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LETTER OF INTENT

to the ISOLDE and Neutron Time-of-Flight Committee

Nuclear electron capture in few-electron systems

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1 Motivation

During the last decade ion storage rings have allowed experiments to be performed on highly charged ions, see [1] for an overview of the many physics results. Recently these studies were extended to the study of nuclear electron capture decays of hydrogenlike ions [2] and a careful experiment performed with only a few ions present in the storage ring at any given time has turned out to give a clear non-exponential distribution of the decay times [3]. There is as yet no consensus on the interpretation of this surprising finding, some theory papers have argued that this is a signature of neutrino-flavour mixing [4] whereas others have contested this suggestion [5]. To resolve this question more experimental data are needed. At present the non-exponential decay, an oscillation with period about 7 seconds on top of an exponential decay, has been observed for hydrogenlike ^{140}Pr and ^{142}Pm ions at the 99% confidence level [3]. More experiments are planned at the ESR storage ring at GSI to increase the confidence in the result and to search for a possible mass dependence of the oscillation as predicted by the neutrino interpretation. The aim of this letter of intent is to explore the possibility of testing for the effect in very different experimental circumstances.

2 A trap experiment and its advantages

The electron capture decaying nuclei will be produced as usual in the ISOLDE targets, bunched in ISCOOL and/or REXTRAP, transferred to REXEBIS where they will be charge bred and finally let to an ion trap where the decay will be monitored. We propose to use the WITCH apparatus for the decay. To see how such an experiment would differ from the storage-ring experiments, we go through each of the stages in more detail. One of the lessons from the ESR experiment is that it is crucial to have a unique decaying state, since the measured oscillation period would convert to an energy difference between two "beating states" of only about 10^{-15} eV.

2.1 Production

In order not to lose phase coherence (and thereby wash out the oscillation signal) the experiment needs a well defined time zero, the time where the decaying state is formed. This is provided automatically in the ESR where the radioactive isotope is created essentially at the same time as the one-electron atomic state is formed. The production of the radioactive isotope is also at ISOLDE done at a well-defined time, whereas the one-electron atomic state is only created some milliseconds lated in REXEBIS. If the oscillation period remains about 7 seconds, this will not be a real problem; if the oscillation period turns out to be shorter, we may take advantage of this by preparing the one-electron atomic state in two different ways: in the first the one-electron state is taken directly out of REXEBIS and the oscillation signal may therefore be decreased, in the second the zero-electron state is chosen from EBIS and the electron added before entering the decay trap – this gives again a well-defined time zero. This may be an elegant cross-check of the signal.

2.2 Storage

In the trap environment there will be much less interaction with the ion than in a storage ring. In the ring the ions are constantly monitored with Schottky electrodes and they are furthermore cooled by electron cooling (after stochastic pre-cooling). The continuous observation and interaction with the ions in the ESR could be a challenge for a detailed theoretical description of them. The ions will of course also interact with the confining electromagnetic fields in the trap, but the environment the ion sees will be static in contrast to the storage ring. We shall return to this in the next section.

There are several technical modifications needed that will be studied during the coming months. The layout of the beamline connecting the REX mass separator with WITCH must be done and sufficient vacuum conditions established to allow the multiply charged ions to survive for several seconds. The ions must furthermore be cooled [6, 7] before being let into the decay trap – various choices for the cooling procedure are currently being discussed.

2.3 Observation of decay

Currently in the ESR the daughter ions need to be cooled for hundreds of milliseconds before they can be seen in the Schottky frequency spectrum. The observation in the trap will in contrast be immediate and direct. Furthermore there are no problems in detecting, say, thousand decays per second in the trap whereas the ESR experiment had to be performed with only a few ions in the ring simultaneously in order to obtain a clear signature of the decay. Our count rate will therefore be signicantly larger, which allows for quicker measurements and a more thorough investigation of systematic effects.

