured cross sections for neutralization as well as stripping cross sections at energies below 1keV/u for different buffer gases. The survival rate strongly depends on the composition of the buffer gas. The preferred choices for a buffer gas is highly pure inert gases where helium stands out because of its high ionization potential of 24.5eV.

We measured the change of the charge state of multiply charged ions after passing through a differentially pumped He gas target. Typically less than 10 collisions are sufficient to reach an equilibrium charge state distribution, while the energy loss is small compared to the total energy. Because of the small number of collisions such a setup is less sensitive to the purity of the gas than in a measurement where we completely stop the ions. In Fig 2 our results for Xe on helium is plotted in addition to data at higher energies and for different isotopes. We could extend these measurements to lower momentum of $15 \times 10^8$ cm u/s, respectively 80 eV/u of energy. The average charge state is decreasing with decreasing momentum of the ions. Measurements at lower momenta were not possible in our apparatus because of the increasing scattering angle.

For the TRIµP facility we are currently commissioning a stopping device of the second type, since it is ideal for alkaline and alkaline earth isotopes. We plan to stopping the ions in thin tungsten foils, which can be heated to temperatures of 2500 K were the expected diffusion times are less than 1 s for 1µm thick foils.

After the stopping device the isotopes are extracted as ions, which allows for easy manipulation. The ions are guided by electrostatic means into a gas filled radio-frequency buncher cooler system. It consists out of two identical segmented rfq’s of 330 mm length, which are separated by small apertures for differential pumping purposes. The rods of the quadrupoles are 10 mm apart and are segmented in order to apply axial field gradient. The segments are connected by a dc resistor chain, while the rf is capacitively coupled to
the segments. This reduces the number of electrical feedthroughs significantly. We use frequencies from 0.5-2 MHz and a voltage $V_{pp}$ of up to 200 V, which is sufficient for the isotopes of interest. The device is housed in standard UHV double crosses (Fig. 3).

The system was commissioned using ions with energies of 10-60 eV. In the first section they are slowed and transversely cooled by collisions with He buffer gas of about $3 \times 10^{-2}$ mbar. A small drag potential of 0.5 V/cm moves the ions along the axis. The second rfq operates at a pressure ten times lower. The axial potential has is shaped to allow for trapping near to the exit. The potential depth is on the order of 5 V. The ions can be ejected into a pulsed drift tube accelerator by switching the last electrode by several ten volt. Preliminary measurements indicate that we find more than 60% of the ions entering the device are transferred into the drift tube. The drift tube is pulsed and the ion pulse is detected by a micro channel plate in the low energy beamline. The pulse width is in the order of several hundredths of ns in agreement with simulations. The ion pulse can then be transported in an electrostatic beamline to the experiments.

The ultimate cooling of the radioactive isotopes is provided in neutral atom traps. Here, atoms are well localized at typical temperatures of the order of $\mu$K. Storage times in a MOT depends on the particular atom and the background pressure and Na trapping times of more than 100 s have been achieved. Recently the first Na MOT for TRI$\mu$P has been brought into operation. An advantage of optical trapping is that it allows to manipulate the state of the systems. The limitation of laser cooling are that the forces are rather small and atomic level scheme has to be suitable. Thus we are developing new laser cooling schemes for atoms like radium, extending the list of trapable atoms.

Research with trapped rare isotopes offer unique possibilities for testing fundamental interactions in a complementary way to high energy physics. Atomic physics techniques
allow for precision measurements which can test extensions to the standard model very sensitively [7, 14]. The upcoming facilities at KVI and other places are on their way to enable promising experimental test in the near future.

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