TRIUMF Research Proposal	Experiment no. **E1066**	Sheet 1 of 27

Title of proposed experiment

Electron capture branching ratios for the odd-odd intermediate nuclei in double-beta decay using TITAN

Name of group

TITANEC

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Members of group (name, institution, status)

(For each member, include percentage of research time to be devoted to this experiment over the time frame of the experiment)

D. Frekers	University Münster	Univ.-Prof.	75 %
J. Dilling(for TITAN coll.)	TRIUMF	Prof. / Res. Sc.	50 %
E. Grewe	University Münster	Post-Doc.	50 %
V. Pilipenko	University Münster	Post-Doc	50 %
S. Hollstein	University Münster	Grad. Stud.	50%
H. Dahmen	University Münster	Grad. Stud.	100 %
J. Thiess	University Münster	Grad. Stud.	100 %
J. Suhonen	Univ. Jyväskylä	Univ.-Prof.	20 %
H. Ejiri	RCNP Osaka	Univ. Prof.	
J. Caggiano	TRIUMF	Res. Sc.	10 %
I. Tanihata	TRIUMF	Prof. / Res. Sc.	15 %
D.A. Hutcheon	TRIUMF	Prof. / Res. Sc.	50 % (2 m)
K.P. Jackson	TRIUMF	Emeritus	10 %
S. Yen	TRIUMF	Prof. / Res. Sc.	15 %
P. Delheij	TRIUMF	Prof. / Res. Sc.	50 %

Date for start of preparations: 01/2006

Date ready: 07/2006

Completion date: 06/2009

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
2 x 6 shifts of test beam to be scheduled in 2006		

SUMMARY	Sheet 2 of 27

We propose to measure the electron capture (EC) branching ratios for the odd-odd intermediate nuclei of the double beta ($\beta\beta$) decay parents. These single decay branches will furnish an important input to the theoretical treatment of both, the 2ν and the $0\nu\beta\beta$ decay modes. Especially for the latter, the single decay modes can significantly enhance the reliability of the theoretical descriptions of the nuclear matrix elements that appear in the perturbative description of $\beta\beta$ decay. So far, only the single β^- decay branches are known experimentally with good precision. The EC-branches are in all cases suppressed by 3 to 5 orders of magnitude owing to the usually much lower decay energy, and are therefore either poorly known or not known at all. Here, the traditional methods of producing the radioactive isotope through irradiation of a suitable target and then measuring the K-shell X-rays have clearly reached a limit of sensitivity.

We propose to measure these rates using a completely novel approach, where the ion traps and the radioactive beam facility are the central components. This approach will dramatically increase the sensitivity limit because of significantly lower background levels. We propose to measure the EC branching ratios for 7 different important cases. In all of these, the daughter isotopes are $\beta\beta$ decay candidates, which are presently under intense experimental investigations (GERDA, CUORE, CUORICINO, COBRA at Gran Sasso, MOON in Japan). These are:

^{100}Mo :	^{100}Tc (EC)	[$1^+ \rightarrow 0^+$, $T_{1/2} = 15.8$ s]	$K_{\alpha 1/2} = 17.5$ keV
^{110}Pd :	^{110}Ag (EC)	[$1^+ \rightarrow 0^+$, $T_{1/2} = 24.6$ s]	$K_{\alpha 1/2} = 21.2$ keV
^{114}Cd :	^{114}In (EC)	[$1^+ \rightarrow 0^+$, $T_{1/2} = 71.9$ s]	$K_{\alpha 1/2} = 25.3$ keV
^{116}Cd :	^{116}In (EC)	[$1^+ \rightarrow 0^+$, $T_{1/2} = 14.1$ s]	$K_{\alpha 1/2} = 25.3$ keV
^{82}Se :	^{82m}Br (EC)	[$2^- \rightarrow 0^+$, $T_{1/2} = 6.1$ min]	$K_{\alpha 1/2} = 11.2$ keV
^{128}Te :	^{128}I (EC)	[$1^+ \rightarrow 0^+$, $T_{1/2} = 25.0$ min]	$K_{\alpha 1/2} = 27.5$ keV
^{76}Ge :	^{76}As (EC)	[$2^- \rightarrow 0^+$, $T_{1/2} = 26.2$ h]	$K_{\alpha 1/2} = 9.9$ keV

In the above list, the nuclei are ordered by their lifetimes, which are of order tens of seconds, minutes and hours. Also included are the K-shell X-ray energies.

We further wish to state that the ion trap facility presently under construction at TRIUMF, in conjunction with the possibility of using the appropriate radioactive beams at ISAC provides a world wide unique situation for performing these measurements.

BEAM and SUPPORT REQUIREMENTS	

Experimental area

ISAC
TITAN with EBIT
This is part of the experimental program of the TITAN collaboration

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

500 MeV proton beam on a suitable production target. Options: Ta, W

Secondary channel

ISAC

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emittance, intensity, beam purity, target, special characteristics)

^{76}As, ^{82m}Br, ^{100}Tc, ^{110}Ag, ^{114}In, ^{116}In, ^{128}I

TRIUMF SUPPORT:
Summarize all equipment and technical support to be provided by TRIUMF. If new equipment is required, provide cost estimates.

NOTE: Technical Review Forms must also be provided before allocation of beam time.

TITAN facility,
Radioactive beam catcher system,
high resolution X-Ray detectors (7) (Si-Li or Ge). Most of them will be paid for by a grant from DF

NON-TRIUMF SUPPORT:
Summarize the expected sources of funding for the experiment.
Identify major capital items and their costs that will be provided from these funds.

DF will apply for fund from the German Science Foundation (DFG) for 2006 – 2009. These fund will cover travel expenses, and X-ray detectors.

SAFETY

Summarize possible hazards associated with the experimental apparatus, precautions to be taken, and other matters that should be brought to the notice of the Safety Officer. Details must be provided separately in a safety report to be prepared by the spokesperson under the guidance of the Safety Report Guide available from the Science Division Office.

The experiment will use the new TITAN facility in a standard set-up. We will adhere to the safety regulations as they will be defined for TITAN.

