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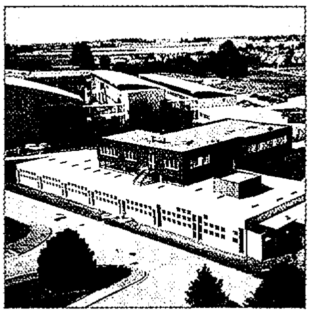

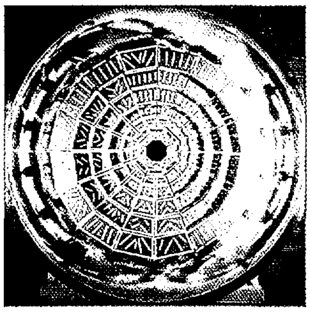

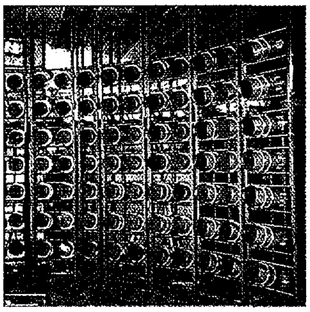

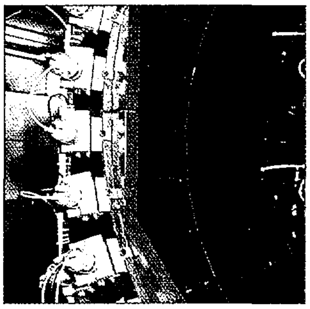

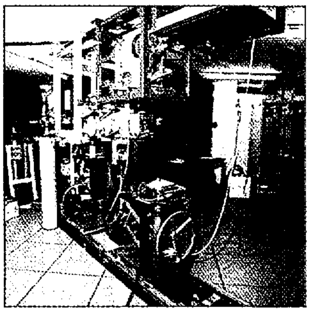

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Measurements of $\beta - \nu$ angular correlations using a transparent Paul trap

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is discussed. is considered is investigated

Abstract

~~We discuss~~ The potentiality to search for physics beyond the Standard Model by means of precision measurements of $\beta - \nu$ angular correlations in nuclear β-decay. ~~(We focus at present the attention on)~~ The possibility to reveal unexpected time reversal invariant tensor type contributions and ~~(we consider)~~ the pure Gamow-Teller decay of ^{6}He as a possible candidate. A new experimental method is proposed which is based on the use of a transparent Paul trap surrounded by detectors to directly record β-ion coincidences in an event-by-event mode. The experiment requires intense beams of radioactive nuclei like those which will become available at the Low Energy Facility near SPIRAL at GANIL. Such beams should preferably be efficiently cooled and bunched prior to their injection into the Paul trap. Estimates of the transmission figure required for the cooling and bunching system and of the measuring time to achieve a first step are presented.

June, 1999

1 Introduction

The actual theory of electroweak interactions, which is embedded into the Standard Model (SM), contains several assumptions and poses a number of problems which are expected to find explanations in further extended and unified theoretical frameworks. There is a general consensus that new particles and processes and deviations from the standard predictions should appear at some level. These are actively looked for both, at the high energy frontier, exploring new energy domains and attempting to directly materialize the particles, and at the precision frontier in atomic, nuclear and particle physics, by searching for tiny effects in the measurements of unambiguously predicted properties.

One of the many questions posed by the theory is that of the Lorentz invariants which determine the structure of the electroweak interaction. In the Standard Model the charged current semi-leptonic processes at low energies are described in terms of polar- and axial-vector currents. Other Lorentz invariants, including scalar and tensor type interactions, are excluded from the theory. The observation of an effect associated with such *exotic* interactions would therefore provide an indication of physics *beyond the Standard Model* which might for instance arise from the exchange of new charged scalar bosons or leptoquarks [1,2].

In this note we analyze the interest and the feasibility of a precision measurement of the $\beta - \nu$ angular correlation in the pure Gamow-Teller decay of ^{6}He. An new experimental method is proposed based on the use of a transparent Paul trap to confine the radioactive nuclei and to allow the direct detection of the recoiling ions. The trap is surrounded by pairs of position sensitive detectors to record the β-ion coincidences in an event-by-event mode.

