Production and trapping of radioactive atoms at the TRIµP facility

E. Traykov*, U. Dammalapati, S. De, O.C. Dermois, L. Huisman, K. Jungmann, W. Kruithof, A.J. Mol, C.J.G. Onderwater, A. Rogachevskiy, M. da Silva e Silva, M. Sohani, O. Versolato, L. Willmann, H.W. Wilschut

Kernfysisch Versneller Instituut, University of Groningen, Zernikelaan 25, 9747 AA Groningen, The Netherlands

Abstract

The structures for the TRIµP facility have been completed and commissioned. At the facility radioactive nuclides are produced to study fundamental interactions and symmetries. An important feature is the possibility to trap radioactive atoms in order to obtain and hold a pure substrate-free sample for precision measurements. In the TRIµP facility a production target is followed by a magnetic separator, where radioactive isotopes are produced in inverse reaction kinematics. Separation up to 99.95% could be achieved for $^{21}$Na. A novel transmitting thermal ionizing device was developed to stop the energetic isotopes. Some 50% of stopped $^{21}$Na could be extracted and transported as low energy singly charged ions into a radio frequency quadrupole cooler and buncher with 35% transmission efficiency. The ions are transported lossless via a drift tube and a low energy electrostatic beam line into the experimental setup. Such ions can be neutralized on hot metal foils and the resulting atoms can be stored in a magneto-optical trap. The functioning of that principle was demonstrated with stable Na extracted from the thermal ionizer, radioactive beams will follow next.

Key words: Magnetic separator, Radioactive ion beam, Thermal ionizer, Atomic trapping

PACS: 23.40.Bw, 25.70.-z, 29.27.Eg, 29.30.Aj, 37.10.Gh, 37.10.Rs, 41.75.-i

* Corresponding author. Tel.: +31 503633569, fax: +31 503633401
Email address: traykov@kvi.nl (E. Traykov).

Preprint submitted to Elsevier 28 March 2008
1 Introduction

Precision measurements of parameters describing $\beta$-decays and searches for permanent electric dipole moments (EDMs) in atomic systems are among the main objectives of the TRI$\mu$P physics programme [1,2,3,4]. Studies of $\beta-\nu$ correlations in nuclear $\beta$-decays require the detection of very low energy recoiling ions. From these correlations, deviations from the V-A structure of the weak interaction can be searched for. Another line of research is to improve the limits for permanent EDMs, which are time-reversal violating moments and to improve the uncertainty of the values for parity non-conservation measuring the weak charge. For this research, advantage can be taken of special high sensitivity to new physics in certain heavy radioactive atoms [5].

The experiments will be performed with samples of radioactive atoms stored in magneto-optical traps (MOT). Atomic trapping allows the storage of radioactive atoms without substrates and thereby boosts the performance of high precision experiments. Other advantages of atomic trapping include confinement and localization of the samples in space (typically in a volume $\leq 1 \text{ mm}^3$) at very low temperatures (in the sub-mK range), exclusive isotopic selectivity, and highly reduced background radioactivity.

At the Kernfysisch Versneller Instituut (KVI) a complex facility was built both to achieve the goals of the TRI$\mu$P group and for experiments with radioactive nuclides by external groups. The facility employs the in-flight method for production and separation of radioactive isotopes utilizing a dual-mode magnetic separator. The separator is commissioned and operating [6]. Various modes to produce radioactive particles have been tested for optimal production [7]. A thermal ionizer [8] stops the fast products and transports the nuclides as low-energy singly charged ions into a radio frequency quadrupole (RFQ) cooler and buncher [9]. This allows the collection and transport of ions towards the optical traps. The optical trapping of Na atoms is done in two separate MOT stages. The first MOT is used for neutralization and accumulation of the Na atoms. It has been commissioned with stable $^{23}\text{Na}$ as described in [10]. The atoms are then transported into a second MOT chamber where they can be trapped again and their decays can be studied in a background-free environment [11]. The second MOT is equipped with $\beta$-detectors and a reaction microscope [12] for detecting of the recoils from the decay.

2 Production and separation of radioactive nuclides

The TRI$\mu$P magnetic separator is used for in-flight production and separation of a large variety of beam-like radioactive isotopes. The nuclides are produced
mainly using transfer reactions in inverse kinematics (heavy projectile and light target) which provides a secondary radioactive beam that can be matched to the angular and the momentum acceptance of the separator.

