Production and trapping of Na isotopes for beta-decay studies
Rogachevskiy, Andrey Valerievich

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2007

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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3. Review of Recent Experiments
Measuring $\beta - \nu$ Correlation Parameter $a$

The current research for deviations from the SM in $\beta$-decay mostly concentrates on measuring the $\beta - \nu$ correlation parameter $a$ (Eq. 2.10). Such a measurement might reveal scalar and tensor components in the weak interaction (Eq. 2.12). A difference between the SM $\beta$-decay and a possible non-SM $\beta$-decay can be seen, for example, from the recoil spectra of decaying nuclei (Fig. 3.1). In this section we discuss some recent experiments that attempt to measure the parameter $a$. An improved measurement of the $\beta - \nu$ correlation parameter $a$ for $^{21}\text{Na}$ will be the first precision measurement among the TRI$\mu$P activities at KVI. For reference, Fig. 3.2 summarizes the results of measurements searching for a deviation of the parameter $a$ from the SM to date.

The recoil energies of the nuclei are at most a few ten eV. Therefore the decaying samples can not be supported on solid substrates for precise measurement, as interactions with this substrate would spoil the momentum distribution of recoiling nuclei significantly. Modern experiments, therefore take advantage of atomic physics trapping techniques which have been developed over past decades. Ions can be trapped in Penning or Paul traps, for neutral atoms magneto-optical traps have been used. The latter have an advantage of shallow trapping potential wells (up to few $\mu$eV). In this chapter we will discuss the most recent experiments in this field.

3.1 TRIUMF-ISAC Potassium Experiment

At the TriUniversity Meson Facility (TRIUMF) in Vancouver, Canada, the $\beta$-decay of $^{38m}\text{K}$ is studied. The metastable isomer $^{38m}\text{K}$ is a $\beta^+$ emitter with $t_{1/2} = 0.924$ s. The $\beta - \nu$ correlation between the $\beta^+$ momentum and the momentum of the recoiling nucleus $^{38}\text{Ar}$ is measured. The isomeric state is a $0^+$ state and it decays to the $0^+$ ground state of $^{38}\text{Ar}$ by a super-allowed Fermi transition and thus allows to search for a scalar component on top of the V-A structure of the weak decay process. The isomer $^{38m}\text{K}$ is produced
Chapter 3: Review of Recent Experiments

Figure 3.1: Characteristic recoil spectra in nuclear $\beta$-decay [Sci03]. For a pure Fermi decay only the vector component contributes and $a_{\beta\nu} = 1$. For a non-SM scalar contribution we have $a_{\beta\nu} < 1$ (panel a). For a pure Gamow-Teller transition only the axial vector component contributes and $a_{\beta\nu} = -1/3$. A non-SM tensor contribution gives $a_{\beta\nu} > -1/3$ (panel b).

Figure 3.2: Compilation measurements of the $\beta - \nu$ correlation parameter $a$ for various elements. Results with precision better than 10 % are shown. Adapted from [Seve06].
on-line at the ISAC (Isotope Separator and ACcelerator) facility at TRIUMF by bombarding a target, made of many thin pressed CaO disks with total thickness 20 g/cm², by a 1 μA proton beam of 500 MeV energy. The ion beam is converted to neutral potassium atoms by stopping the beam in a hot (≈ 900°C) Zr foil. In the TRIUMF $^{38m}$K measurement the atoms of the $\beta$-decaying sample are trapped in a MOT [Gore 05]. The setup, which consists of two MOTs, is sketched in Fig. 3.3. The first MOT captures only metastable potassium and serves as a filter for other isotopes. Only a tiny fraction of the atoms determined by the Maxwell Boltzmann distribution is trapped in the MOT from a single passage through the trap’s laser beams. A standard vapor-cell technique was used, letting the untrapped atoms re-thermalize by bouncing off a hollow Pyrex cube surrounding the trap (see Fig. 3.3). This glass cube is coated with SC-77 Dryfilm to help to prevent permanent chemisorption of the alkalies [Step 94a] on the glass surface.