With the WITCH spectrometer the energy spectrum of the recoil ions is measured. The mono-energetic recoils from EC decays will show up as a peak that is, in the mass region we will focus on at ISOLDE (i.e. between about $A = 20$ and $A = 40$), typically about 80 eV more energetic than the endpoint energy of the recoils from β^+ decays. With the about 1% energy resolution of the spectrometer, which is determined by the ratio of the magnetic field values B_{max} (in the Penning trap region) and B_{min} (in the retardation region), these energies will be clearly separable. The energy resolution of the spectrometer will be tested as soon as possible with ^{144}Eu (10.2 s; EC in highest energy branch = 9.7%, β recoil endpoint = 125 eV, EC recoil peak position = 149 eV) or ^{140}Pm (9.2 s; EC in highest energy branch = 9.9%, beta recoil endpoint = 116 eV, EC recoil peak position = 140 eV) that were selected for this [8]. A random and flat beta particle background will be present under the recoil energy spectrum, the amplitude of which can be determined in the energy region above the EC recoil peak.

One may worry that the ion-ion interaction could disturb the uniqueness of the decaying state and that it would be crucial to have only a few atoms present for the oscillations to be observed. It seems unlikely that this would be the case since the ions are subjected to strong confining potentials in both storage environments, as well as the aforementioned interaction with the diagnostic and cooling devices in the storage ring case, but we should point out that the trap experiment of course can be run also at a very low countrate at the expense of longer running times.

2.4 Decaying isotope

An efficient detection of the Schottky frequency signal requires an ion with charge above 50 and the ESR experiments therefore proceed with isotopes from the upper half of the table of isotopes, the first runs being done with ions of mass $A = 140$ and 142 [3]. Our proposed experiment would also be limited in the range of isotopes, since the energy of the electron beam in REXEBIS only allows one-electron atoms to be made up to around Ca ($Z = 20$). If the oscillation period scales inversely with the mass of the decaying isotope (as suggested in [3]) it may turn out to be closer to one second for the lighter isotopes. Suitable candidates should therefore have halflives in the range of one second to one minute. Combining this with the production yields at ISOLDE leaves ^{19}Ne and ^{35}Ar as clear candidates. For ^{19}Ne the β recoil endpoint is 203 eV, with the EC recoil peak position at 296 eV and a EC/β^+ fraction = 0.100(1) % for the neutral atom. For ^{35}Ar the β recoil endpoint is 453 eV, with the EC recoil peak position at 546 eV and a EC/β^+ fraction = 0.073(1) %. Our currently preferred isotope is ^{19}Ne with a halflife of 17.2 s (for the neutral atom) and a 99.99% branch to the ground state of ^{19}F. It is of course an advantage to have most decays proceeding to one final state; this will happen naturally for many light isotopes just "above" the valley of stability where most strength is collected in the IAS transition.

3 Comments and possible generalizations

As mentioned above it is important to have a unique decaying state. In case one needs at one point to study the role of the hyperfine structure in the initial and final states, experiments could also be foreseen for ^{34}Ar (a 0^+ to 0^+ transition, halflife 0.84 s). Another check that could be valuable to perform, should an oscillation be found, would be to look at the decays of heliumlike atoms. Since the preparation of these only needs the removal of electrons from the L-shell and upwards, REXEBIS could deliver a larger range of isotopes and one may envisage finding an isotope that could be studied both at ISOLDE and at ESR/GSI.

If the oscillation seen at ESR is confirmed, but the neutrino physics explanation turns out to be non-tenable, it will be important to check for alternative explanations. All natural energy scales are much higher than the 10^{-15} eV in question here, but one may try to look for dynamical effects due to the interactions between the ion and the timevarying fields it sees in the storage ring. This type of effects may be investigated in detail in the trap environment where excitation pulses could be added and kept under experimental control. We note that millisecond oscillations on top of an exponential decay have been observed for anionic gold clusters stored in a Penning trap [9] and tentatively attributed to the magnetron motion of the ions in the trap. Although the physics explanation for the non-exponential decay may well be rather different in the two cases, it demonstrates the complexity of the motion of the stored ion and the rich phenomenology it may give rise to.

4 Summary

The intriguing results from the ESR storage ring at GSI need independent confirmation, whatever the physics explanation may be: neutrino physics, subtle effects of the confining environment on the stored ion, or an as yet undiscovered effect. Our proposed experiment at REXEBIS and WITCH would give important independent experimental information on the process of nuclear electron capture in few-electron systems. We request that off-line beam time is used to test REXEBIS charge breeding to zero- or one-electron systems.

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