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Weak interaction studies with an on-line Penning trap mass spectrometer

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Superallowed β-decays are a sensitive probe of the fundamental aspects of the weak interaction. Such decays are used to stringently test the CVC hypothesis, deduce a precise value of the weak vector coupling constant, test the unitarity of the CKM matrix and look for deviation from the V-A structure for the weak interaction. The ability to efficiently capture and store short-lived superallowed beta-emitters in ion traps will help to elucidate discrepancies in the most precise unitarity test of the CKM matrix and tighten the present limits on interactions outside the standard V-A form.

1.Introduction

Superallowed 0^+ to 0^+ β-decays are compelling because of their simplicity. The axial-vector decay strength is zero for such decays, so the measured ft values are directly related to the weak vector coupling constant through the following equation:[1]

$$Ft = ft(1+\delta_R)(1-\delta_c) = \frac{K}{M_F^2 G'^2_V}$$

where K is a known constant, G'_V is the effective weak vector coupling constant and M_F is the Fermi matrix element between analogue states. Radiative corrections, δ_R, modify the decay rate by about 1.5 % and charge-dependent corrections, δ_c, modify the "pure" Fermi matrix element by about 0.5 %.

Accurate experimental data on Q_{EC}-values, half-lives and branching ratios combined with the two correction terms then permit precise tests of the Conserved Vector Current hypothesis, via the constancy of Ft values, irrespective of the 0^+ to 0^+ decay studied.[2,3] At present, precise studies of 9 superallowed 0^+ to 0^+ beta decays[4] (fig. 1) have confirmed the CVC hypothesis at the 3 X 10^{-4} level. From these results we can deduce G'_V, which in combination with the weak vector coupling constant for the purely leptonic muon decay, provides the most precise value for V_{ud}, the up-down quark mixing element of the Cabibbo-

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Kobayashi-Maskawa (CKM) matrix. When used in a first row test of CKM unitarity, the tests fails at the two standard deviation level. This discrepancy can have many origins spanning the range from the trivial (error in the analysis, bias in the data) to the sublime (right-handed currents, physics beyond the Standard Model).

At present V_{ud} is the most precisely known element of the CKM matrix[5] but, because of its large size, also the largest contributor of uncertainty in the first row and CKM unitarity test. It is therefore vital to improve the precision of this element. The consistency of the analysis used to determine V_{ud} can be tested by improving the quality of the existing 0^+ to 0^+ data set but most importantly by adding a few specific cases to the data set particularly sensitive to the nuclear structure dependent corrections. These are considered by many to be the weakest link in the superallowed 0^+ to 0^+ studies. In particular, the corrections[2,6,7] calculated for the next heavier superallowed emitters ^{62}Ga, ^{66}As and ^{70}Br are unusually large and the shell-model space used is different from the previous nine cases. If the corrected Ft values for the three suggested new cases agree with the previous nine case then the confidence in the CVC hypothesis and the charge-dependent correction calculations would receive a significant boost.