The following information should be included:

(a) **Scientific value of the experiment**: Describe the importance of the experiment and its relation to previous work and to theory. All competitive measurements at other laboratories should be mentioned. Include examples of the best available theoretical calculations with which the data will be compared.

(b) **Description of the experiment**: Techniques to be used, scale drawing of the apparatus, measurements to be made, data rates and background expected, sources of systematic error, results and precision anticipated. Compare this precision with that obtained in previous work and discuss its significance in regard to constraining theory. Give a precise list of targets to be used in order of their priority.

(c) **Experimental equipment**: Describe the purpose of all major equipment to be used.
Details of all equipment and services to be supplied by TRIUMF must be provided separately on the Technical Review Form available from the Science Division Office.

(d) **Readiness**: Provide a schedule for assembly, construction and testing of equipment. Include equipment to be provided by TRIUMF.

(e) **Beam time required**: State in terms of number of 12-hour shifts. Show details of the beam time estimates, indicate whether prime-user or parasitic time is involved, and distinguish time required for test and adjustment of apparatus.

(f) **Data analysis**: Give details and state what data processing facilities are to be provided by TRIUMF.

1. Scientific value of the experiment

1.1 General considerations

The nuclear double beta ($\beta\beta$) decay is characterized by a transition among isobaric isotopes, whereby the nuclear charge Z changes by two units. All $\beta\beta$ emitters are among even-even nuclei, and therefore the decay connects their ground state spin and parity predominantly through a $0^+ \rightarrow 0^+$ transition. The $\beta\beta$ transition is believed to occur in at least two different modes, the 2ν mode and the 0ν mode, the latter is forbidden in the Standard Model and requires the neutrino to be a Majorana particle. Of course, there are exotic modes proposed as well, mostly connected with right handed currents, or with additional particles like majorons, to which the neutrino can couple, or more recently with super-symmetry.

The $2\nu\beta\beta$ process

$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta\text{-decay})$$

conserves lepton number and is allowed within the Standard Model, independent of the nature of the neutrino. This mode is a second order weak process and therefore the decay rate is proportional to $\left({G_F}/{\sqrt{2}}\cos(\Theta_C)\right)^4$ and, consequently, lifetimes are long compared to ordinary β-decay. The decay rate is given by

$$\begin{aligned}\Gamma^{2\nu}_{(\beta^-\beta^-)} &= C\left(\frac{G_F}{\sqrt{2}}\cos(\Theta_C)\right)^4 \mathcal{F}^2_{(-)}\left|M^{(2\nu)}_{\mathrm{DGT}}\right|^2 f(\mathrm{Q}) \\ &= G^{2\nu}(\mathrm{Q,Z})\left|M^{(2\nu)}_{\mathrm{DGT}}\right|^2 \qquad (1.1)\end{aligned}$$

$$\mathcal{F}_{(-)} = \frac{2\pi\alpha Z}{1-exp(-2\pi\alpha Z)}.$$

Here, G_F is the Fermi constant, θ_C is the Cabibbo angle, $\mathcal{F}_{(-)}$ is the Coulomb factor for β^- decay, α the fine structure constant and Z the final Z-value of the nucleus. The factor C is a relativistic correction term for $\beta\beta$ decay, which enhances the decay for high-Z nuclei (C is of order unity for Z=20 and ~5 for Z=50). The factor $f(\mathrm{Q})$ can be expressed in terms of a polynomial of order Q^{11}, where Q is the Q-value of the reaction. This high Q-value dependence is essentially a result of the phase space. $G^{2\nu}(\mathrm{Q,Z})$ is the combined phase space factor, and various values for different nuclei are e.g. summarized in [SUH98]. The nuclear structure dependence is given by the $\beta\beta$ decay matrix element $M_{\mathrm{DGT}}^{(2\nu)}$. For the case of $2\nu\beta\beta$ decay this matrix element is the product of two Gamow-Teller transition operators,

$$
\begin{aligned}
M_{\mathrm{DGT}}^{(2\nu)} &= \sum_m \frac{\left\langle 0_{g.s.}^{(f)} \middle| \sum_k \sigma_k \tau_k^- \middle| 1_m^+ \right\rangle \left\langle 1_m^+ \middle| \sum_k \sigma_k \tau_k^- \middle| 0_{g.s.}^{(i)} \right\rangle}{\tfrac{1}{2}\mathrm{Q}_{\beta\beta}(0_{g.s.}^{(f)}) + \mathrm{E}(1_m^+) - \mathrm{E}_0} \\
&= \sum_m \frac{M_m\left(GT^+\right) M_m\left(GT^-\right)}{\mathrm{E}_m}
\end{aligned}
\tag{1.2}
$$

$\mathrm{E}(1_m^+) - \mathrm{E}_0$ is the energy difference between the m^{th} intermediate 1^+ state and the initial ground state, and the sum Σ_k runs over all the neutrons of the decaying nucleus. (Note that the sign change in the second equation is the result of time invariance, also note that the energy denominator is units of the electron rest mass m_e.) Contributions from Fermi-type virtual transitions are negligible, because initial and final states belong to different isospin multiplets. In fact, the transition matrix is essentially a sum of products of two ordinary β-decay Gamow-Teller matrix elements between the initial and the intermediate states, and between the intermediate states and the final ground state, respectively. Because in this case two real neutrinos are emitted, the intermediate states m that contribute will only be 1^+ states, whose transition matrix elements one could determine e.g. through charge-exchange reactions in the β^+ and β^- direction at intermediate energies (100–200 MeV/nucleon), or, for the ground state transitions, by measuring the single (β^+EC) and β^- decay rates.

