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To cite this article: X Fléchard et al 2007 J. Phys.: Conf. Ser. 58 431

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The LPCTrap facility: A transparent Paul Trap for the search of exotic couplings in the beta decay of radioactive $^6$He$^+$ ions

X Fléchard$^{1,3}$, G Ban$^1$, J Blieck$^1$, D Durand$^1$, F Duval$^1$, M Herbane$^{1,4}$, M Labalme$^1$, Y Lemière$^1$, E Liénard$^1$, F Mauger$^1$, A Méry$^1$, O Naviliat-Cuncic$^1$, J C Thomas$^2$ and D Rodríguez$^1$

$^1$LPC-ENSICAEN, 6 Bd du Maréchal Juin, 14050 Caen Cedex, France
$^2$GANIL, Bd Henri Bequerel B.P. 55027, 14076 Caen Cedex 5, France

Abstract. The LPCTrap facility, coupled to the low-energy beam line LIRAT of the SPIRAL source at GANIL (France), has been designed to perform in-trap decay experiments. In this contribution, we describe the experimental setup devoted to the measurement of the $E$-$Q$ angular correlation coefficient $a_{GT}$ in the pure Gamow-Teller $\beta$ decay of $^6$He$^+$. This coefficient constitutes a sensitive observable to search for exotic couplings in the weak interaction. We present the first $E$-recoil spectra obtained using this technique that will provide a new precision measurement of $a_{GT}$.

1. Introduction

Despite the remarkable success of the Standard Model (SM), for many theoretical reasons, and especially because of the large number of undetermined parameters, the existence of new physics is expected [1]. Nuclear $\beta$ decay is still of vital importance in the search of physics beyond the SM since it is a unique and relatively easy-to-access laboratory for investigations of weak interactions. In the framework of the SM, nuclear $\beta$ decay is described in terms of current-current couplings either vector or axial vector. Other current-current couplings such as scalar or tensor are permitted by Lorentz invariance but forbidden by the V-A theory of the Standard Model. The contribution of such exotic interactions is accessible through high precision measurements of unambiguously predicted properties like the $E$–$Q$ angular correlation parameter $a$. For allowed transitions, the decay rate function for measurements insensitive to all angular momentum vectors takes the following simple form:

$$W = W_0(E_\beta) \left(1 + b \frac{m_\beta}{E_\beta} + a \frac{p_\beta \cdot p_\nu}{E_\beta E_\nu}\right)$$  \hspace{1cm} (1)$$

where $W_0(E_\beta)$ is a function of the $\beta$ energy including the phase space and the coulomb interaction, $p_\beta$ and $E_\beta$ (resp. $p_\nu$ and $E_\nu$) are the momentum and energy of the $\beta$ particle (resp. neutrino), $b$ is the Fierz

3 To whom any correspondence should be addressed.
4 Present address : IKS Leuven, B-3001 Leuven, Belgium
interference term and $\alpha$ the $\beta-\nu$ angular correlation coefficient. In the case of a pure Gamow-Teller $\beta$ decay as is the case of $^9$He, a deviation of $a_{GT}$ from the Standard Model value $-1/3$ would imply the existence of tensor currents, mediated by new gauge bosons called leptoquarks [1].

The most precise measurement of the $\beta-\nu$ angular correlation parameter $a_{GT}$ was performed 40 years ago using $^6$He nuclei ($T_{1/2} = 808$ ms) with a relative precision of 1% [2], and put constraints on possible tensor contributions to less than 13%. In this experiment, only the energies of the recoiling nuclei were measured. Our goal is to improve the precision on the $a_{GT}$ measurement using the low-energy radioactive beam line of SPIRAL at GANIL, and a transparent Paul trap as a confinement device. With the radioactive ions stored nearly at rest in a small volume defined by the driving RF field of a transparent Paul trap, the measurement of the $\beta$-recoil ion coincidence spectrum can be performed in a very clean environment.

2. The LPCTrap Setup
The LPCTrap setup (figure 1) has been recently installed at the low-energy beam line, LIRAT, of the SPIRAL facility at GANIL (Caen). The $^6$He production is performed with a 75 MeV/A $^{12}$C$^{6+}$ beam at 2.0 kW impinging a $^{12}$C target. The $^6$He atoms released by the graphite target are then ionized by the SPIRAL ECR source, and extracted at 10 keV with an emittance of about 80 $\upmu$m mrad. After mass separation, a current of $10^8$ $^6$He$^+$ ions per second is delivered to the experiment. For an efficient injection of such a beam in the Paul trap, deceleration, cooling and bunching of the $^6$He$^+$ ions are required. The LPCTrap setup has then to ensure three functions: i) the beam preparation with a linear Radio-Frequency Quadrupole (RFQ), ii) the ion confinement in a transparent Paul trap, iii) the detection of the recoil ions in coincidence with the $\beta$ particles.

Figure 1. Layout of the LPCTrap setup with a horizontal cut of the Paul trap chamber and a picture of the “ring” trap (see text for details).

2.1. The Radio-Frequency Quadrupole
A linear radio-frequency Quadrupole (RFQ) filled with H$_2$ buffer-gas has been specially designed for the cooling and bunching of $^6$He$^+$. This fast and efficient method is well adapted to radioactive ions, but it was a critical point to demonstrate its applicability to very light ions [3,4]. The RFQ is mounted on a high-voltage platform to decelerate the ions down to about 70 eV prior injection. Inside the RFQ, the radial confinement is ensured by the RF field, while the ions are cooled down by elastic collisions with the buffer-gas molecules. A longitudinal DC potential guides and traps the ions in the buncher near the exit of the RFQ, where they are accumulated. A fast switch of the potential shape triggers the
extraction of the ion bunch. With the $^6$He$^+$ beam delivered by LIRAT in July 2006, a global efficiency of 5-10% was measured for a 100 Hz repetition rate of transferring the ions to the Paul trap. For the in-trap decay measurement, an optimal transfer rate of 10 Hz is required. With 10 Hz, the transmission went down to about 1-2%, because of loss processes caused by radio-frequency heating and charge exchange. After the bunch extraction, the electrostatic energy of the ions was reduced using two pulse-down electrodes located between the RFQ and the Paul trap.