2 Nuclear β-decay parameters

The most general description of the β-decay process –assuming derivative free local type interactions but making no restrictions with respect to the possible Lorentz invariants and to time reversal and parity transformation properties– is characterized by the Hamiltonian [3]:

$$H_\beta = \frac{G_F}{\sqrt{2}}\, V_{ud} \sum_i (\bar{\psi}_p \mathcal{O}_i \psi_n)(\bar{\psi}_e \mathcal{O}_i (C_i + \gamma_5 C_i')\psi_\nu) \;+\; hc. \tag{1}$$

where $\mathcal{O}_i$ $(i = S, P, V, A, T)$ are all the five possible operators allowed by Lorentz invariance. The relative strength of each term in the Hamiltonian is determined by two coupling constants, C_i and C_i', which might in general be complex. The assumption of maximal violation of parity imposes $C_i = C_i'$ and invariance under time reversal requires all couplings be relatively real. The Standard Model corresponds to $C_V = C_V' = 1$ and $C_A = C_A'$, all other couplings being zero.

The rate distribution function, calculated in the allowed approximation for non-oriented nuclei and with no sensitivity to the β polarization, contains only two relevant terms [3]:

$$W(E,\Omega_e,\Omega_\nu)dEd\Omega_e d\Omega_\nu = W_0(E)\,(\,1 + b\frac{m}{E} + a\frac{\mathbf{p}\cdot\mathbf{p}_\nu}{EE_\nu}\,)dEd\Omega_e d\Omega_\nu \qquad (2)$$

Here m, E and $\mathbf{p}$ refer to the mass, total energy and momentum of the β particle and E_ν and $\mathbf{p}_\nu$ to the energy and momentum of the accompanying neutrino. W_0 is a function of the β energy which includes the Coulomb correction due to the electrostatic field of the nucleus. The dynamic of the process is contained in the two coefficients, the Fiertz interference term, b, and the $\beta-\nu$ angular correlation coefficient, a, which are functions of the C_i and C_i' couplings defined above. For the angular correlation coefficient one can write:

$$a = a_0(1-\alpha)/(1+\alpha) \approx a_0(1-2\alpha) \qquad (3)$$

where a_0 is the Standard Model value and α contains contributions due to exotic interactions.

3 Limits on exotic couplings

In nuclear β-decay, scalar (resp. tensor) type interactions would manifest themselves most clearly in pure Fermi (resp. Gamow-Teller) transitions through small anomalies which could be revealed by precision measurements. The Fiertz interference term and the $\beta-\nu$ angular correlation coefficient are sensitive observables which have played a crucial role in establishing the Lorentz structure of the weak interaction.

Measurements of the Fiertz term have provided very tight constraints [4] on both scalar and tensor couplings as these enter linearly in the observable. The conclusions are however valid under restrictive assumptions with respect to the space-time transformation properties which are introduced in order to limit the unmanageable large number of a-priori possible couplings involved in the general phenomenological description of β-decay. When no assumptions are done with respect to parity violation on the non standard couplings the $\beta-\nu$ angular correlation coefficient provides unique constraints to complement those obtained from the Fiertz interference term but which, in comparison, are looser [4] as the couplings enter quadratically in the observable.

For pure Fermi and pure Gamow-Teller transitions the values and expressions appearing in eq. (3) are:

Fermi: $a_0 = 1,\quad \alpha = (|C_S|^2 + |C_S'|^2)/(|C_V|^2 + |C_V'|^2)$
Gamow-Teller: $a_0 = -1/3,\quad \alpha = (|C_T|^2 + |C_T'|^2)/(|C_A|^2 + |C_A'|^2)$

The present (95% C.L.) constraints on the time reversal invariant (TRI) scalar and tensor contributions deduced from $\beta-\nu$ angular correlation measurements are[1]:

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[1] The angular correlation coefficient is also sensitive to time reversal violating (TRV) contributions through a Coulomb correction term [3]. The best limit on a possible TRV tensor interaction is obtained

$$|C_S/C_V| < 0.08, \quad |C_S'/C_V| < 0.08 \tag{4}$$

$$|C_T/C_A| < 0.13, \quad |C_T'/C_A| < 0.12 \tag{5}$$

The constraints given by eq. (4) includes the recent result from the pure Fermi decays of ^{32}Ar and ^{33}Ar [2] and those in eq. (5) are obtained from the analysis of the pure Gamow-Teller decay of ^{6}He [4,7].