The alternative $0\nu\beta\beta$ decay mode is

$$(Z, A) \rightarrow (Z+2, A) + 2e^- \quad (0\nu\beta\beta\text{-decay}),$$

which is a lepton number violating process, and which is only possible if neutrinos are Majorana particles. Moreover, to allow for helicity matching, a neutrino mass is required. In this case, the decay rate is given by:

$$\Gamma_{(\beta^-\beta^-)}^{0\nu} = G^{0\nu}(\mathrm{Q,Z}) \left| M_{\mathrm{DGT}}^{(0\nu)} - \frac{g_V}{g_A} M_{\mathrm{DF}}^{(0\nu)} \right|^2 \left\langle m_{\nu_e} \right\rangle^2 \tag{1.3}$$

$G^{0\nu}(\mathrm{Q,Z})$ is in general a more favourable phase space factor than in $2\nu\beta\beta$ mode although it scales with Q^5. The quantities $M_{\mathrm{DGT}}^{(0\nu)}$ and $M_{\mathrm{DF}}^{(0\nu)}$ are generalised Gamow-Teller and Fermi matrix elements for $0\nu\beta\beta$ decay, and $\left\langle m_{\nu_e} \right\rangle$ is the effective Majorana neutrino mass given as

$$\left\langle m_{\nu_e} \right\rangle = \left| \sum\nolimits_i \mathsf{U}_{ei}^2 \, m_i \right| = \left| \sum\nolimits_i \left|\mathsf{U}_{ei}\right|^2 exp(2\,i\,\alpha_i\,)\, m_i \right| \tag{1.4}$$

with U_{ei} as the mixing matrix, m_i as the corresponding mass eigenvalues and $\alpha_i/2$ as the CP-phases. Clearly, if one wishes to extract the neutrino mass from an observed decay rate, the nuclear matrix elements need to be known at least with some reliability. Whereas the matrix elements in the 2νββ decay have a rather simple structure, the ones for the 0νββ are significantly more complex, since the neutrino enters into the description as a virtual particle. Usually, the generalized matrix elements are expressed in a form, which introduces a neutrino potential operator:

$$\begin{aligned} M_{\mathrm{DGT}}^{(0\nu)} &= \langle f \,|\sum_{lk} \sigma_l \sigma_k \tau_l^- \tau_k^- \; H(r_{lk}, E_a\,)\,|\, i \rangle \\ M_{\mathrm{DF}}^{(0\nu)} &= \langle f \,|\sum_{lk} \tau_l^- \tau_k^- \; H(r_{lk}, E_a\,)\,|\, i \rangle , \end{aligned} \tag{1.5}$$

where r_{lk} is the proton-neutron distance in the nucleus, and E_a is an energy parameter related to the excitation energy. (Note that short range effects become important here.) As the distance r_{lk} is of order the size of the nucleus, the momentum transfers involved can be large, typically of order 0.5 fm^{-1}, which then allows excitation of many intermediate states. After a multipole expansion of Eq. (1.5), one can re-write the general structure of the Eq. (1.3) in the following way:

$$\Gamma^{0\nu}_{\beta^-\beta^-} = G^{0\nu} \left| \sum\nolimits_m \frac{\left\langle 0^{(f)}_{g.s.} \left\| \mathcal{O}_{\sigma\tau^-}(r,S,L) \right\| J^{\pi}_{m} \right\rangle \left\langle J^{\pi}_{m} \left\| \mathcal{O}_{\sigma\tau^-}(r,S,L) \right\| 0^{(i)}_{g.s.} \right\rangle}{\tfrac{1}{2}\, \mathrm{Q}_{\beta\beta}(0^{(f)}_{g.s.}) + \mathrm{E}(J^{\pi}_{m}) - \mathrm{E}_0} + \mathrm{Fermi} \right|^2 \left\langle \mathsf{m}_{\nu_e} \right\rangle^2 . \tag{1.6}$$

The two different situations of ββ decay are sketched in Fig. 1.

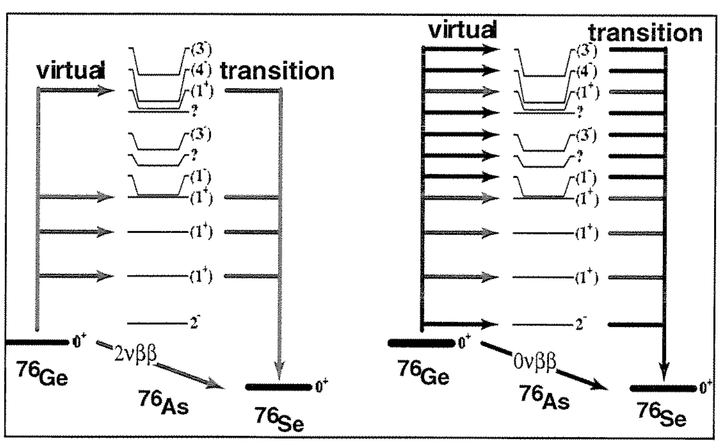

Fig.1: Sketch of the two modes of ββ decay and the various possible excitations of the intermediate nucleus.

Clearly, an experimental determination of these matrix elements is an insurmountable task, unless one could show that low-lying states of lowest multipolarity (e.g. 1^+, 2^-, 3^+) were the main contributors to the rates factor. Nonetheless, in order to give guidance to theoretical descriptions of 0νββ half-lives (or extracted neutrino mass parameters), any experimental information about details of the nuclear wave function, or any specific property or decay branching ratio of the nucleus involved is highly warranted.

1.2 Description of theoretical approaches and the problem of g_{pp}

In this section, we briefly review some of the theoretical work connected with the determination of ββ decay matrix elements. Unfortunately, the theory community seems to be in some disarray, and the various groups involved in calculating ββ matrix elements cannot agree on some of the very basic parameters (for more information we refer to [SUH05, SIM01] and references therein). However, according to Refs. [SUH05] and [SUH05a], some universal features seem to emerge, namely the dominance of a few low-lying nuclear states of low multipolarity (like e.g. the 2^- states, which could exhaust nearly 50% of the total summed strength in 0νββ decay). On the other hand, the authors of [SUH05] also point out that there is a worrisome inability to correctly describe the single decay rates (like the β^-, and most notably the EC rate (if available)). It is argued that the theoretical agreement with the experimental 2νββ decay rate is a result of two compensating errors, much too high an EC rate and a too low β^- rate. Discrepancies of 1 to 2 orders of magnitude in the EC matrix elements are possible, and since the understanding and correct description of the 2νββ process is a pre-requisite for the 0νββ decay, one could be forced to re-evaluate many of the models that have so far been advocated. Unfortunately, EC decay branches are in many cases either not well enough known, or not known all, contrary to the β^- decay branches, which have been measured with high precision. This means, there is presently a rather uncomfortable loose end in the theoretical models.

