TRIμP — A NEW FACILITY TO PRODUCE AND TRAP RADIOACTIVE ISOTOPES*

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At the Kernfysisch Vensneller Institiutr (KVI) in Groningen, NL, a new facility (TRIμP) is under development. It aims for producing, slowing down, and trapping of radioactive isotopes in order to perform accurate measurements on fundamental symmetries and interactions. A production target station and a dual magnetic separator installed and commissioned. We will slow down the isotopes of interest using an ion catcher and in a further stage a radiofrequency quadropole gas cooler (RFQ). The isotopes will finally be trapped in an atomic trap for precision studies.

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1. Introduction

Rare and short lived radioactive isotopes are of interest because they can offer unique possibilities for investigating fundamental physical symmetries [2]. Fundamental symmetries are at the basis of the Standard Model (SM). Using radioactive isotopes, limits for the validity of the SM can be explored in high precision measurements. In particular, high accuracy can be achieved, when suitable radioactive isotopes are stored in atom or ion traps [3, 4].

The TRIμP (Trapped Radioactive Isotopes: μicrolaboratories for fundamental Physics) facility at the Kernfysisch Vensneller Instituut (KVI) in Groningen, The Netherlands, is being developed to conduct such high precision studies. The local group concentrates on precision measurements of nuclear β decays [5] and search for permanent electric dipole moments [5]. We will briefly describe the complete facility consisting of a production target, a Magnetic Separator with cooling stages and atom traps. We will describe also the method of the precision measurements in β decay studies.

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2. Magnetic separator

Heavy-ion beams from the superconducting cyclotron AGOR at KVI are used to produce a wide range of products (Fig. 1). A hydrogen gas target cooled to liquid nitrogen temperature [6] and various solid targets have been employed in different types of reactions, from fusion evaporation to charge exchange. Using inverse kinematics, products are selected by the dual magnetic separator [7].

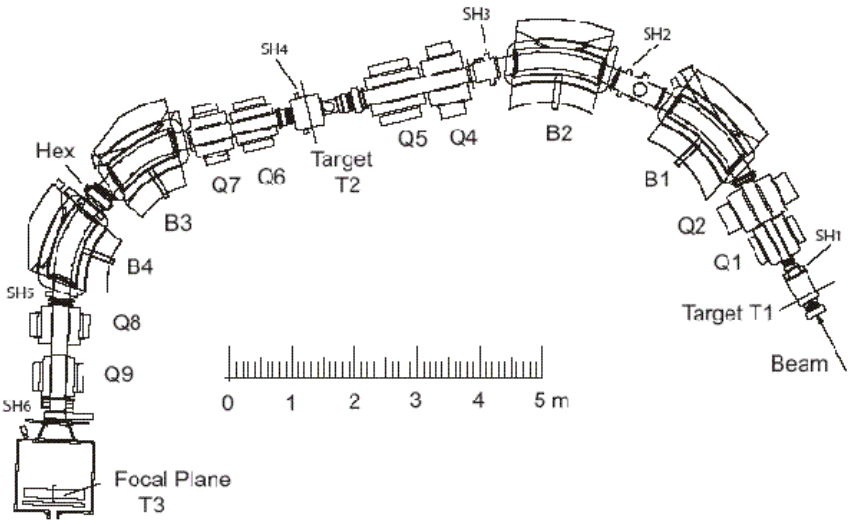


Fig. 1. Layout of the TRIμP separator.

The TRIμP separator has been commissioned. The experiments included ^{21}Na production using ^{21}Ne (43 MeV/n and 20 MeV/n). Typical rates were 3×10^3/s/pnA for ^{21}Na. Recently 10^4 /s/pnA for ^{19}Ne and 10^3/s/pnA ^{20}Na was achieved. In a first physics experiment ^{21}Na and ^{22}Mg were used to measure branching ratio of ^{21}Na β decay to the excited state and of ^{21}Ne at 350 keV [8]. The population of this state is of relevance for β–ν correlation measurements [9]. A stack of two silicon detectors registered the incoming particles and the subsequent β decay. A set of Ge detectors detected the γ ray emission following part of the β decays. The Ge Clover detectors include a BGO Compton-shield to reduce background. The systematic variation in the branching ratio, that has been observed in various experiments [10], may have been caused by a line in the ambient background from the ^{238}U decay chain (352 keV, ^{214}Pb). This line is clearly seen in the spectrum (see Fig. 2 right-hand side).