First, it is seen that the level of present constraints are similar for both types of exotic couplings, due to the fact that the 1σ relative error on the measured values of a is about 1% in both cases. Second, contrary to general believe, the constraints on tensor type contributions are looser than on the scalar and this state of affairs would remain so considering on going and planned experiments (see below). Third, the constraints given above allow still to accommodate sizable contributions of such interactions without affecting our conclusions on the phenomenology of semi-leptonic weak processes.

Within this model independent approach there is no particular reason to favor or disregard either Fermi or Gamow-Teller decays in the searches for signatures of new physics. The precision aim of new measurements is then at the level of $\Delta a/a = 0.01$ or better, which places severe requirements to the experiments.

4 Status of new searches and motivation

Prior to the results obtained recently in the decay of ^{32}Ar [10], the best constraints on *scalar* couplings had been deduced as a by-product of measurements which were focused in the spectroscopy of β-delayed proton decays [2]. Previous constraints on scalar couplings were a factor of about two looser than on tensor ones. Consequently, a number of projects were initiated [8, 10, 11] or are being considered [12, 13] in pure Fermi transitions, with the aim to search for effects associated with the presence of scalar contributions, to confirm the limits given by eq. (4) and eventually improve them.

Because the neutrino is never directly detected the measurements of the $\beta - \nu$ angular correlation are based on momentum conservation to deduce p_ν. Most of the early experiments [14] have deduced the parameter a from integrated time of flight (TOF) or energy measurements of the recoiling ions. A modern version of such integrated measurements was recently proposed [13], with the focus on pure Fermi and mixed transition. Later approaches were based on the observation of the Doppler or kinematic shifts or broadenings of subsequently emitted γ-rays or charged particles such as to avoid the direct detection of the recoiling ions [8, 10, 12]. A very challenging and original experiment is progressing at TRIUMF [11] where atoms of the ^{38m}K isotope are confined in a magneto-optical trap and the β-ions coincidences are recorded

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at present from a measurement of the R parameter in the decay of ^{8}Li [5]. The corresponding limit on a TRV scalar interaction is deduced from a measurement of the a coefficient in the decay of ^{33}Ar [2] and should not be mixed with limits on TRI couplings obtained under different assumptions.

directly. This technique, which in practice is limited so far to alkalis species, is also being considered by other groups.

The best statistical error obtained up to now from these experiments is[2] $\Delta a_{stat}/a = 0.005$ [9] and, in view of the number of projects presently focused on pure- or dominantly Fermi transitions, it is then likely that, in the absence of the observation of a signal, the constraints on scalar couplings will become even tighter in the near future. Meanwhile no attempts have been made to improve upon those on the tensor couplings, i.e. to take up the challenge of improving the spectacular measurement on ^{6}He [15] which has remained unequalized over more than 35 years!

5 Experimental considerations

The β-decay of ^{6}He nuclei: $^6\text{He} \rightarrow\ ^6\text{Li} + \beta^- + \bar{\nu}_e$ proceeds at 100% by a $(0^+ \rightarrow 1^+)$ pure Gamow-Teller transition to the ground state of ^{6}Li. The end-point energy is $E_0 = Q_\beta = 3.51\ MeV$ and the half-live $T_{1/2} = 0.808\ s$. The attractive aspects of this transition for measurements of the $\beta - \nu$ angular correlation were noticed very early: the decay is absolutely clean; the daughter nucleus is light so that the energy of the recoiling ion is among the highest available over the whole table of isotopes; in the atomic form the source is a noble gas which for chemical reasons is ideal for the measurements of the recoils.

To achieve a higher sensitivity than in inclusive energy spectrum measurements of recoiling ions, we propose here to extract the angular correlation coefficient a from an experiment where: *i)* the interaction between the recoiling nucleus and an eventual solid source or sample is eliminated by confining ions in a transparent Paul trap; *ii)* the full kinematics for every decay event is directly recorded.

