EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

MEASUREMENT OF THE β ASYMMETRY PARAMETER IN ^{35}Ar DECAY WITH A LASER POLARIZED BEAM.

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Abstract With this proposal we request beam time for the first two phases of a project that aims at measuring the β asymmetry parameter of the mirror-β-decay branch in ^{35}Ar using an optically polarized Ar atom beam. The final goal of the experiment is to measure this parameter to a precision of 0.5%. This will allow the most precise determination of the V_{ud} quark mixing matrix element from all the mirror transitions with an absolute uncertainty of 0.0007. The proposal will be presented in phases and we ask here 11 shifts (7 on-line + 4 off-line) for phase 1 and 15 shifts (6 on-line and 9 off-line) for phase 2. Phase 1 aims at establishing the optimal laser polarization scheme as well as the best implantation host for maintaining the polarization. Phase 2 aims at enhancing the beam polarization by removing the unpolarized part of the beam using re-ionization.

Requested shifts: 26 shifts (with 13 requiring protons), split into 2 runs over 1 year

1 Introduction

Over the years, a large set of measurements and theoretical calculations have been performed, leading to the corrected $\mathcal{F}t$-values for the superallowed pure Fermi β transitions. The weighted mean from these values leads to a high precision value for the V_{ud} quark mixing matrix element, i.e. $V_{ud} = 0.97425(22)$ [1]. In combination with significant advances in the determination of the V_{us} matrix element from Kaon decay [2], this has led to a very high precision test of the unitarity of this matrix and subsequently to strong limits on several types of new physics beyond the Standard Model [3, 4].

To further improve on the precision of V_{ud} obtained from these measurements the set of input data is continuously being improved, thereby also extending the data set with new superallowed transitions [5]. In addition, new studies are being performed to gain a better understanding of the isospin symmetry breaking corrections δ_C, which is one of the least well known theoretical corrections needed to extract V_{ud} from the corrected $\mathcal{F}t$-values.

Another source to address V_{ud} is provided by the mirror β transitions between isospin T=1/2 states [6]. Here, similar to the Fermi β-transitions, one has to determine the $\mathcal{F}t$-value [7] but one has also to measure the ratio between the Fermi and the Gamow-Teller strengths, by e.g. performing a β-ν correlation or β asymmetry measurement. Using data readily available in the literature from experiments that were not originally performed for this purpose, a value of $V_{ud} = 0.9717(17)$ was obtained [6]. Dedicated studies of these mirror-decays can significantly improve the precision on this value, and at the same time contribute to the ongoing study of the δ_C corrections, which are often larger for the mirror-β-transitions. New measurements leading to corrected $\mathcal{F}t$-values for mirror β transitions have already been reported [8, 9, 10, 11]. β-ν correlation measurements with ^{19}Ne and ^{35}Ar have recently been performed at GANIL [12, 13] and more measurements are planned [14]. However, recently **a critical survey [15] has shown that the measurement of the β asymmetry parameter, A, in the mirror β decay of ^{35}Ar to the ^{35}Cl ground state (gs.) is the most sensitive among all β-ν correlation and β asymmetry parameter measurements for the mirror β decays**. Indeed, a measurement of the asymmetry parameter A in the gs. to gs. positron decay of ^{35}Ar, with a relative precision of 0.5%, would yield a highly competitive value for V_{ud} which will be the most precise among mirror transitions.

A collaboration was therefore set up to pursue such a measurement at ISOLDE, where the required intensity and beam purity, as well as the means to polarize ^{35}Ar by collinear optical pumping are readily available.

2 Measuring principle of the A_{gs} asymmetry parameter.

To measure an asymmetry parameter in nuclear β decay, the nuclei have to be spin-polarized. The method of optical pumping with a circularly polarized laser beam will be used. It is foreseen to implant the laser-polarized ^{35}Ar beam provided by the future VITO beam line into a suitable crystal host surrounded by a holding magnetic field, in order to maintain the polarization during the nuclear lifetime $\tau(^{35}\text{Ar}) = 1.8$ s.