In fact, the 2νββ decay is always used as a test case for a nuclear model, since the decay proceeds via the 1^+ states of the intermediate nucleus only. The nuclear models used are the nuclear shell-model or, more often, the proton-neutron-QRPA (pn-QRPA), designed for spherical or nearly spherical nuclei.

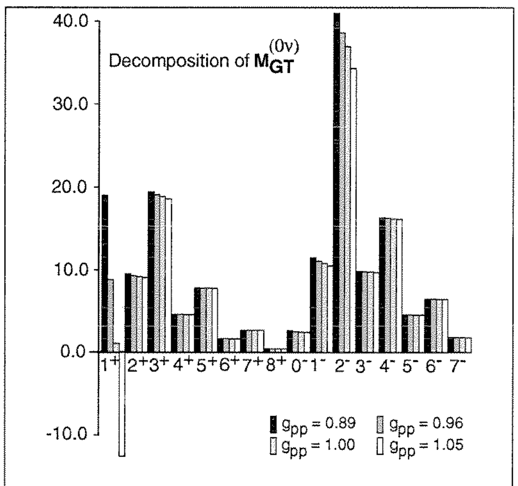

Fig.2: Decomposition of the ^{76}Ge $\rightarrow$ ^{76}Se 0νββ decay matrix elements into multipole components as a function of various values of g_{pp}. (From Refs. [ZUB05, SUH05a])

The pn-QRPA has an adjustable particle-particle parameter part of the proton-neutron two-body interaction, called g_{pp}. The parameter appears in all single- and double-beta decay calculations and defines part of the nuclear many-body Hamiltonian. It turns out that the nuclear matrix elements of the 2νββ decay seem to be rather sensitive to g_{pp}, which requires this parameter to be tuned by this decay. This is, in fact, the procedure followed by all theoretical groups, i.e.: the interaction strength parameter g_{pp} of the pn-QRPA is determined by fitting the computed nuclear matrix elements of (Eq. 1.2) to the one extracted from the experimental half-life of the corresponding 2νββ decay. This fitted value is then used for the evaluation of the 0νββ decay matrix elements of Eq. 1.6, which, unlike their 2νββ decay counterpart, seem to be rather insensitive to g_{pp} (except for the 1^+ part, of course). Thus, one could be tempted to conclude that the 0νββ decay is well controlled by the theory, – if one assumes, of course, that the energy denominator in Eq. 1.6, which contains the excitation energy, is equally well understood. In Fig. 2 this situation is depicted for the case of ^{76}Ge $\rightarrow$ ^{76}Se. As, however, pointed out in [SUH05], there are serious pitfalls in this procedure casting serious doubts on the usefulness of the method and the universal parameter g_{pp}. The inadequacies of the model become apparent when confronting them with single decays, most notably with EC rates (in case they are available).

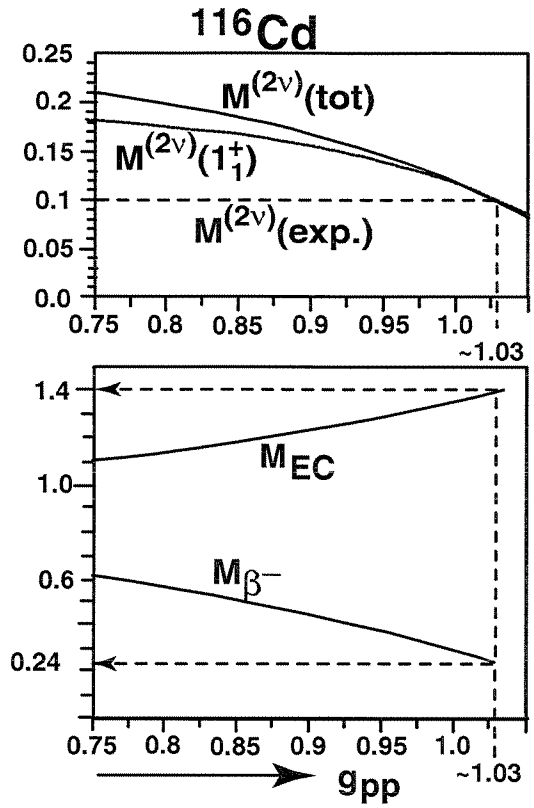

Fig.3: Nuclear matrix elements for ^{116}Cd as a function of the parameter g_{pp}. The top part shows the 2νββ matrix elements for the full calculation ($M^{(2\nu)}_{\text{tot}}$) (full line), the contribution from the first 1^+ state, i.e. ground state (dashed line), and the extracted experimental value, which fixes g_{pp}. The lower part shows the extracted single decay matrix elements as a function of g_{pp}.

The situation is best illustrated in the case of ^{116}Cd. The calculations of the 2νββ decay matrix elements have been performed on the basis of the pn-QRPA (for more information about the details of the calculations, we refer to [SUH98]). The results are summarized in Fig. 3. Following the above indicated recipe of fixing the parameter g_{pp}, one has to compare the total 2νββ matrix element $M^{(2\nu)}_{\text{tot}}$ of Eq. (1.2) with the one evaluated from the experimental half-life $M^{(2\nu)}(\text{exp.})$, by which a value of g_{pp}=1.03 is deduced. Also indicated in Fig. 3 is the contribution $M^{(2\nu)}(1^+_1)$ of the lowest-lying 1^+ state, which happens to be identical to the ground state. It thus appears that near $g_{pp} = 1$ the nuclear matrix element for the 1^+ ground state coincides with the total value of the matrix element. This is a characteristic of the so-called single-state-dominance (SSD). Although the extreme SSD model may not be realistic, as was recently shown by us comparing the charge exchange reactions (^{3}He,t) and (d,^{2}He) on the A=116 system (cf. [RAK05]), it is nevertheless instructive to follow up the consequences.