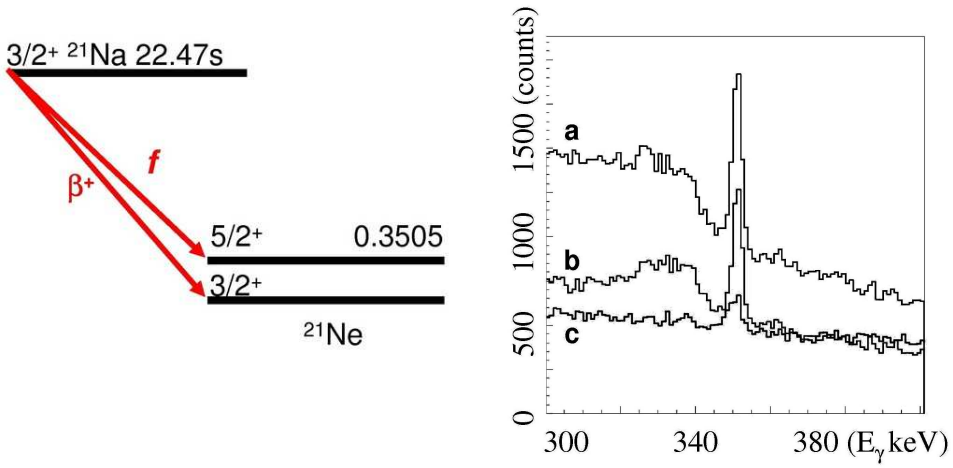


Fig. 2. Left-hand side: ^{21}Na β decay scheme. The experiment aims to determine the fraction f ending in the $5/2^+$ state. Right-hand side: Observed γ-ray spectra: (**a**) total spectrum in coincident with β decay; (**b**) Compton suppressed spectrum of (**a**); (**c**) Compton suppressed background spectrum.

3. Cooling stages

In order to perform precision measurements, radioactive ions produced and separated from the primary beam and unwanted products need to be cooled and trapped in atom traps. The cooling procedure needs to be fast and efficient in view of the short lifetime of isotopes. For light isotopes such as ^{21}Na, the high energy and fully stripped secondary beam passes through several cooling stages before it can be delivered as a low energy and singly charged ion beam with acceptable emittance. Neutralization and laser trapping is the last step to collect radioactive atoms in a well defined cold atomic cloud.

3.1. Ion Catcher

The main principle of an Ion Catcher is to stop high-energy ions in matter, *i.e.* in a gas or a solid. Electronic stopping causes fast slowing. In order to extract a low energy ion beam at the end of the ion catching process, the particles must remain ionized. Neutralization of atoms is a poisoning process which must be avoided. The commonly used techniques include gas-filled ion catchers and thermal ionizing devices.

Gas-filled ion catcher: Collisions and charge exchange processes bring ions to lower energies and charge states as long as they move trough the gas. At low energies, re-ionization and neutralization are in competition.

Cross sections of these processes are highly dependent on the energy of the ions and the relative ionization potential of the particle and the stoping gas. There are two strategies: one either relies on the survival of the particles as singly charged ions or on active re-ionization after neutralization. In the latter case extraction can be done *e.g.* after resonant laser ionization [12]. Principally, the gas-filled ion catcher can only work when the space charge built up during stopping does not hinder the extraction optics. Therefore, the efficiency for this device depends on the input ion rate [12, 13].

Thermal ionizer: A device consists of one or several metal foils that stop the beam. Atoms will diffuse out of the foils particularly at high temperature. Collisions with the surface of the foils and the cavity body can ionize these atoms. A potential electric field allows to extract ions. Choosing proper material such as W for the stopping foils and the cavity is important. The difference between the ionization potential of the beam element and the foil element determines the ionization probability and re-neutralization after each collision with the surface. Therefore, a thermal ionizer mainly works for alkali and alkali-earth elements that have low ionization potential [14].

Investigations for both types of devices were performed in the framework of the TRIμP program. Because of the priority of the experiments on Na and Ra isotopes, a thermal ionizer is under the construction and will be tested soon. A stack of W foils at high temperature has been chosen as stopper inside a hot W cavity.

3.2. RFQ cooler and buncher

A segmented radio frequency quadrupole cooler and buncher is the second stage of the cooling procedure in the TRIμP facility. Input ions coming from the thermal ionizer have an energy spread of order several eV. In the first part of the RFQ, they pass through a low-pressure gas-filled medium. A longitudinal drag voltage guides them to the exit while confined at the same time in the transverse direction by a set of radio frequency electric quadrupoles [11]. The second part of the RFQ collects ions in a Paul-trap. By switching the last electrode of the trap, a bunch of ions can be released and sent to the atom traps through an electrostatic low-energy beam line.