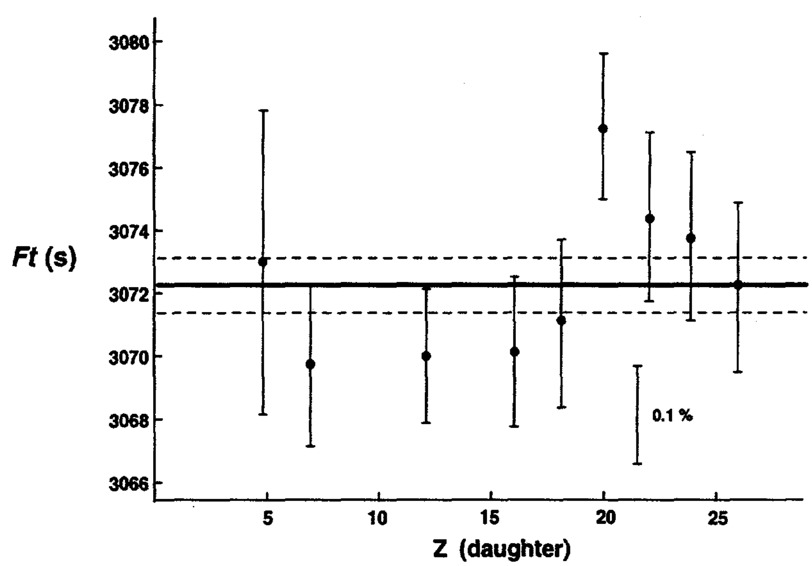

Figure 1. Ft-value for the 9 precisely determined 0^+ to 0^+ emitters

The measurements necessary include precise half-lives, branching ratios and Q_{EC} values. The weak branching ratio and half-life measurements both require large sample activity but the extrapolation of the techniques used so far to these new cases is otherwise straightforward. The high-precision Q_{EC} values on the other hand cannot be obtained for these new cases with the threshold type reactions used so far because of the lack of stable targets as these isotopes are further from stability. The Q_{EC} values will be obtained by high-precision mass measurements on the parent and daughter isotopes with the CPT mass spectrometer, an on-line Penning trap mass spectrometer designed for this task.

2.High-accuracy mass measurements with the CPT mass spectrometer

The Canadian Penning Trap (CPT) Mass Spectrometer Facility[8] is a powerful tool designed for the precise determination of the atomic masses of both stable and unstable nuclides. The device was designed and constructed by a collaboration involving groups at the TASCC facility in Chalk River, the University of Manitoba and McGill University and is presently located at the ATLAS facility of Argonne National Laboratory.

The main functional components of the CPT mass spectrometer are depicted in figure 2 and consist of a laser ion source and two ion traps. The first ion trap is a radio-frequency quadrupole (RFQ) trap used for accumulation and preparation of an ion sample obtained from the laser ion source or an external source. The second trap is a precision machined Penning trap which is located inside the highly homogeneous 5.9 Tesla field of a superconducting solenoid. This trap is fed by the RFQ trap and is used to determine accurately the mass of the stored ions by measuring their cyclotron frequency ω_c = qB/m in the field B of the superconducting solenoid.

The laser ion source provides the CPT with ions of stable isotopes either for calibration of the device or actual precision measurements. Unstable isotopes are injected in the device from a transfer line connecting it to the Enge-split-pole magnet operated in the gas-filled mode. The unstable isotopes produced at the target location of the Enge-split-pole magnet, are separated from the primary beam and other reaction products before being stopped in a helium gas cell located at the focal plane of the magnetic spectrograph. The gas cell is continuously evacuated through a segmented linear RFQ structure which extracts the ions from the gas and leads them to a linear trap where they are accumulated before being transported to the RFQ trap by a transfer line at low potential.

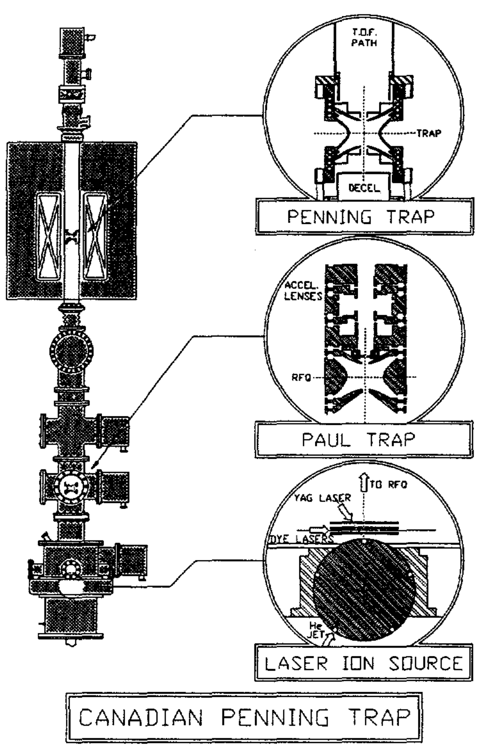

Figure 2. Schematic view of the CPT spectrometer

The performance of the spectrometer and its injection system are tailored to the experimental needs of a program on precise Q-value measurements of superallowed 0^+ to 0^+ emitters. The CPT is designed to obtain mass measurement accuracy of about 10^{-8} - 10^{-9} for unstable isotopes. The injection system has a fast cycling time allowing isotopes with half-lives down to the 50-100 ms time range to be injected into the CPT. The injection system has recently demonstrated a capture efficiency of 10% for fission products and isotopes produced on-line by fusion-evaporation reactions, orders of magnitude higher than previous results obtained in on-line conditions for ion or atom traps. The fast moving radioactive ions produced in the nuclear reactions at ATLAS are first stopped and cooled in this device before being extracted in a pulsed fashion and transferred to the new ion trap with essentially 100% efficiency These high efficiency and short half-life capabilities are essential for the studies of the heavier superallowed emitters.