In the case of an SSD (or an approximate SSD), the nuclear matrix element of the 2νββ decay of Eq. (1.2) simplifies to:

$$M^{(2\nu)}_{\text{tot}} \simeq \frac{M_{EC}\, M_{\beta-}}{\frac{1}{2}\,Q_{\beta\beta}(0^{\emptyset}_{g.s.}) + E_{g.s.}(1^+) - E_0}, \tag{1.7}$$

where M_{EC} is the electron capture branch and M_β^- is the single β^- decay branch. As g_{pp} also appears in the single β^- decay calculations, the model makes a prediction for the single β^- decay and thereby for the EC branch as well. This is indicated in the lower part of Fig. 3. Theory can therefore already at this stage be confronted with experiment.

Taking the value of g_{pp} =1.03, as required by the experimental 2νββ half-life, gives for the single β^- decay matrix element a value of $M_\beta^- = 0.24$ and for the EC matrix element a value of $M_{EC} = 1.4$. The experimental value for the β^- decay is, however, M_β^- = 0.506, as determined from the ^{116}In half-life $T_{1/2}$=(14.10±0.03)s (*log ft* = 4.7). A matrix element of M_β^- = 0.24 would slow down this transition to

$T_{1/2}$ ~ 63 s. However, one could re-adjust the parameter to g_{pp} =0.85 to match the experimental β^- decay matrix element using as an argument the experimental error of the $2\nu\beta\beta$ half-life. In this case, the EC matrix element decreases from M_{EC} = 1.4 to a slightly more favourable value of M_{EC} = 1.2. The experimental value for the EC matrix element is, however, M_{EC} = 0.18 (as deduced from (^{3}He,t) charge exchange reactions [AKI97]) or M_{EC} = 0.69 (as deduced from a direct measurement using the conventional technique of detecting the K-shell X-rays after irradiation [BHA05]). These different values have rather dramatic effects on the EC branching ratio ε (for the β^- branch we use the experimental β^- value):

- M_{EC} = 1.4 / 1.2 translates into ε = 0.095 / 0.07 % (*log ft* = 3.77 / 3.91) (theory)
- M_{EC} = 0.69 translates into ε = (0.023 ± 0.007) % (*log ft* = 4.39) (expmt-1)
- M_{EC} = 0.18 translates into ε = (0.0016 ±0.0008) % (*log ft* = 5.5) (expmt-2)

Clearly, none of the experimental values for ε can be made consistent with the g_{pp} dependence shown in Fig. 3.

<u>Summarizing the above:</u>

> The use of $g_{pp}(\beta\beta)$ = 1.03 reproduces the $2\nu\beta\beta$ decay half-life via a conspiracy of two errors: a much too large EC matrix element (too fast EC decay) is compensated by a much too small β^- matrix element (too slow β^- decay).

A comment on the contradicting experimental values for the EC branch is in order:

The EC branching ratio for the ^{116}In (EC)→^{116}Cd has recently been measured by Bhattacharya, et al. [BHA05] at the Notre Dame FN Tandem Accelerator using for the ^{116}In production the ^{115}In(d,p) reaction. A He-jet system was used to transport the radio-isotope away from the production onto a tape station, where the X-ray detection system was located. The authors report a branching ratio ε = 0.023 ± 0.06 %, which translates into $log\ ft = 4.39^{+0.10}_{-0.15}$, *B(GT)* = 0.47, and M_{EC} = 0.69. These values are at variance with a recent measurement at RCNP of the ^{116}Cd(^{3}He,t)^{116}In charge-exchange reaction at 450 MeV [AKI97], where it was observed that the ground state transition was only weakly excited. Here, the corresponding values were *log ft* = 5.5 ± 0.06, *B(GT)* = 0.032, and M_{EC} = 0.18. Of course, one could argue that the proportionality between *B(GT)* and the (^{3}He,t) charge-exchange cross section is not safely established [AUS94]), but such a large factor would be exceptional, especially since the EC *log ft* value indicates a rather low degree of forbiddeness, which ought to translate into a rather strong charge-exchange transition. We may also refer to a recent publication, where this issue and its consequences for double-beta decay are discussed in the context of the (d,^{2}He) charge-exchange reactions performed by the Münster-group at the KVI Groningen [RAK05].

In view of the general importance connected with double-beta decay, the particular situation around the ^{116}In weak decay is everything but re-assuring. Not only are there serious deficiencies being exposed in the theory, but the experimental situation as well is equally uncomfortable.

As the second test case one can take the $2\nu\beta\beta$ decay of ^{128}Te to the ground state of ^{128}Xe. The intermediate nucleus is ^{128}I with a ground state spin $J^{\pi} = 1^{+}$. This case can be analysed in much the same way as indicated above, and we refer to [SUH05], where this case is discussed in detail and where similar conclusions to the ones above are drawn:

> The matrix elements extracted for the two branches, i.e. the EC and the β^{-} decay, cannot be brought together with a single g_{pp} value. The g_{pp} value that fits the $2\nu\beta\beta$ decay would lead to a much too fast EC rate and a much too slow β^{-} rate. To make things worse, a re-adjustment of g_{pp} to the experimental β^{-} decay does not notably improve the EC rate prediction. It would still be almost one order of magnitude to fast.