The TRIμP RFQ has been constructed and is commissioned. Measuring the transmission of the ions and optimizing the settings are the main issues of the commissioning.

3.3. Atomic trap

The β decay experiments at the TRIμP facility will be carried out using a set of two subsequent magneto-optical traps. The first trap is to collect atoms and bunch them toward the second trap inside a detection chamber.

The first trap is made of a small glass cavity and has wide laser beams for efficient collection of atoms. It will contain a hot Yttrium foil to neutralize the incoming ion beam. The second trap is located in a precision measurement chamber that is serving as a reaction microscope, composed of the recoil ion and beta-electron counters.

4. β decay spectroscopy

Correlations between particles from β decay manifest the symmetries and symmetry violations of the weak interaction [15, 16]. In weak interactions (a current–current interaction) several currents can contribute. These are Scalar (S), Vector (V), Axial-vector (A) and Tensor (T) currents. In the Standard Model (SM), the weak interaction is exclusively the result of V and A currents. The V current is observed in Fermi (F) decay and the A current in Gamow–Teller (GT) decay. Contribution of other currents in β decay will affect the correlations between the particles and their kinematics. Deviations from the standard V–A model indicates physics beyond the SM.

It is not practical to measure the ν particle in β–ν correlations. Therefore, one measures the correlation between the β-electron and recoil ion in order to measure the complete phase-space of the β decay. Recoil-Ion-Momentum Spectroscopy (RIMS) is an advanced method to measure the recoil ion. This method is used at KVI to study charge exchange process with the recoil energy of the order of eV [17,18]. In RIMS the recoil ions are projected with an electric field on a position sensitive microchannel plate detector (MCP) (Fig. 3). This method has been used successfully by other groups for β decay studies [9, 19]. The time of flight measurement of the recoil ion is started by observing a hit in the β-detector and is stopped by the hit on the MCP. Together with the position of the recoil ion on the MCP, this provides information about the initial momentum. A position sensitive β-detector allows to restrict the momentum of the β-electron.

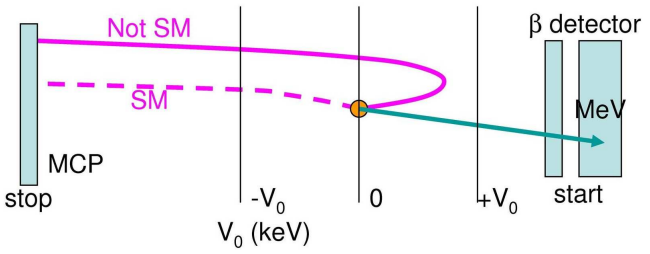
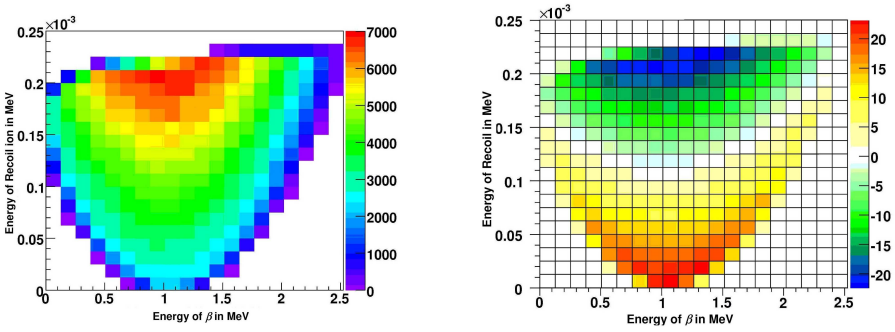


Fig. 3. Recoil-Ion-Momentum Spectroscopy sketch.

The differential rate of β decay is proportional to the 3-body phase-space and the week interaction matrix element. The general derivation of the matrix element (Eq. (1)) shows all the possible correlations between the particles [20].

$$\begin{aligned}\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim\ & 1 + a\,\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\,\Gamma\,\frac{m_e}{E} \\ & + \langle \boldsymbol{J}\rangle \cdot \left[A\,\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\,\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E}\right] \\ & + \langle \boldsymbol{\sigma}\rangle \cdot \left[G\,\frac{\boldsymbol{p}}{E} + Q\,\langle \boldsymbol{J}\rangle + R\,\langle \boldsymbol{J}\rangle \times \frac{\boldsymbol{p}}{E}\right], \end{aligned} \tag{1}$$