5.1 Kinematic variables

The three body final state kinematics of the β-decay process is fully specified by two variables once the direction of one of the particles and the decay plane is fixed in space. Given for instance the β energy E, and the momentum of the recoiling ion r, uniquely fixes the angle ϕ between the β particle and the ion. In practice, because of finite energy-, time- or space resolutions of the detectors, and because all regions of the phase space are not equally sensitive to these instrumental effects, it is suitable to measure all three quantities allowing some redundancy in specific regions of the phase space.

It is useful to express eq. (2) in terms of the experimentally accessible variables defined above. Applying energy and momentum conservation one obtains, after substitutions[3]:

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[2] The result given in ref. [9] was however found to be strongly sensitive to the Q-value of the relevant transition [10]. An independent direct measurement of the ^{32}Ar mass to a few keV would be desirable to fully exploit the result without having to assume the validity of the IMME.

[3] For the purpose of the following discussion, dealing with an approximate rate estimate for such an experiment, the Fiertz term was omitted from the rate function, the ion recoil energy has been neglected in the energy balance and the Coulomb correction was not considered in the Fermi function.

$$P(E,r)dEdr = P_0\,[\,1 + a\cdot s(E,r)\,]rdEdr \tag{6}$$

where P_0 is a function of the β energy and the kinematic factor $s(E,r)$ is given by:

$$s(E,r) = \frac{r^2 - E^2 + m^2 - (W_0 - E)^2}{2(W_0 - E)E} \tag{7}$$

with $W_0 = E_0 + m$ being the maximal total energy of the β particle. These expressions can be easily modified when the ion energy ($E_r \approx r^2/2M$, M being the ion mass) or its time of flight ($t \approx ML/r$, L being the flight path) is directly measured by a specific experiment instead of the recoil momentum r.

5.2 Figure of merit

From the experimental point of view it is of interest to identify the regions of the allowed phase space corresponding to the highest sensitivity to a tensor type contribution when extracting the angular correlation coefficient from a measurement of the decay distribution. It is possible to define a figure of merit f, associated to the statistical uncertainty on a and which actually accounts on both: *i)* the fact that for any variation Δa of the correlation coefficient from its SM value, the sensitivity of the rate function to Δa is highest for $(v/c)|\cos\theta_{e\nu}| \to 1$, where (v/c) is the velocity of the β particle; *ii)* the fact that for a pure Fermi or Gamow-Teller allowed decay the statistical precision on a is driven by the rate function associated with the standard distribution $w = w_0\{1 + a_0(v/c)\cos\theta_{e\nu}\}$. Assuming that the determination of the phase space element for every measured bin does not contribute to the uncertainty on Δa, the figure of merit can then be defined as $f = (w_0 \cdot s)^2/w$.

Fig. 1a shows the distribution of f over the allowed phase space calculated from eqs. (6) and (7) as a function of the β kinetic energy and recoil momentum, for the pure Gamow-Teller decay of ^{6}He. Fig. 1b shows the contour plot which results from the projection of the figure of merit onto the allowed phase space. The dotted lines correspond to different angles ϕ between the directions of the β and the ion, in steps of 30°.

It is seen, first, that the most sensitive region of the phase space corresponds to $\cos\theta_{e\nu}$ close to unity where the rate for an exotic signal is favored while, simultaneously, that for the standard contribution is reduced. For these events the ion and the β are emitted back to back and the ion momentum compensates the sum of momenta of the β and the neutrino. Second, the sensitive region is located at about half of the end-point energy in the β spectrum, which corresponds to a region of relatively high rate.

Although these considerations are indicative to determine which is the region of the phase space to be favored in the measurement of the decay distribution its full value can only be assessed after the evaluation of the impact of the instrumental effects in the determination of the phase space elements. For example, the region defined by $\phi > 90°$ and $p > p_\nu$ deserves some attention for technical reasons. Here, given the