The third case, the $\beta\beta$ decay of ^{76}Ge to ^{76}Se can also be discussed along the same lines. ^{76}Ge can be considered the most important case, because of the recent claim for an observation of the 0ν decay mode [KLA04]. The intermediate nucleus, ^{76}As, has a 2^{-} ground state, which undergoes a weak first order unique transition by β^{-} decay and by electron capture. Apart from the fact that this provides an important opportunity to determine the matrix element for the next hierarchy up, i.e. the matrix element, which is most relevant to $0\nu\beta\beta$, it is nevertheless instructive to comment on the structure of the low-lying 1^{+} levels in the context of g_{pp}. The Münster group has just completed a measurement of the (d,^{2}He) charge-exchange reactions, where the transition strength B(GT^{+}), which is the quantity that connects to the β^{-} decay, was extracted. The spectrum is shown in figure 4. The first 1^{+} level is only 44 keV above the ground state and carries a strength of B(GT) = 0.1, which translates into a matrix element of a hypothetical β^{-} decay, $M_{\beta^{-}} = 0.3$. A g_{pp} value that fits the $2\nu\beta\beta$ decay (g_{pp} =0.95) would result in $M_{\beta^{-}} = 0.09$. Again, we see that even for the excited states the calculated β^{-} decay branch is too slow by more than an order of magnitude.

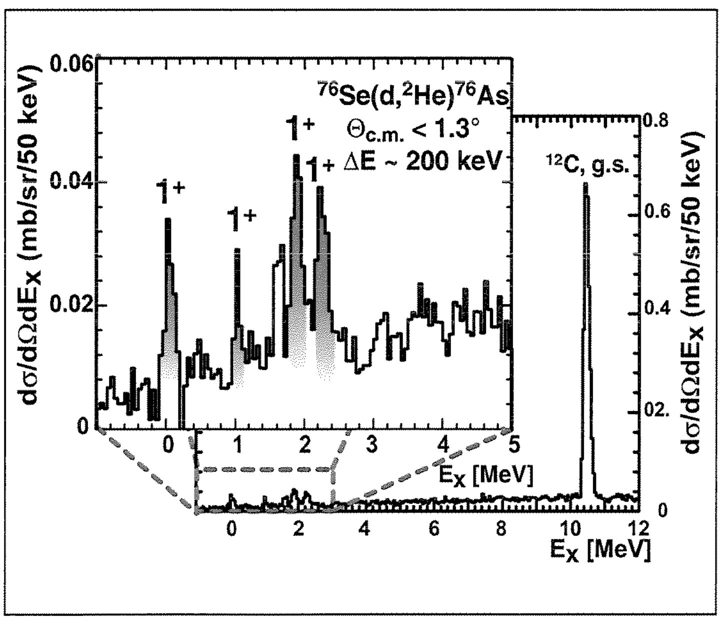

Fig. 4: Spectrum of the charge-exchange reaction ^{76}Se(d,^{2}He)^{76}As at 175 MeV. The GT transitions strengths are related to the matrix elements for the β^{-} decay direction.

Details of the decays

In this section we will provide detailed information about the various isotopes we wish to investigate. It is envisaged that we will use the TITAN ion trap facility to capture the atoms and detect the X-ray transitions with high-resolution X-ray detectors. This will be the applied technique in all cases, with the exception of the decay of the ^{82m}Br, which requires more studies of the technique, e.g. like the loading capacities of the traps, particular vacuum requirements etc. The power of the trap technique lies in its ability to provide largely a background-free situation for low-energy X-ray detection. Further, there will be no X-ray absorption (except for the effect of the 250μm Be-windows), which one would typically have to deal with when implanting the isotope into/onto some carrier material. Electrons from the far more intense β^- decay will be guided away from the X-ray detectors by the high magnetic field of the trap (~6T) and can be detected on the beam axis when exiting the magnet. This provides an additional (soft) anti-coincidence gate, which can be used to gate on unwanted X-rays associated with the β^- decay.

We have opted to use high-resolution X-ray detectors because then there will be additional information gained about the K/L capture ratio. This is an important quantity to test details of the electronic wave function. Here, we envisage that the technique could spawn further activities, especially studies of the electronic wave function for high-Z atoms.

As will be seen, the most important case ^{76}As, will particularly profit from these considerations, as it has the lowest X-ray energy of 9.9 keV.

The case ^{100}Tc

In Fig. X1 the decay scheme ^{100}Tc is presented

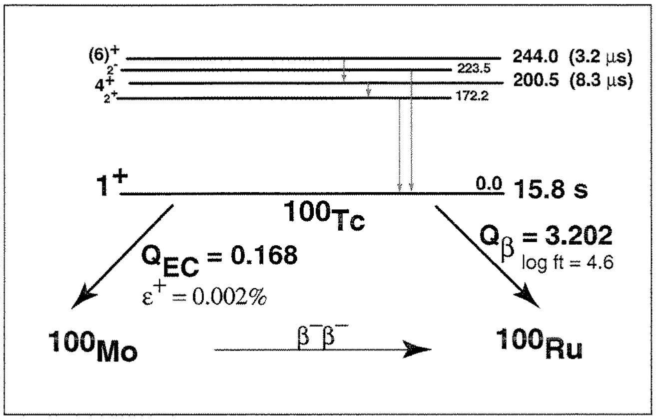

Fig. X1: Decay scheme of ^{100}Tc.

The intermediate nucleus in the ^{100}Mo ββ decay is ^{100}Tc. Its half-life is 15.8 s. At ISAC the isotope is produced exclusively in its ground state; there are no isomers, which could be of any concern for the measurement. The EC decay will only populate the ground state of ^{100}Mo as there are no excited states below 168 keV in ^{100}Mo.

The β^- decay of ^{100}Tc has a 93% branch to the ground state (*log ft* = 4.6) and a 5.7% branch to a 1.130 MeV (0^+) state in ^{100}Ru. There are a number of other weak transitions (mostly below 0.1%), all of them producing γ-rays at significantly higher energies then the typical X-ray energies. Internal conversion (IT) coefficients are not known and are likely small.

X-ray energies involved are:

^{100}Mo: 17.5 keV,
^{100}Ru: 19.3 keV (only through IT after β^- decay and shake-off electrons)
no X-ray transition in ^{100}Tc

Because of the importance to ββ decay, the ^{100}Tc isotope is presently also being investigated by the group at Univ. Washington (A. Garcia and collaborators) using the radioisotope facility at Jyväskylä. However, the group will use the traditional technique of catching the isotope onto a tape station. We find it important to show how the present technique can compete.