To avoid large background arising from the decays of untrapped atoms, the collected metastable potassium atoms are transferred to the adjacent measurement trap by a laser push beam. The transport channel has two 2-dimensional optical funnels (see Fig. 3.3). The transport efficiency is approximately 75%. The overall capture efficiency is around $10^{-3}$. 

![Double MOT setup at TRIUMF](image-url)
Figure 3.4: Monte Carlo fit to $^{38}$Ar recoil ion time-of-flight spectra. The TOF spectra are shown for three different charge states (+1, +2 and +3) (from [Gore 00]).

The measurement trap is equipped with two detectors: one for measuring the recoil ions and the other for the $\beta^+$-particles. The recoil ions are detected on a microchannel plate (MCP) triplet in a Z-stack configuration. The position of an event on the MCP is read out by a resistive anode with a resolution of 0.25 mm. The active diameter of the MCP plates is 2.5 cm. All recoils are guided electrostatically to the MCP. The positrons are measured by a $\beta$-telescope which consists of a position-sensitive Si-detector backed by a plastic scintillator. In the experiment time-of-flight (TOF) spectra of all charged recoiling ions ($^{38}$Ar$^{+1,+2,+3}$) were recorded. The $\beta$-telescope serves as a trigger to start the time of a measurement and the position sensitive MCP detector also yields the time of the arrival of the ions, which are guided and focused by static electric fields. Typical spectra are shown in Fig. 3.4. From the time-of-flight distribution of the recoil ions it is seen that several charge states are produced after the $\beta$-decay. The data are compared to Monte Carlo (MC) simulations of the process. Two independent analyses of the data were performed. In the first analysis TOF spectra of ion recoils for various positron energies were compared to a MC simulation carried out with the GEANT [Goos 94] particle physics simulation software package. In the second analysis the complete information of the positron and the recoil ion is used to deduce the momentum of the neutrino and the angle between the $\beta$-particle and the neutrino momenta. The measured angular distribution was compared to another MC simulation. Both methods agree with each other.
The value $\tilde{a} = a/(1 + b m_\beta / \langle E_\beta \rangle) = 0.9989 \pm 0.0052 \pm 0.0036$ is in agreement with the SM. It is the most precise value measured for the parameter $a$ to date. An experiment with $^{32}\text{Ar}$ decaying on a substrate at the ISOLDE facility at CERN achieved a comparable precision [Adel 99].

Since the $\beta$-decay of $^{38_m}\text{K}$ is of pure Fermi type, it sets a limit for a scalar contribution to the interaction. The result of this experiment served as an input for a fit to the data [Seve 06] by different models to extract a limit of the scalar contribution $C_S/C_V = 0.0045(127)$ which is consistent with zero.

### 3.2 The WITCH Setup

At the CERN ISOLDE facility, Geneva, Switzerland, the WITCH experiment aims to search for a possible admixture of scalar and tensor type interactions in $\beta$-decay by measuring a recoil-ion energy spectrum. This information, in principle, is sufficient to deduce the $\beta - \nu$ correlation parameter $a$ (Fig. 3.1). This experiment is in its test stage. First recoil ions of the $\beta$-decay were observed [Kozl 06], [Beck 03]. To avoid stopping of the recoiling daughter ions in the source, and to be as independent of other properties of the isotope as possible, the WITCH experiment utilizes a double Penning trap to store the radioactive mother ions. Both traps are placed in a magnetic field of $B=9$ T.