The production target [13] is filled with a light gas, usually hydrogen, deuterium, or helium. The length of the gas volume is 10 cm. The gas is kept at high pressure using Havar windows at the two ends of the target. The windows are exchangeable and their thickness can be varied depending on the gas pressure. Windows of 2.5 and 10 µm thickness allow safe operation at 1 and 10 atm respectively. The target thickness is increased several times by cooling of the target to liquid N\textsubscript{2} temperature.

The production yield of the desired isotopes in the target should be considered together with the selection in the separator when the aim is to obtain the highest isotope production rate at the end of the separator. The factors contributing to the momentum distribution of the secondary beam are related to the production mechanism, i.e. the nuclear reactions, and to the angular and energy straggling in the target and other materials in the separator. The interplay between the cross sections for a specific reaction, the momentum and angular distributions of the products, and the separator acceptances is
considered for the choice of the initial energy of the primary beam. For the production of $^{21}\text{Na}$ various combinations of reactions and beam energies were examined. We have found that the reaction $^2\text{H}(^{20}\text{Ne},^{21}\text{Na})n$ is the most convenient, with a typical yield of $10^4$/s/particle nA of primary beam at 1 atm. The magnetic rigidity of $^{21}\text{Na}$ is 6.4% lower than the rigidity of the $^{20}\text{Ne}$ beam which allows their complete separation. When the separator settings are optimized for the rate of $^{21}\text{Na}$ various other reaction products are also present in the spectra (see Fig. 1). Additional purification (up to 99.95% for $^{21}\text{Na}$) is obtained by using an achromatic degrader in the dispersive plane of the separator. For the planned $\beta$-decay experiments the high yield of $^{21}\text{Na}$ is of primary importance and degraders are not used. Mass and element selectivity is featured in the stages of the facility following the separator.

The $^{21}\text{Na}$ momentum distributions are shown in more detail in Fig. 2. Extrapolating to higher pressures, we conclude that a 10 atm target can be used, allowing the production of at least $10^8$ $^{21}\text{Na}$ particles/s. This will allow us to measure $\beta$-$\nu$ correlations with a precision of $10^{-4}$ in less than one week of beam time. This is an order of magnitude improvement over exist-
ing measurement [14]. It also requires theoretical work to describe final state interactions [15].

Several experiments have been performed at the TRIµP facility with the objective to measure properties of various radioactive elements and their decays. Depending on the goals of the experiment, the optimization was focused on either element purity, or on maximal production rate. Table 1 summarizes the isotopes produced to date with the magnetic separator.

Table 1
Produced radioactive isotopes; gas target at 1 atm.

| Product | Beam    | Energy | Reaction type | Target | Rate [s/pnA] | Ref. |
|---------|---------|--------|---------------|--------|--------------|-----|
| $^{21}\text{Na}$ | $^{21}\text{Ne}$ | 20     | (p,n)         | CH$_2$ |              | [6] |
| $^{21}\text{Na}$ | $^{24}\text{Mg}$ | 30     | (p,a)         | CH$_2$ |              |     |
| $^{21}\text{Na}$ | $^{24}\text{Mg}$ | 30     | fragm.        | C      |              |     |
| $^{12}\text{B}$ | $^{11}\text{B}$ | 22.3   | (d,p)         | D$_2$  |              | [16]|
| $^{12}\text{C}$ | $^{12}\text{C}$ | 22.3   | (p,n)         | H$_2$  | 1.1·10$^3$   | [17]|
| $^{19}\text{Ne}$ | $^{19}\text{F}$ | 10     | (p,n)         | H$_2$  | 1.0·10$^4$   | [9] |
| $^{20}\text{Na}$ | $^{20}\text{Ne}$ | 22.3   | (p,n)         | H$_2$  | 3.0·10$^3$   | [18]|
| $^{21}\text{Na}$ | $^{21}\text{Ne}$ | 43     | (p,n)         | H$_2$  | 1.3·10$^4$   | [9] |
| $^{21}\text{Na}$ | $^{20}\text{Ne}$ | 22.3   | (d,n)         | D$_2$  | 8.0·10$^3$   | [10]|
| $^{22}\text{Mg}$ | $^{23}\text{Na}$ | 31.5   | (p,2n)        | H$_2$  |              | [18]|
| $^{42}\text{Ti}$ | $^{40}\text{Ca}$ | 45     | (3He,n)       | $^3\text{He}$ | 20 |     |