Assuming cylindrical symmetry around the nuclear polarization axis, the transition rate for vector polarized nuclei decaying via positron emission, is given by [16]:

$$W(\theta) = W_0 \left(1 + \frac{v}{c} J A cos(\theta)\right) \tag{1}$$

where W_0 is the transition rate in the absence of polarization, A is the asymmetry parameter of the β^+ decay, J is the polarization of the nuclei, θ is the angle between the positron momentum and the nuclear spin, and v is the velocity of the emitted positron. Using detectors located close to the $\theta = 0$ and π positions and a reversible nuclear polarization ($\pm J$) the following experimental asymmetry can be defined:

$$\mathcal{A} = \left\langle \frac{v}{c} \cos(\theta) \right\rangle JA = \frac{R-1}{R+1} \tag{2}$$

with

$$R = \sqrt{\frac{N(0,+J)N(\pi,-J)}{N(0,-J)N(\pi,+J)}} \tag{3}$$

where $N(\theta, \pm J)$ are the numbers of counts detected in each detector-polarization combination. The $\left\langle \frac{v}{c} \cos(\theta) \right\rangle$ factor accounts for experimental corrections and requires a careful evaluation of the geometry.

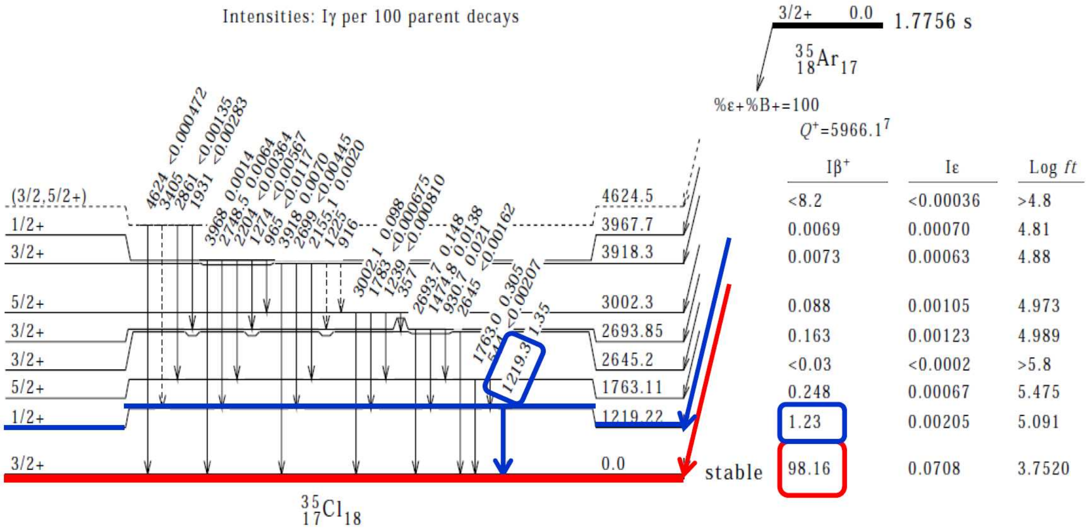

Figure 1: Decay scheme of ^{35}Ar with the relevant branches indicated in color.

In order to avoid the determination of the factor $\left\langle \frac{v}{c} \cos(\theta) \right\rangle$ with high precision, we will use the method employed in [18, 19]: measure the ratio of the experimental asymmetry in two branches of the ^{35}Ar positron decay (Fig. 1):

$$\frac{A_{gs}}{A_{ex}} = \frac{\left\langle \frac{v}{c} \cos(\theta) \right\rangle_{ex} \mathcal{A}_{gs}}{\left\langle \frac{v}{c} \cos(\theta) \right\rangle_{gs} \mathcal{A}_{ex}} \tag{4}$$

As the nuclear spin polarization cancels out from this ratio, and because the asymmetry parameter of the pure Gamow-Teller transition to the first excited state of ^{35}Cl is exactly known ($A_{ex} = 1$), the precision on the asymmetry parameter of the gs. to gs. decay will depend on the following uncertainties:

- the statistical and systematic error on the two experimental asymmetries.
- the precision on the calculated ratio of the geometrical and kinematic factors.