The first trap (cooler trap in Fig. 3.5) is designed for cooling a sample of radioactive ions. For that purpose Helium gas is used. The second trap (decay trap in Fig. 3.5) is placed just behind the cooler trap and separated from it.
by an aperture to allow differential pumping. The decay trap is placed at the entrance of a retardation spectrometer (Fig. 3.5). The retardation spectrometer itself is located in the region where the magnetic field reaches a plateau of \( B = 0.1 \) T. Provided that the magnetic field lines change sufficiently slow along the path of the ions, their motion can be considered adiabatic. Under this (adiabatic) condition the radial energy of the ions gets converted into axial energy while the ions are spiraling from the high to the low magnetic-field region. Due to an electrostatic retardation potential \( U_{\text{ret}} \) that is applied between the trap and the low-field region (Fig. 3.5) only ions of charge \( q \) with an axial energy

\[
E_{\text{axial}} > q \cdot U_{\text{ret}} \tag{3.1}
\]
can pass this analysis region. By counting how many ions pass the analysis plane as function of the retardation potential, the cumulative energy spectrum can be measured and compared to theory. The experiment is designed for various different radioactive isotopes (\(^{35}\)Ar, \(^{26}\)Al etc.). It aims for \( \leq 0.5 \% \) precision for the parameter \( a \). This corresponds to an upper limit for \( C_S / C_V < 9 \% \) at 95 \% confidence level.

### 3.3 The LPC-Caen \(^6\)He Experiment

The goal of an experiment at Laboratoire de Physique Corpusculaire (LPC) in Caen, France, is to improve the precision of the value of the parameter \( a \) in the pure Gamow-Teller decay of \(^6\)He, which has been measured more than 40 years ago at Oak Ridge [John 63] \((a = 0.334(3))\). The \( \beta - \nu \) correlation will be deduced from a TOF measurement and the coincidence between the \( \beta \)-particle and the recoiling ion. The \(^6\)He nucleus decays with a half-life of \( t_{1/2} = 806.7 \) ms from the \( 0^+ \) ground state to the \( 1^+ \) ground state of \(^6\)Li. A schematic overview of the set-up can be found in Fig. 3.6. The low-energy radioactive beam line LIRAT of GANIL can produce \( 3.8 \cdot 10^8 \) \(^6\)He ions/s. After passing the Radio-Frequency Quadrupole (RFQ), ions are decelerated and pulsed for injection into a Paul trap [Rodr 06]. The RFQ is needed for reducing the \(^6\)He beam emittance and also for cooling and bunching. Cooling inside the RFQ is achieved by collisions with a buffer gas. The Paul trap is shown in Fig. 3.7. It consists of two hyperbolic surfaces (end cap electrodes) and one ring electrode. Ions can be confined in three dimensions by applying an RF voltage between the end cap electrodes and the ring electrode. The advantage of using a Paul trap for ion storage is that ions are confined in such a trap without magnetic fields. Especially the open geometry of the trap allows a high detection solid angle. To detect \( \beta \)-particles, a telescope
3.4 The Berkeley $^{21}\text{Na}$ Experiment

At Laurence Berkeley National Laboratories (LBNL) in Berkeley, California, an experiment to measure $\beta - \nu$ correlations in the mixed decay of the nucleus $^{21}\text{Na}$ to its mirror nucleus $^{21}\text{Ne}$ was conducted [Scie 04]. The $^{21}\text{Na}$ nuclei consisting of a 300 $\mu$m Si-strip detector and a thick plastic scintillator is used. The recoil ions are counted with a position sensitive MCP detector. The setup is complete and in July 2006 the first data were collected [Lien 06]. The present statistics allows for a measurement of the parameter $a$ with 2% accuracy. To improve efficiency of the setup the transport between RFQ and Paul trap will be studied. The experiment aims for 0.5% precision in the $\beta - \nu$ correlation parameter $a$.

Figure 3.6: Schematic view of the LPC-Caen $^6\text{He}$ setup (from [Lien 06]).