3 Slowing of radioactive ions

The achromatic focus of the separator coincides with the location of a thermal ionizer (TI) which functions as an ion stopper. The extraction efficiency from a TI can be close to 100% for alkali ions. The separator completely decouples the production site from the TI and the experimental setup. The stopping of the products in the TI is accomplished using a stack of thin W foils which are heated up to at least 2800 K. The total thickness of the foils is chosen to match the maximum of the energy distribution ($\Delta E/E = \pm 4\%$) of the ions at the focal plane of the separator. The stopping range is adjusted by using a rotatable degrader upstream the TI. In the TI, only the ionized particles are extracted but they have multiple chances to be ionized inside the TI and to be electrostatically extracted by an electrode at a negative potential (up to -10 kV). A yield increase from the TI as function of temperature and of Na-isotope lifetime was observed, but has not yet reached the point where the output is saturated. A maximal efficiency of 48(3)% was achieved for $^{21}\text{Na}$. The thermal ionizer principles, design, and operation are described in more detail in [8].
Together with the radioactive Na isotopes, various stable ions are present in the low energy beam extracted from the TI. These ions are formed from diffusion of impurities in the W walls and foils of the TI. In order to reduce space charge effects, mass selection is desired. This is accomplished using a Wien filter downstream the extractor electrode of the TI.

4 Cooling and transport of low energy ion beams

The $^{21}$Na ion beam leaves the thermal ionizer with a large transverse emittance and an energy distribution width defined by the temperature of the W cavity. The large emittance is often affecting the transmission of the ions in the beam line and, depending on the requirements of the experimental setup, cooling may be required. This can be done by the radio frequency quadrupole (RFQ) cooler and buncher system [9] as part of the low energy beam line (see Fig. 3).

The cooling technique is based on collisions with a buffer gas in combination with RF electric fields confining the ions in transverse direction [19]. The buffer gas is composed of light atoms/molecules, typically helium at pressures from $10^{-2}$ to $10^{-1}$ mbar. The RF electric field originating from 4 axisymmetric cylindrical electrodes (330 mm long rods) creates a pseudo potential which confines the ions between the rods. Opposite rods are separated radially by $2r_0 = 10$ mm and potentials $\pm \Phi = U_{DC} + U_{RF}\cos(\omega_R t)$ are applied to them.
To transport the ions through the cooler a DC drag potential is applied in the longitudinal direction. It is obtained by dividing the RFQ in longitudinal sections (36 segments per rod) allowing different potentials to be applied. The DC potentials are set on the separated sections whereas the RF potentials are applied on the rods which are capacitively coupled with the segments. The capacitative coupling is achieved using a 20 µm thin Kapton® foil between the rods and the segments.

The cooled ions enter the buncher (mechanically identical to the cooler) through a small aperture on an electrode plate separating the cooler and the buncher and allowing differential pumping (Fig. 3). The ion transmission through the aperture is critical because of the damping of the RF fields near the aperture causing a reduction of the radial confinement. To overcome this, a DC longitudinal acceleration is applied before the aperture and a subsequent deceleration in the beginning of the buncher.

The operation pressure in the buncher varies from $10^{-4}$ to $10^{-2}$ mbar. This pressure allows the further reduction of the ion velocity and is sufficient to confine the ions in the longitudinal direction by creating a DC potential well close to the exit of the buncher. The trapped ions are then accumulated and extracted in bunches by switching the DC potential configuration when the trapping region is filled. The accumulation time is in the range from several milliseconds to several seconds.

The ion bunches are accelerated to several keV in a drift tube accelerator and guided into an all-electrostatic low energy beam line where they are transported to the experimental sites. With the drift tube installed, both the RFQ and the low energy beam line can be kept on ground potential.