Although for a given transition the geometrical and kinematic factor can be determined to the 1-2% level of precision with state-of-the-art Monte-Carlo simulations (in which the Leuven team has specialized during the last years [17]), the ratio between these factors for two decay branches can easily be determined to a much higher precision. Based on earlier simulations and experimental verifications, a precision better than 0.5% can easily be achieved for this term.

Because the transition to the first excited state has only a 1.23% branching ratio, the precision on A_{gs} will be limited by the statistical and systematic error on the $\mathcal{A}_{ex}$ measurement. Therefore, the experimental apparatus should be designed such that the efficiency to detect coincidence events between the positron and the delayed 1.219 MeV γ-ray is maximized. The design study for the β-γ coincidence detection setup is currently in progress and detailed MC simulations have been performed showing that the 0.5% statistical precision on the measurement of the gs. to gs. asymmetry parameter can be achieved within a reasonable beam time. Using the current state of the detection setup design, assuming a 10^6 decay/s for the implanted ^{35}Ar and a $J = 0.3$ polarization, a data taking duration of less than 24 h would be enough to collect the required statistics. With a more pessimistic scenario where only 5.10^5 decay/s with a $J = 0.2$ polarization are achieved, the data taking extends to 5 days which remains a reasonable duration.

3 Implementation using the VITO beam line at ISOLDE.

The actual performance of the VITO beamline to provide a polarized ^{35}Ar beam and the efficiency to maintain the nuclear polarization during the implantation will play an important part in order to reach the desired sensitivity and precision. For this reason, several steps in the experiment have to be developed and optimized. Therefore the proposal will be presented in phases and beam time will be requested for each phase separately in the forthcoming years. In the current stage we ask for beam time for phase 1 and phase 2, to run in 2015.

- Phase 1: study of polarized ^{35}Ar in different host materials using the optical pumping and β asymmetry detection setup at COLLAPS.
- Phase 2: optimizing the ^{35}Ar polarization by state-selective and laser re-ionization at the VITO beam line.
- Phase 3: proof of principle experiment, with the full β-γ coincidence setup at the VITO beam line.