^{100}Tc is therefore a high priority item on our project list: **(priority ^{100}Tc: ****)**

The case ^{110}Ag

In Fig. X2 the decay scheme ^{110}Ag is presented

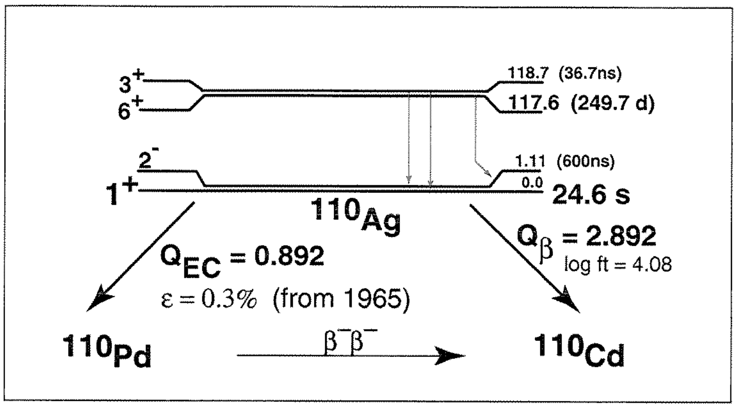

Fig. X2: Decay scheme of ^{110}Ag.

The intermediate nucleus in the ^{110}Pd ββ decay is ^{110}Ag. It has a 249.7 days isomeric 6^+ state at 117.6 keV, which mainly decays by β^- emission (98.6%). There is a 1.36% IT branch producing a 22.2 keV X-ray of ^{110}Ag. A de-exitation of the isomeric state through EC is not possible. The ground state EC branching ratio has been measured in 1965 [FRE65] through production of ^{110}Ag by neutron activation. The EC branching ratio of $\varepsilon = 0.3\%$ translates into a *log ft* = 5.1.

The β^- decay populates the ground state of ^{110}Cd with a 94.9% branch and the first excited 2^+ state at 657.8 keV at a level of 4.4%. The 249.7 days isomer populates high-lying high spin states in ^{110}Cd. However, because of the long half-life, it presents no concern to the experiment. Furthermore, the production of ^{110}Ag in its isomeric state at ISAC is likely negligible.

X-ray energies involved are:

^{110}Pd: 21.2 keV,
^{110}Ag: 22.2 keV, (only if isomeric state is present)
^{110}Cd: 23.3 keV (low level)

The EC branch has been measured in 1965 using traditional techniques [FRE65]. The high branching ratio together with the short life-time is a distinct advantage for a measurement with traps. We feel that the measurement can be easily accomplished and can be used by us for proof of principle.

^{110}Ag is a high priority item on our project list: **(priority ^{110}Ag: ****)**

The case ^{114}In

In Fig. X3 the decay scheme ^{114}In is presented

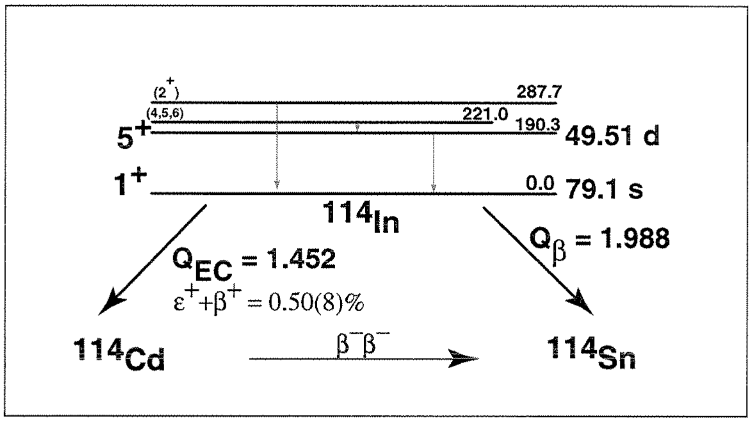

Fig. X3: Decay scheme of ^{114}Cd.

The intermediate nucleus in the ^{114}Cd ββ decay is ^{114}In. Its half-life is 79.1s. It has a 49.51 days isomeric 5^+ state at 190.3 keV, which decays by an internal conversion branch with 95.6% and with a 4.3% branch by a combined (β^++EC) transition. Further, there is a 43ms, 8^- isomer located at 502 keV (not shown here), which has a 100% internal conversion coefficient. Both isomers are not likely being produced at ISCAC and should therefore not affect a measurement of the ground state EC rate.

The ground state EC branching ratio has been measured in 1956 [GRO56] !! to ($\varepsilon + \beta^+$) = 0.5%, which translates into a *log ft* = 4.85, if there is exclusive decay into the ground state (note that the β^+ branch can be calculated to be about 0.6% of the EC branch [GOV71]). Because of the high Q-value, the EC decay can reach a number of excited states in ^{114}Cd , most notably the first excited 2^+ state at 558.4 keV. The branching ratios are not known.

The β^- decay populates the ground state of ^{114}Sn with a 99.4% branch and the first excited 2^+ state at 1.300 MeV at a level of 0.14%.

K-shell X-ray energies involved are:

^{114}Cd: 23.2 keV
^{114}Sn: 25.3 keV (only through IT after β^- decay)
^{114}In: 24.3 keV (only if isomer is produced)

^{114}In is a medium to high priority item on our project list: **(priority ^{114}In: ***)**

The case ^{116}In

In Fig. X4 the decay scheme ^{116}In is presented.