Monte Carlo simulations of the RFQ performance were made for Na ions in order to estimate the effects of the fringe fields near the apertures and to optimize the coupling of the RFQ sections and the subsequent extraction. The interactions of the ions with the buffer gas atoms were implemented in the simulations by taking into account the diffusion related random force [20]. The amplitude of the random force was normalized using data for ion mobilities in gases.

The RFQ system was commissioned with stable Na ions. Various measurements were made in order to characterize the system and establish the operation ranges of various parameters, e.g. potentials, pressures, accumulation times. Transmission was optimized and efficiencies up to 60% were measured for each of the RFQ stages. Measured storage times in the buncher showed strong dependence of the buncher efficiency on the buffer gas purity and the vacuum system.

The RFQ structures can also be exploited for mass selectivity. The variety
of elements at a wide span of masses extracted from the thermal ionizer was used to determine the mass selectivity of the RFQ (Mathieu parameter $a \neq 0$). Different ion masses were identified using a microchannel plate detector after the drift tube and measuring time-of-flight spectra of the ions. The optimal selectivity was achieved by applying a potential $U_{DC}$ in the buncher (due to lower operation pressures and longer trajectories compared to the cooler). Selection was achieved for $\Delta M = 2$ u in the mass region of Na.

5 Neutralization and trapping

To trap atoms, the secondary ion beam needs to be neutralized. This is done inside a small glass cell, the collection MOT [10], using a heated neutralizer foil in which the ions are implanted with energies up to a few keV. The neutralizer has thus common issues with the thermal ionizer, i.e. fast diffusion from a hot foil, surface sticking time and ionization probability. In both cases diffusion delay is the slowest time component in the process. Various materials (e.g. Zr, Y, W, and LiF) were used for neutralization of Na ions. Stable $^{23}$Na ions were used for characterization of the neutralizers by observing the number of captured particles in the MOT. Trapping was maximal for Zr which is considered currently as the optimal neutralizer material.
Once neutral, the particles can be trapped in the MOT (shown in Fig. 4). The atoms in the cell have a thermal velocity distribution (the neutralizer temperature) and only a fraction of them are in the velocity range allowing trapping. The maximal velocity for which atoms can be trapped can be increased by increasing the red detuning of the lasers but require higher laser power. The atoms which are not trapped when passing through the trap region collide with the walls of the cell and may be lost due to sticking and re-diffusion in the glass. The atoms desorbed from the surface have lower velocities than the ones from the neutralizer since their velocity distribution is defined by the temperature of the walls. Figure 5 shows two sets of data: from a glass cell without (●) and with (▲) a non-stick coating. The data obtained using the coated cell are higher in yield because the atoms can bounce of the walls and make multiple passes through the trapping region. The number of trapped atoms increases with temperature due to faster diffusion in the neutralizer. The fact that at higher temperatures the number of trapped atoms decreases again is due to the increase of the pressure with temperature of the neutralizer. The trap lifetime is inversely proportional to the pressure.

The trapped atoms will be guided using lasers into a second MOT which will be employed for the actual measurements of the $\beta$-decay observables. In contrast to the first MOT cell, where many atoms can decay without being trapped, in the decay MOT the atoms will be well localized in the trap reducing the uncertainty of the measurements. This trap is situated in a large vacuum chamber including detectors for the $\beta$ particles, a microchannel plate
(MCP) detector with position sensitive read-out, and guiding electrodes for
the detection of the recoiling $^{21}$Ne ions. The MOT setup for the measurements
of the $\beta-\nu$ correlations is currently being commissioned [21].

6 Outlook

A secondary beam of $^{21}$Na ions has been produced, purified, and transferred
successfully to a neutralizer in the glass cell around the collection MOT site.
We have exploited $^{20}$Na and $^{21}$Na for the optimizing process using pairs of
$\gamma$-ray detectors at various places along the low energy beam line to observe
the annihilation radiation or $\beta$-delayed $\alpha$ decay ($^{20}$Na). Stable $^{23}$Na from the
thermal ionizer is used as a pilot beam in the low energy beam line. We are
currently in the process of optimizing the trapping and detection efficiencies in
preparation of our first physics experiment, a $\beta-\nu$ correlation measurement
in the decay of $^{21}$Na. The successful trapping and detection of $^{21}$Na in the
MOT, which we expect very soon as the next and remaining last step in a
series of successful preparation stages, will be the start of the physics program
at the TRI$\mu$P radioactive beam and trapping facility at KVI.