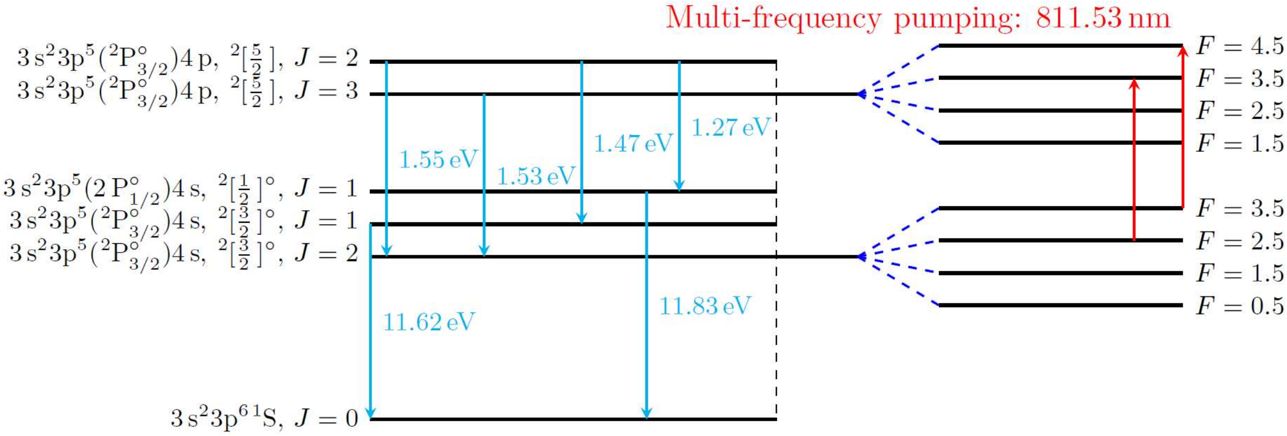

Figure 2: Levels of Ar I and hyperfine levels of the transition that will be used for the optical pumping. Decays are indicated by blue arrows. The transition that will be used for optical pumping is indicated in red. We plan to use multi-frequeny pumping between the different hyperfine levels to enhance the polarization.

- Phase 4: final data taking for high precision β asymmetry measurements of the two decay branches in ^{35}Ar at the VITO beam line.

4 Phase 1: Polarization and crystal tests at COLLAPS

The production of ^{35}Ar at ISOLDE is expected to be between 10^6 and 10^7 ions/s using a CaO target. After mass separation with the GPS, the ion beam will be directed to the COLLAPS beam line where it will be neutralized with K vapour in the charge exchange cell. In the charge exchange between K (E(K)=4.34 eV) and Ar$^+$ (E(Ar)=15.76 eV) the difference in ionization potential is 11.4189 eV which is 0.129 eV away from the metastable $(3p^5 4s[3/2])_2$ state (Fig. 2). This difference is sufficiently small to have 30-40% of the neutral Ar in this state after the charge exchange process [20].

Subsequently, 811 nm circularly polarized laser light will be used for exciting and optically pump the $(3p^5 4s[3/2])_2$ to $(3p^5 4p[5/2])_3$ transition, in order to polarize the Ar atoms. A holding field along the beam line will maintain the atomic polarization. As the $(3p^5 4p[5/2])_3$ fine structure level only decays to the metastable $(3p^5 4s[3/2])_2$ state, a system of closed levels is created. The J=2 metastable state contains 4 hyperfine structure levels (right part of Figure 2). As the desired transition wavelength for the optical pumping will be generated with a cw Titanium-Sapphire (Ti:Sa) laser, only one of the hyperfine transitions will be resonantly excited and pumped. Thus the amount of atomic polarization will be of the order of 30% only. In order to enhance this polarization we plan to apply simultaneously more than one laser frequency in order to almost fully polarize the Ar atoms. This will be achieved with acousto-optic modulators.

The other Ar I fine structure levels around 11 eV are also populated in the charge exchange process, but those will not be affected by the optical pumping. Thus these unpolarized atoms will reduce the final spin polarization of the Ar atom beam to a maximum of 30-40%.

Different host materials will be tested to find the crystal which best holds the nuclear polarization. This holding time will have to be longer than the lifetime of ^{35}Ar (1.8 s).

The 30% polarization which can be expected from this optical pumping scheme in combination with the approximate value of the asymmetry parameter for this β decay $A \approx 0.43$ results in an anticipated maximum experimental asymmetry of 10%. Given that the strongest hyperfine structure component will contain 40% of this asymmetry and assuming that the relaxation in the crystal results in a time averaged asymmetry half that of the peak asymmetry, we can finally expect 2% experimental asymmetry on the strongest hyperfine structure component. Based on these considerations and on the fact that previous COLLAPS measurements with ^{29}Mg showed a assymetry of about 2%, we can expect to obtain sufficient statistics to characterize the hyperfine structure within a scan of less than 30 min. duration. Once completed, the acousto-optic modulators can be set to pump on all hyperfine structure components, thus providing maximum polarization for measurement of the relaxation times.