The measurement program on superallowed β-emitters will follow a three-pronged approach: A) improve the knowledge of the Q-value for the cases where the contribution to the uncertainty of the corrected Ft value (eq. 1) from our imperfect knowledge of Q- values is significant, B) extend the range of superallowed emitters to heavier cases to test the δ_c calculations and C) perform very high-accuracy measurements on a few selected candidates to test calculated atomic corrections which are present in the data set but that no experiment has the possibility to confirm up to this point. An absolute accuracy of better than 0.1 keV ($\Delta m/m \sim 4 \times 10^{-9}$) will be necessary for topic C. In order to achieve this level of accuracy possible systematic biases in the CPT spectrometer will need to have been fully explored and characterized with stable masses. Topic B involves high accuracy mass measurements on isotopes along the N=Z line with half-lives below 100 ms requiring the level of performance recently demonstrated by the RF gas cooler injection system.

3.Angular correlations in the β-decay of stored radioactive ions

Precision measurements of the beta decay of superallowed emitters can provide information not only on the strength of the weak interaction but also on the nature of the interaction itself via the correlations between the momentum and spin directions of the particles (β, neutrino and recoil) emitted in the decay. Such experiments however require well defined sources essentially free of backing to minimize scattering effects and allow the detection of the slow recoiling nucleus. The ideal source would require that a high-purity radioactive sample be "floating", well localized, in a vacuum system. This can be realized by capturing radioactive isotopes produced at an on-line facility into storage devices such as ion or atom traps. Laser traps have been suggested as confinement device for such experiments but at present the very high trapping efficiency required limits their usefulness to the few cases where the candidate radioactive isotope is an alkali. Ion traps, on the other hand, are not sensitive to the atomic structure of the isotope to be captured and can be used for essentially any atomic species. They could then provide a universal source confinement method for these experiments.

Ion traps use electromagnetic fields to confine charged particles in space. It was perceived at first that the confining fields would be a limitation for ion traps in the proposed application since the fields will perturb the trajectories of the charged leptons and recoils. It turns out however that upon closer analysis two approaches remove (or use) this limitation: 1) the confining fields can be used to ones advantage in many geometries where the channelling of the charged particles along the field lines allow detectors to be located farther from the source, without loss in efficiency, limiting multiple scattering and other difficulties related to experiment performed in close geometry, 2) observables not sensitive to the confining fields can be studied.

A new ion trap system suited to angular correlation measurements in nuclear beta-decay is being built at the CPT facility. It will consist of a linear RF trap with a highly open geometry and a cylindrical Penning trap in a large bore superconducting solenoid with long homogeneous field region. The ions will be first injected into the linear RF trap whose open geometry will allow the installation of either a detection system used for the angular correlation measurements where no magnetic field is required (such as the search for scalar interaction in the decay of ^{14}O outlined below) or other hardware required for the preparation of the samples (e.g. polarization or purification and selective cooling of the ion cloud using techniques first developed for high-accuracy mass measurements on trapped unstable isotopes) before injection into the Penning trap. For experiments where magnetic field confinement of the charged particles provides significant advantage, the ions will be transferred, after suitable preparation, from the linear RF trap to the Penning trap where experiments with much simplified detector systems are possible because of the "channelling" of the emitted particles. .

Radioactive ions will be injected into this trap system using the RF gas cooler recently installed behind a large magnetic spectrograph at the ATLAS facility for the injection of radioactive ions in the CPT mass spectrometer. They will be further purified and cooled in the trap system before and/or while the measurement takes place. The high transfer efficiency and purification of the sample that will be available with this new system are key in reducing possible sources of background close to the trapping volume.