Figure 3.7: Schematic view of LPC-Caen $\beta$-decay detection system (from [Lien 06]).
Figure 3.8: Experimental setup of the LBNL $^{21}$Na measurement (from [Scie 03]). The produced $^{21}$Na atoms are pre-cooled in a Zeeman Slower and trapped in a MOT. In the reaction microscope around the MOT cloud electrically charged recoiling daughter atoms from the $\beta$-decay are guided to an MCP detector. The $\beta$-particles are recorded in an energy sensitive scintillator counter. The $\beta - \nu$ correlation is deduced from the time-of-flight distribution of coincident $\beta^+ - ^{21}\text{Ne}$ events.

are produced by bombarding a MgO powder target with a beam of protons at a few $\mu$A current and with 25 MeV energy. The target is heated in an oven (Fig. 3.8) to release atomic sodium. These atoms are pre-cooled in a
1.2 m long Zeeman Slower. This device allows to decelerate the atoms down to velocities, at which they can be loaded into a Magneto Optical Trap. A Time-of-Flight (TOF) measurement similar to the TRIUMF $^{38}$K experiment (Sec. 3.1) is carried out to deduce the $\beta - \nu$ correlation. The Zeeman Slower increases the capture efficiency from the atomic beam by a factor of 5 to 10 as compared to loading the MOT without such slowing (see [Scie 03]). During the measurement up to $8 \cdot 10^5$ $^{21}$Na atoms were maintained in the MOT [Scie 04]. After a $\beta$-decay the $^{21}$Ne recoil ions and atoms have energies up to 230 eV in several charge states. The recoiling particles are focused by a static electric field onto a microchannelplate (MCP) detector (Fig. 3.8). The positrons from the $\beta$-decay were measured by a $\beta$—telescope consisting of an energy loss ($\Delta E$) and a total energy (E) detector. To reduce false triggers the $\beta$-detector was surrounded by a tungsten-alloy collimator, which restricts the field-of-view of the detector to a region containing the trapped cloud.\[93x542]\

The $^{21}$Ne flight time was measured with respect to the trigger from the $\beta$-telescope. The $\beta - \nu$ correlation was deduced from TOF spectra using the fact that aligned lepton momenta result in shorter flight times because of the larger nuclear recoil towards the MCP (see Fig. 2.2). Detailed Monte Carlo simulations were performed for the interpretation of the results [Scie 04].

Since $^{21}$Na decays via a mixed transition, it is sensitive to possible scalar and tensor components in the interaction. From the measured TOF of the recoil ions a value of $a = 0.524(9)$ could be extracted. This result deviates
by 3 standard deviations from the SM calculations. The largest uncertainty in this result is the error in the branching ratio $R_b$ of decays into the first excited state of $^{21}\text{Ne}$ with respect to the total number of decays. At the time of the data analysis in the Berkeley experiment this ratio was taken to be $R_b = 5.02 \pm 0.13\%$. However, there is a history of incompatible experimental results for this quantity (Fig. 3.9). This gave rise to two new measurements recently. One of them was the first physics experiment carried out at the TRI$\mu$P separator [Acho 05] which has provided a preliminary value of $R_b = 4.85(12)\%$ [Acho 06], [Jung 07]. The second experiment was performed at the TEXAS A&$\mu$M university, College Station, USA, and resulted in a branching ratio of $R_b = 4.74(4)\%$ [Iaco 06]. The most up to date values for the branching ratio do not remove the discrepancy of the parameter $a$ with the SM prediction.

3.5 Conclusion

A measurement of $^{21}\text{Na}$ $\beta$-decay correlation parameters is one of the main near future goals in the TRI$\mu$P research program. Such measurements are strongly motivated by a number of reasons:

1. The precisely measured value of the correlation parameter $a$ (Eq. 2.12) that deviates from the Standard Model, comes from a $^{21}\text{Na}$ $\beta$-decay experiment.

2. The technique to trap Na with optical traps is well established and today a standard in atomic physics laboratories. Therefore potential technical complications are minimized for Na isotopes.

3. The decay scheme involves a mixed Fermi and Gamow-Teller transition. Therefore, the time reversal violating coefficient $D$ (Eqs. 2.10, 2.17) can be measured in a polarized sample of atoms.