2.2. The transparent Paul trap
The choice of a Paul trap was motivated by its versatility (it can be used with any ion), and the easy access to the trapping region for the detection of the decay products. A “ring” trap made of six concentric rings (figure 1) has been developed to provide full transparency in a large detection solid angle [5]. Furthermore, the application of independent voltages to the six rings allows optimization of the injection of the ions and to implement extraction schemes for monitoring the ion cloud. For the ion confinement, a RF voltage with a typical amplitude of 100 Volt peak-to-peak and a typical frequency of 1 MHz is applied to the inner rings. This Paul trap has first been tested with several singly charged alkali and rare gas ions which were previously cooled and bunched by the RFQ [6]. It has been shown that the small H$_2$ residual pressure in the trapping chamber provides an additional cooling process with a period of about 30 ms. According to simulations of the ion motion in the RF field including the collisions with this residual gas, a final temperature of the ion cloud of ~0.1 eV, and a diameter of ~1mm are expected. During the July 2006 run, 5 to10% of the ions delivered to the Paul trap could be successfully trapped and were available for the in-trap decay studies.

2.3. The Detection Setup
For the detection of the recoil ion in coincidence with the $\beta$ particle, a micro channel plate (MCP) detector with a delay line anode and a $\beta$ telescope are used. The later one is made of a thick plastic scintillator coupled to a double sided stripped silicon detector (DSSD). Both detectors are mounted 10 cm apart from the Paul trap centre in a back to back geometry (figure 1). A detailed description of the detectors with their performances can be found in [7,8]. An event is triggered by a signal in the plastic scintillator, providing the $\beta$ particle energy, and a start signal for the recoil ion time of flight (TOF). At the same time, the 128 signals from the DSSD are recorded for the $\beta$ position measurement. During 10 $\mu$s, a signal from the MCP detector is waited for. The TOF of the recoil ion is then obtained using a TAC conversion, and its position is deduced from the signals of the delay line anode. The measurement of the $a_{GT}$ coefficient can be extracted from the recoil ion TOF spectrum alone, but for each event, this detection setup gives access to three observables of the kinematics: the $\beta$ energy, the recoil energy deduced from the recoil TOF, and the $\beta$--recoil angle deduced from their positions. When the $\beta$ is detected, the RF phase in the Paul trap as well as the relative time within the duty cycle are also recorded for off-line study and control.

3. Preliminary results
During the July 2006 run at GANIL, a $^6$He$^+$ beam at 10 keV with an intensity ranging from 5 $10^7$ to $10^8$ ions per second was delivered at the end of the LIRAT beam line. About 24 hours were required for beam tuning and optimization of the RFQ, pulse-down electrodes, and Paul trap parameters. With a repetition rate of 10 Hz, the following efficiencies have been estimated: 1-2% for the RFQ, 10-20% for the first pulsed cavity, about 30% for the second pulsed cavity, and 5-10% for the Paul trap injection. The fluctuations of these efficiencies are attributed to small changes in the properties of the incoming beam and to very little drifts of the timing sequences and voltages applied to different elements of the apparatus. For each cycle, between 200 and 500 ions were successfully trapped resulting in a coincidence count rate ranging from 0.3 to 0.8 counts per second. A total of roughly $10^9$ coincidences has been recorded. Figure 2a shows the TOF distribution of the recoil ions as a function of the $\beta$ energy. This spectrum as well as the information on the $\beta$--recoil angle, the RF phase in the
Paul trap, and the delay in respect to the start of the duty cycle, will be analysed in order to study the sources of systematic errors. In a next step of the analysis, the raw TOF spectrum of the recoils displayed in figure 2b will be corrected that way and fitted by a combination of the theoretical spectra shown in figure 2c consisting of an axial component and a small admixture of a tensor one. With the present statistics, the $a_{GT}$ value should be extracted with a statistical relative precision of 1.5%.

Figure 2. $\beta$ energy measured by the scintillator as a function of the time of flight distribution of the recoil ions (a) and raw time of flight spectrum for a small fraction of the statistics (b). Theoretical curves for two values of $a_{GT}$ (c).

4. Conclusion and outlook
The data presented here will provide the first precision measurement of the $\beta$–$\nu$ angular correlation coefficient using a Paul trap and will demonstrate the efficiency of this technique. The $10^5$ coincidences obtained during the July 2006 beam time will also allow a careful study of the sources of systematic errors inherent to the apparatus. However, an order of magnitude improvement on the statistics will still be required to reach the aimed 0.5% relative precision. Several improvements of the experimental setup will be achieved in the coming year and should increase the overall efficiency. On the long term, the LPCTrap facility could be used with other radioactive species for $\beta$–$\nu$ angular correlation measurements in mixed transitions and for other in-trap decay experiments requiring the detection in coincidence of the emitted particles.

Acknowledgments
We warmly thank J Brégéault, Ph Desrues, B Jacquot, Y Merrer, Ph Vallerand, Ch Vandamme and F Varenne for their participation and assistance in different aspects of the LPCTrap experiment. This work was realised in part within the European NIPNET network (contract Nr HPRI-CT-2001-50034) and is being pursued within the TRAPSPEC JRA of the EURONS 13-activity (contract Nr 506065). D. Rodriguez acknowledges support from the U.E. under a Marie Curie Intra-European Fellowship.

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