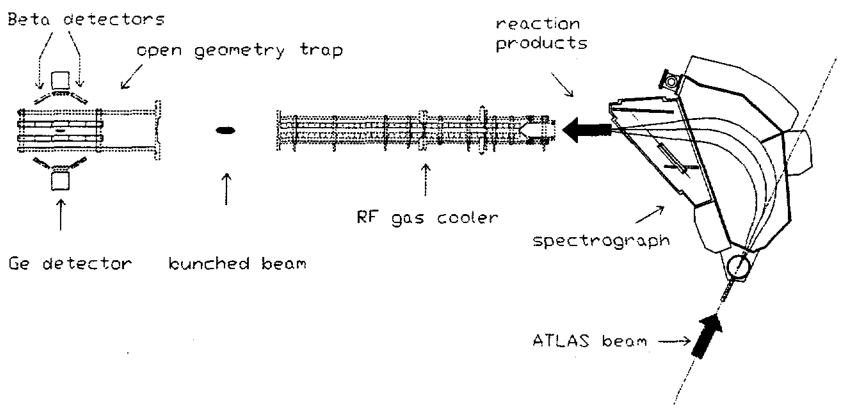

Figure 1. Suggested layout for an experiment to search for scalar interactions in the β-decay of ^{14}O.

The trap system is capable of measuring correlation coefficients for most superallowed beta-decay candidates. The first measurements contemplated for this new device will involve simple sample preparation on candidates with high sensitivity to new physics. A simple observable sensitive to new interactions, without requiring polarization of the source, is the so-called beta-neutrino angular correlation. Since the neutrino cannot be observed directly, this measurement requires gathering experimental information on the low-energy recoiling nucleus. The experimental signature comes from simple kinematics with the nucleus recoiling with higher velocity if the positron and neutrino are emitted preferentially in the same direction. The main difficulties previous such measurements had to face are overcome by the absence of source backing when an ion trap is used to confine the source. A radioactive isotope decaying via a pure Fermi 0^+ to 0^+ superallowed transition is an ideal first candidate providing high-sensitivity to possible scalar currents and most straightforward theoretical interpretation of the results. Preliminary numerical simulations indicate that the superallowed decay of ^{14}O is a prime candidate. In this case, the momentum of the recoiling nucleus can be determined from the Doppler shift of the beta-delayed gamma-ray deexciting the recoil from the excited 0+ state populated by the superallowed beta-decay to its ground-state. The measurement then involves a simultaneous detection of the gamma-ray and the beta particle to determine the gamma-ray Doppler shift as a function of the angle between the directions of emission for the beta and gamma-ray. This approach, which involves measuring a relative shift in gamma-ray energy, relaxes greatly the requirements that must be fulfilled by the detector systems, eliminating many sources of systematic errors. The maximum gamma-ray energy shift is of about 800 eV between both directions for the emission of the beta particle. An ^{14}O sample stored in the RF linear trap surrounded by a detection system composed of two high-resolution Ge detectors together with a beta-detector array would allow us to perform a measurement exceeding 0.5% accuracy, a factor of about 50 improvement for that particular decay and a significant improvement on the current published limits on scalar interactions. A similar type of experiment could be carried out on superallowed pure Gamow-Teller decays to improve the limit on tensor interactions. A second series of experiments requiring polarization of the radioactive sample would be pursued to look for example for the presence of right-handed currents in mixed Fermi-Gamow-Teller decays. These experiments would best be performed with the radioactive sample (^{39}Ca for example which has a high sensitivity to such effects while being easily laser polarizable in the ionic state) captured in the Penning trap and a two detector system, one at each ends of the solenoid. The detection system in such experiments becomes quite inexpensive with each detector having 2π detection efficiency while being far enough from the sample to eliminate (or make tractable) backscattering events.

4.Conclusion

The CPT spectrometer, in its new home at the ATLAS facility, will be a powerful tool for the study of atomic masses. The sensitivity of the technique, its high resolution and the ability to make accurate (10^{-9}) measurements amongst all elements will provide us with an opportunity to build a broad, panoramic view of nuclear masses across the table of isotopes. Precise measurements of the energy available for superallowed beta decays become possible with this instrument. Such measurements can improve the precision of the most poorly known cases, test the atomic corrections applied in reaction Q-value studies and extend our knowledge to previously inaccessible cases.

In addition to mass measurements the instrument provides a pure source of ions, from both stable and unstable nuclides, floating at rest in vacuum. Studies of beta-decay asymmetry of trapped ions, which provide tests of the standard model, also become possible. Thus the present CPT program and its future extensions should allow significant advances in low-energy weak interaction studies.

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