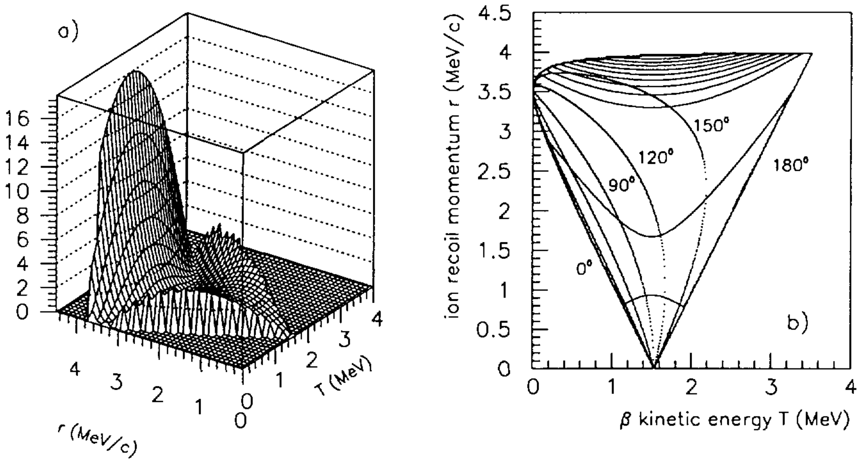

Figure 1: *a) distribution of the figure of merit as a function of the β kinetic energy and ion recoil momentum r. b) contour plot of the figure of merit projected onto the allowed phase space. The dotted lines correspond to the indicated angles ϕ between the directions of the β and the ion.*

β energy and the angle ϕ, the ion momentum has two values corresponding to the two opposite directions of emission of the neutrino, a fact which could be exploited to reduce dependences associated with the β energy measurement, provided the angular resolution is sufficient.

5.3 Setup

The experimental setup, defined partly on the basis of the results above, is schematically presented in Fig. 2. The ^{6}He ions are confined in the central region of a Paul trap which is rendered *transparent* by constructing the hyperbolic ring electrode out of thin wires which generate the shape in steps from the geometrical definition of a revolution hyperboloid.

A pair of detectors is located perpendicular to the symmetry axis of the trap. The β telescope is constituted by a first thin position sensitive detector (SSD), to record the two coordinates perpendicular to the telescope axis, followed by an assembly to measure the β energy which must be fast enough to provide the trigger. The ion detection is performed by a micro-channel plate (μCP), with position sensitive readout, which is located vis-à-vis to the β detector. In addition to the space coordinate information the TOF of the ion relative to the β trigger will be registered. We don't consider at this stage to install an electrostatic collection system to accelerate the ions from the central region to the μCP. We plan instead to perform the post-acceleration of the ion in the neighborhood of the μCP and to multiply the number of β-ion detectors pairs such as to increase the solid angle and access also other regions of the phase space.

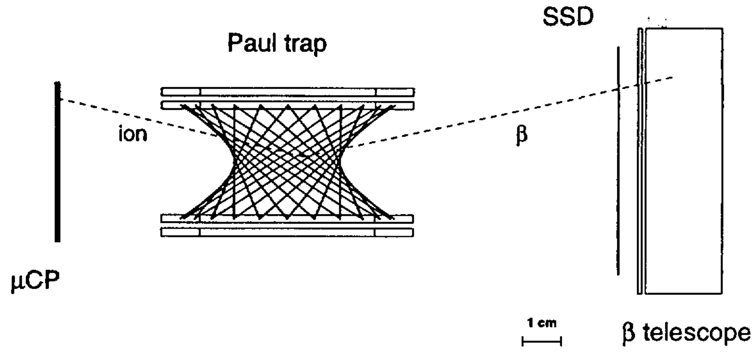

Figure 2: *Scheme of the experimental setup (see text for details).*

In summary, the informations recorded for each event (the β coordinates and energy, the ion coordinates and TOF) allow to reconstruct the decay kinematics in terms of the β energy, the time of flight relative to the detection of the β and the angle ϕ. A critical point for the determination of ϕ from the coordinates is the control of the ion cloud extension inside the trap volume. The monitoring of the cloud size in parallel, by an independent tracking system is being studied.

5.4 Measuring sequence

The ion beam has no time structure prior to the creation of the bunches to be injected into the Paul trap. The injection will be performed through one of the end-cups ("hats") electrodes made out of grids embracing an hyperbolic shape. The injection rate will result from a compromise involving: the primary ion beam current, the transmission of the cooling/bunching system, the capacity of the trap and the lifetime of ^{6}He. The quadrupole field of the trap is synchronized with the injection of a bunch and is switched at a frequency in the range $\omega_{RF} \leq 1\ MHz$.