References

[1] H.W. Wilschut, M.N. Harakeh, R. Hoekstra, R. Morgenstern, TRI$\mu$P project
proposal, 1999.

[2] K. Jungmann, Acta Phys. Pol. B 33 (2002) 2049.

[3] H.W. Wilschut, Hyp. Int. 146/147 (2003) 77.

[4] K. Jungmann, Nucl. Phys. A 751 (2005) 87c.

[5] V.A. Dzuba, V.V. Flambaum, J.S.M. Ginges, Phys. Rev. A 63 (2001) 062101.

[6] G.P.A. Berg, O.C. Dermois, U. Dammalapati, P. Dendooven M.N. Harakeh,
K. Jungmann, C.J.G. Onderwater, A. Rogachevskiy, M. Sohani, E. Traykov,
L. Willmann, H.W. Wilschut, Nucl. Instr. and Meth. A 560 (2006) 169.

[7] E. Traykov, A. Rogachevskiy, M. Bosswell, U. Dammalapati, P. Dendooven,
O.C. Dermois, K. Jungmann, C.J.G. Onderwater, M. Sohani, L. Willmann,
H.W. Wilschut, A.R. Young, Nucl. Instr. and Meth. A 572 (2007) 580.

[8] E. Traykov, U. Dammalapati, S. De, O.C. Dermois, L. Huisman, K. Jungmann,
W. Kruithof, A.J. Mol, C.J.G. Onderwater, A. Rogachevskiy, M. da Silva e
Silva, M. Sohani, O. Versolato, L. Willmann, H.W. Wilschut, Nucl. Instr. and
Meth. B, these proceedings.
[9] E. Traykov, Production of radioactive beams for atomic trapping, PhD thesis, KVI, University of Groningen, 2006.

[10] A. Rogachevskiy, Production and trapping of Na isotopes for $\beta$-decay studies, PhD thesis, KVI, University of Groningen, 2007.

[11] M. Sohani, Acta Phys. Pol. B 37 (2006) 231.

[12] J.W. Turkstra, R. Hoekstra, S. Knoop, D. Meyer, R. Morgenstern, R.E. Olson, Phys. Rev. Lett. 87 (2001) 123202.

[13] A. Young, KVI Annual Report, (2004) 17.

[14] N. Severijns, M. Beck, O. Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006) 991.

[15] M. van Veenhuizen, Time reversal Violation in nuclear beta-decay of $^{19}$Ne and $^{21}$Na, Masters thesis, KVI, University of Groningen, 2006.

[16] S.G. Pedersen, M. Alcorta, M.J.G. Borge, S. Brandenburg, J. Buscher, P. Dendooven, C.A. Diget, P.V. Duppen, B. Fulton, H.O.U. Fynbo, M. Huyse, A. Jokinen, B. Jonson, K. Jungmann, M. Madurga, G. Nyman, C.J.G. Onderwater, K. Perajärvi, R. Raabe, K. Rüisager, A. Rogachevskiy, A. Saastamoinen, M. Sohani, O. Tengblad, E. Traykov, H.W. Wilschut, J. Aysto , International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos - IX, PoS(NIC-IX)244

[17] L. Broussard, A.R. Young, U. Dammalapati, S. De, P. Dendooven, O.C. Dermois, K. Jungmann, A.J. Mol, C.J.G. Onderwater, A. Rogachevskiy, M. Sohani, E. Traykov, L. Willmann, H.W. Wilschut, KVI Annual Report (2005) 11.

[18] L. Achouri, J.-C. Angélique, G. Ban, B. Bastin, B. Blank, S. Dean, P. Dendooven, J. Giovannazzo, S. Grévy, K. Jungmann, B. Laurent, E. Liénard, O. Naviliat-Cuncic, N. Orr, M. Sohani, A. Rogachevskiy, E. Traykov, H.W. Wilschut, KVI Annual Report (2005) 13.

[19] H. Dehmelt, Adv. At. Mol. Phys. 3 (1967) 53.

[20] F. Reif, Fundamentals of statistical and thermal physics, McGraw-Hill, New York, 1965.

[21] M. Sohani, PhD thesis in preparation, KVI, University of Groningen.