We would like to test five different host crystals, i.e. KBr, NaF, CaF, NaCl and Si, by comparing the β asymmetry observed in them as well as by measuring the relaxation time of ^{35}Ar in each crystal at different temperatures. Earlier, ^{35}Ar was already implanted into a cubic single crystal of KBr cooled to 20 K, for the measurement of its magnetic moment with β-NMR [21]. NaF has been used as a catcher at 15 K for β-NMR studies of the noble gas isotope ^{23}Ne [22]. NaCl and Si, finally, were found to be good implantation hosts for several elements, especially in this mass region, in work performed by the Osaka team and experiments with the COLLAPS setup [23, 24]. We envisage that one host relaxation measurement will take in the region of 3 hours of ISOLDE beam. We want to measure relaxation times at 3 temperatures at least per crystal, from 15 K to room temperature. In total, we conclude that the time required to complete the tests of possible host materials is well characterized by the planning presented in the first part of the table in section 6.

5 Phase 2: Polarization enhancement by re-ionization at VITO and CRIS

Whilst the polarization attainable in the atomic system would be sufficient to perform a competitive measurement of the ^{35}Ar β asymmetry parameter, identification of means to improve the degree of polarization could have a substantial impact on the beam time requirements of the data taking campaign. To achieve that, the polarized part of the beam could be re-ionized and separated from the atomic (non-polarized) beam. This could be achieved either by state-selective collisional re-ionization or by laser re-ionization with a pulsed laser (as in the CRIS technique).

It is known that the re-ionization efficiency of Ar by collision with Cl has a 3 times higher cross section for the metastable Ar I state than for its ground state [20]. Figure 2 shows that the atoms that do not end up in the metastable state will eventually decay to the ground state. Collisional re-ionization with Cl can therefore potentially increase the polarization by roughly a factor of 2. The loss of polarization due to the collisions and the efficiency of this process have to be investigated. At TRIUMF, collisional re-ionization of polarized Li beams using a He gas has proven not to significantly reduce the polarization [25]. As a re-ionizing gas target will be installed at the VITO beamline (anticipated late 2015) we request a second short run of 3 shifts to explore the viability of state selective collisional re-ionization for ^{35}Ar.

Alternatively, laser re-ionization may provide a very selective means of enhancing the polarization available [26]. Whilst we expect to maintain the polarization by selection of an appropriate scheme, the efficiency of this process requires investigation and characterization. Here we propose to perform initial off-line tests of laser ionization schemes with the CRIS beam line (9 off-line shifts distributed). After identification of an appropriate scheme we would request a further 3 shifts on VITO to enable a direct comparison between laser and collisional re-ionization.

For this phase, we may use the COLLAPS detection setup as in phase 1 or already mount the β-γ detection setup on the VITO beam line depending of its stage of advancement. The beam time requirements for phase 2 of this proposal are outlined in the second part of the table in section 6.

6 Beam time requirements for the phases 1 & 2.

	Shifts	Notes
Phase 1: Test of various host materials at COLLAPS		
Locate ^{35}Ar transitions, characterize HFS and set AOM's	1.3	
KBr relaxation time measurement	1	
Vent, change crystal, pump	1	Protons not required
Si relaxation measurements	1	
Vent, change crystal, pump	1	Protons not required
NaCl relaxation time measurement	1	
Vent, change crystal, pump	1	Protons not required
NaF relaxation time measurement	1	
Vent, change crystal, pump	1	Protons not required
CaF relaxation time measurement	1	
Contingency	0.7	
Total for COLLAPS	7 online + 4 offline	
Phase 2: Polarization enhancement by Re-ionization at VITO		
Test of Collisional Re-ionization with Cl on VITO	3	
Ar ionization with CRIS	9	Protons not required
Test of LASER Re-ionization on VITO	3	HRS required
Total for VITO	6 online + 9 offline	
Total for phases 1 & 2	13 online + 13 offline	

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
COLLAPS	☒ Existing	☒ To be used without any modification
VITO	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
CRIS	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT: Hazards named in the documents relevant for the fixed COLLAPS, CRIS and VITO installations.