In the absence of a trigger after a given time a new bunch is injected while the remaining confined ion cloud is ejected from the trap by applying a suitable voltage difference between the end-cups. For monitoring purposes and to reduce the background in the detection region it is suitable to eject the cloud through the end-cup at the opposite side to the injection.

The measuring sequence which is considered for the moment is presented on Fig. 3. Following a trigger, which in principle is associated with the detection of a β particle, the radiofrequency (RF) field should be switched off within 100 ns in order not to deviate the ions from their initial trajectories and not to accelerate or decelerate them on their way to the μCP. Preliminary simulations with the SIMION code [16] showed that, with hyperboloid electrodes in a standard configuration, the effect of the quadrupole field on the trajectories is negligible during that time interval even for ions with energies as low as 100 eV. However, because of the field geometry, for a given flight path between the cloud and the μCP, the TOF depends on the phase of the

RF. With typical trap operating conditions for ions with $m/q = 6\ amu/e$, the relative spread in the ion TOF can vary from few % for the most energetic ones up to infinity for those with such a low energy that cannot escape from the trap. As a consequence, in order to be able to correct for this effect it becomes necessary to sample the RF phase signal so as to distribute the events in bins of fixed phase. We recall that the most sensitive region of the phase space corresponds to ions with high recoil energy (see Fig. 1b). Monte-Carlo simulations are being improved in order to include field imperfections introduced by different wire and grids geometries.

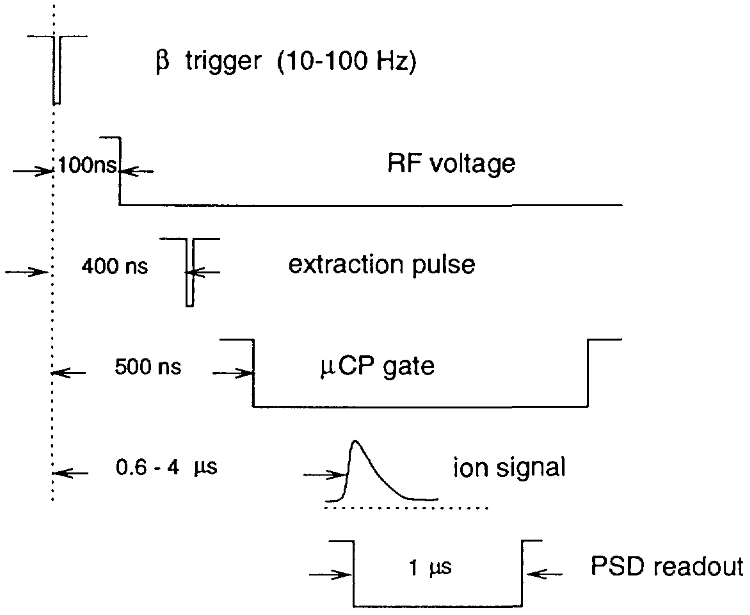

Figure 3: *Relative timing between signals involved in the measuring sequence.*

The absence of the RF field after 100 ns allows then the recoiling ion to escape from the trap without being deviated from the initial trajectory. Simultaneously, the ion cloud inside the trap starts to diffuse isotropically. After additional 300 ns the recoiling ions of interest have escaped through the transparent ring electrode and it is then possible to eject the radioactive cloud with a voltage difference between the end-cups. The efficiency of this ejection step, following the absence of the RF field over a time of 300 ns, requires detailed experimental verifications with stable light ions under different time and voltage conditions. Besides preparing the trap for the injection of a new bunch the main aim of this step is to remove the radioactive source from the sight of the ion detector prior to the gate opening used for the time of flight measurement relative to the trigger.

The opening of the gate occurs then after about 500 ns in total and remains open for about $3 - 4\ \mu s$ depending on the actual flight path. The presence of a μCP signal within the gate will trigger the readout of the devices providing the position sensitivity.

It is seen that, within this scheme, only one event per bunch can at most be recorded.