where $\boldsymbol{p}$ and $\boldsymbol{q}$ are momentum of the β-electron and the neutrino, $\langle \boldsymbol{J}\rangle$ and $\langle \boldsymbol{\sigma}\rangle$ are polarization of the parent nuclei and the β-electron and E is the energy of the β-electron. a, b, A, B, D, G, Q and R coefficients depend on the fundamental weak coupling constants and nuclear matrix elements. The D and R coefficients are zero if time reversal symmetry is conserved. Experimental searching for finite value of the D and R coefficients requires a sample of polarized nuclei ($\langle J\rangle \neq 0$). For the R coefficient also measuring the polarization of the electrons is required. We aim primarily at measuring D. In the initial studies without polarization, measuring a and b coefficient explores the effect of the non-SM weak currents. In general, there are two free parameters out of 9 parameters for the 3-body phase-space, including all the conservation laws and geometrical symmetries for non-polarized atoms. Therefore, one can choose any pair of the parameters to explore the β decay



(a) (b)

Fig. 4. An event distribution according to a MC simulation of energy of the recoil ion *versus* energy of the β-particle. (a) distribution for ^{21}Na β decay. (b) difference in the distribution for a 1% smaller value of a as compared to the SM prediction. The sensitivity to a is largest for β energies around 1 MeV and recoil ion energies around 0.2 MeV.

events with a 2D histogram. One choice uses the energy of the recoil ion and the β-particle as free parameters to express all the other parameters in terms of these two. A deviation of a from the SM prediction results in a change in the corresponding distribution as showed in Fig. 4.

5. Outlook and conclusion

The TRIμP facility is a user facility to deliver radioactive beams and to perform precision measurements. The TRIμP production target and the separator are functioning. A first user experiment has been already completed. Several experiments using a clean radioactive beam have been requested.

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REFERENCES

[1] The TRIμP group contributing to this work: G.P. Berg, S. De, S. Dean, O.C. Dermois, U. Dammalapati, P. Dendooven, K. Jungmann, C.J.G. Onderwater, A. Rogachevskiy, M. Sohani, E. Traykov, A. Mol, L. Willmann, H.W. Wilschut.

[2] NuPECC Report available from `http://www.nupecc.org/pub/`.

[3] K. Jungmann, *Nucl. Phys.* **A751**, 87c (2005).

[4] H.W. Wilschut, *Hyperfine Interactions* **146**/**147**, 77 (2003).

[5] K. Jungmann, in *Spin 2004*, Eds. K. Aulenbacher, T. Bradamante, A. Bressan, A. Matini, World Scientific, Singapure 2005, p. 108.

[6] A.R. Young, M. Boswell, G.P. Berg, A. Rogachevskiy, M. Sohani, E. Traykov, KVI Annual Report 2004, p. 17.

[7] 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, submited to *Nucl. Instrum. Methods* `nucl-ex/0509013`.

[8] L. Achouri, J.-C. Angélique, G. Ban, G.P.A. Berg, B. Blank, G. Canchel, P.G. Dendooven, J. Giovinazzo, K. Jungman, E. Liénard, I. Matea, O. Navilat-Cuncic, N. Orr, A. Rogachevskiy, M. Sohani, E. Traykov, H.W. Wilschut, KVI Experiment P01 and Annual Report 2004, p. 11.

[9] N.D. Scielzo, S.J. Freedman, B.K. Fujikawa, P.A. Vetter, *Phys. Rev. Lett.* **93**, 102501 (2004).

[10] See *e.g.* D.E. Alburger, *Phys. Rev.* **C9**, 991 (1974); H.S. Wilson *et al., Phys. Rev.* **C22**, 1696 (1980).

[11] See *e.g.* M.D. Lunney, R.B. Moore, *International Journal of Mass Spectrometry* **190/191**, 153 (1999).

[12] M. Huyse *et al., Nucl. Instrum. Methods* **B187**, 535 (2002).

[13] D.J. Morrissey, private communication.

[14] R. Kirchner, *Nucl. Instum. Methods* **A292**, 203 (1990).

[15] H.W. Wilschut, AIP Conferance Proceedings **802**, 223 (2005).

[16] N. Severijns, M. Beck, O. Naviliat-Cunicic, submited to *Rev. Mod. Phys.*

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

[18] S. Knoop, M. Keim, H.J. Lüdde, T. Kirchner, R. Morgenstern, R. Hoekstra, *J. Phys. B: At. Mol. Opt. Phys.* **38**, 3163 (2005).

[19] A. Gorelov *et al., Phys. Rev. Lett.* **94**, 132501 (2005).

[20] J.D. Jackson, S.B. Treiman, H.W. Wyld, *Phys. Lett.* **106**, 517 (1957).