5.5 Beam handling

A critical parameter to assess the feasibility of the experiment is the transmission efficiency of the cooling and bunching system to be inserted between the ion source and the Paul trap. For radioactive ions a technique which is being implemented at several laboratories is one based on buffer-gas cooling. It requires a rod structure providing what is called a linear quadrupole ion guide [17,18]. The creation of bunches is accomplished by segmenting the rod electrodes so that different DC voltages can be applied to each segment [17]. The efficency of the buffer gas cooling technique was calculated for ions with masses larger than the mass of the buffer-gas molecules [18]. In general He is used as buffer-gas because it is light and has a high ionization potential. The question of the extension of this scheme to such light ions as ^{6}He required detailed calculations which are still presently under way. In particular, the transmission figure obtained by using H_2 as buffer-gas for light ions is under evaluation [19] and appears as a promising solution.

The design considerations of the cooling and bunching system is also strongly coupled to the parameters of the ion source producing the low energy radioactive beam. The evaluations made so far assumed the beam intensities and emittances of the ECR sources used in the starting phase of the SPIRAL facility at GANIL [20].

5.6 Precision aim and requirements

The probability of a decay event to contribute to the useful statistics is given by:

$$p_c = (\frac{\Omega_\beta}{4\pi}) \cdot f_c \cdot \epsilon_r \tag{8}$$

where $(\Omega_\beta/4\pi)$ is the solid angle covered by the β telescope, f_c is the fraction of the correlated phase space which contributes to the statistics, including thresholds, cuts and the geometrical efficiency of a pair of detectors, and ϵ_r is the absolute detection efficiency of the μCP. For a setup with a single pair of detectors the location of the β telescope can be fixed such that $(\Omega_\beta/4\pi) \approx 0.01$. For the estimate of f_c it was assumed that only events with $E_\beta > 1\ MeV$, $E_r > 300\ eV$ and $\phi > 150°$ contribute to the statistics, leading to $f_c \approx 0.12$. The probability above is then $p_c \approx 6 \times 10^{-4}$.

In a first phase of the project we aim at a precision level of $\Delta a/a = 0.01$. The number of useful events to reach such precision is about 3×10^6. If the operation is performed at low bunching repetition rate the dead times associated with the bunch injection and extraction and with the readout of detectors can be neglected. The capacity of the Paul trap is expected to be in the range of $10^4 - 10^5$ ions. The bunches are to be produced from a separated low energy beam. For example, the intensity expected for the ^{6}He beam of the SPIRAL facility at GANIL, after extraction from the target-source system, is $6 \times 10^8\ s^{-1}$ [21]. Assuming that the transmission of the cooler is only 10^{-2} (which is a very conservative figure in comparison with those expected for the linear RF ion guides under construction [17]) then the collection time of say 6×10^4 ions is $10\ ms$. If the trapping efficiency of the cold bunch is 100% the time required to collect the number of useful events above is less than 2 days of continuous running.

6 Project status and prospects

A prototype transparent Paul trap has been built and mounted at the LPC in Caen in an ultra high vacuum chamber which includes a time of flight spectrometer for monitoring purposes. The trapping of stable Mo and Al ions has been demonstrated with this prototype where the ions where obtained from the evaporation of a plasma produced by a laser impact on a target. Further injection and trapping tests are in preparation in collaboration with the CIRIL laboratory in Caen. The operating characteristics of the trap for light ions will then be studied with noble gases using an ion source. Besides optimizing the operating point of the trap, the confinement and ejection losses will also be measured.

In parallel, Monte-Carlo simulations are being carried out on the different aspects of the experiment, starting from the cooling process of the ^{6}He ions up the instrumental effects associated with the detection of the decay events.

7 Conclusions

We have explored in this note the potentiality to search for physics beyond the Standard Model by a precision measurement of the $\beta - \nu$ angular correlations in the pure Gamow-Teller decay of ^{6}He. A new method is proposed based on a transparent Paul trap to confine the radioactive ions and to directly detect β-ion coincidences in an event-by-event mode. The experiment requires intense beams of radioactive nuclei which should be efficiently cooled and bunched prior to their injection into the Paul trap. A prototype transparent trap has been built and preliminary tests with stable ions are presently being carried out. Monte-Carlo simulations are in progress to address specific aspects of the experiment. Questions regarding the transmission of the cooling techniques extended to light ions require further investigation prior to the presentation of a detailed proposal.

This work is being performed in collaboration with the GANIL laboratory in Caen, the CSNSM and Aimé Cotton laboratories in Orsay and with the EXOTRAP network.

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