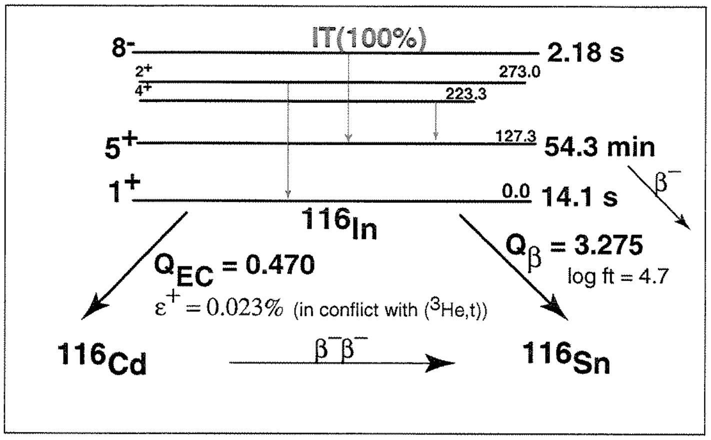

Fig. X4: Decay scheme of ^{116}In

The intermediate nucleus in the ^{116}Cd $\beta\beta$ decay is ^{116}In. Its half-life is 14.1s. It has a 54.3 minutes isomeric 5^{+} state at 127.3 keV, which decays exclusively through β^{-} emission populating high-lying high spin states in ^{116}Sn. Further, there is a 2.18 second 8^{-} isomer at 289.7 keV, which decays by internal conversion only. It is likely not being produced at ISAC, but even if it were, it could easily be identified through its short life-time. The β^{-} ground state decay branch populates the ground state of ^{116}Sn at a level of 98.6%. X-ray production through internal conversion of higher lying states is negligible.

The present EC branching ratio of ε = 0.023% is, as indicated earlier, in conflict with the (^{3}He,t) charge-exchange reaction [AKI97]. We therefore consider a re-measurement of this ratio a high priority. The short lifetime has a significant advantage as it is well matched to the presently envisaged holding time in the trap.

K-shell X-ray energies involved are:

^{116}Cd: 23.2 keV
^{116}Sn: 25.3 keV (negligible)
^{116}In: 24.3 keV (only if 2.18 second isomer is produced)

^{116}In is a high priority item on our project list: **(priority ^{116}In: ****)**

The case ^{82m}Br

In Fig. X5 the decay scheme ^{82}Br is presented

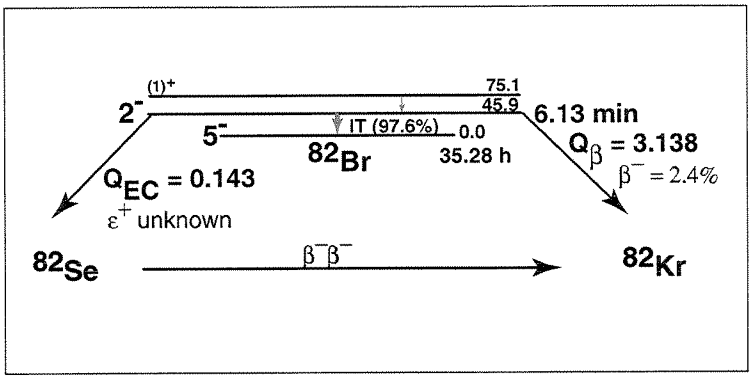

Fig. X5: Decay scheme of ^{82}Br

The intermediate nucleus in the ^{82}Se ββ decay is ^{82}Br. It has a 5^- ground state, which decays predominantly into a 4^- state in ^{82}Kr. The ground state is of low importance for the ββ decay, much in contrast to the first 2^- isomeric state at 45.9 keV. As indicated earlier, 2^- excitations can be the largest contributors to the $0\nu\beta\beta$ matrix element. In a case of a single state dominance (or "near single state dominance") this single matrix element can make up the dominant fraction of the total $0\nu\beta\beta$ matrix element. The 2^- state decays with 97.6% through internal conversion and with 2.4% by β^- emission. The 0^+ ground state of ^{82}Kr is then populated with an 88% probability, by which a *log ft*=8.4 has been deduced.

K-shell X-ray energies involved are:

^{82}Se: 11.2 keV (expected branching $4 \cdot 10^{-9}$)
^{82}Kr: 12.65 keV (IT following β decay, not negligible in view of low EC branching)
^{82}Br: 11.92 keV (most intense contribution from internal conversion of 2^- level)

A measurement of the EC rate is a significant challenge and will not be done in an early phase of the project. Given the Q-value, the estimated branching ratio will be about $\varepsilon \sim 10^{-8} - 10^{-9}$ for a *log ft* that is similar to the β^- decay. This requires a loading capacity of the trap well above the present possibility. However, there are realistic plans to increase the loading capacity to a few times 10^6 atoms. A measurement could then be envisaged.

Measuring the K-shell X-ray emission may not be the best possible option either, because of the near-by X-ray of ^{82}Br from the overwhelming internal conversion of the 2^- level. A different technique, by which the daughter could be expelled from the trap and then counted (thereby avoiding the detection of X-rays) is presently under discussion.

^{82m}Br is therefore a low priority item on our early project list: **(priority ^{82m}Br: *)**

The case ^{128}I

In Fig. X6 the decay scheme ^{128}I is presented

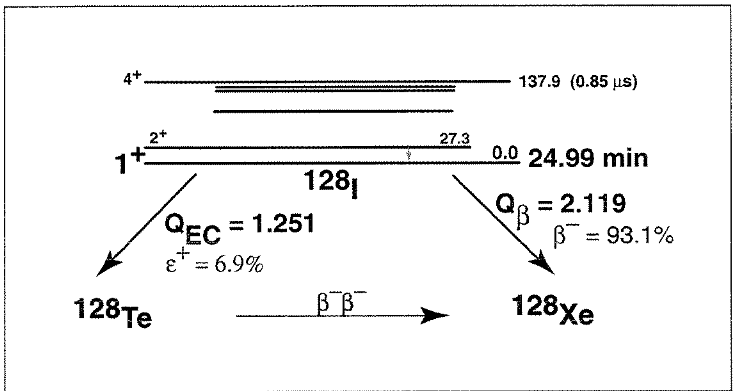

Fig. X6: Decay scheme of ^{128}I

The intermediate nucleus in the ^{128}Te ββ decay is ^{128}I. Its half-life is 24.99 min. There are no long-lived isomers, which would have to be considered. The EC branching ratio has been measured with high precision to 6.8±0.8 % [BEN56,SCH79]. The Q-value allows a transition into the first excited 2^+ state at 743.2 keV (0.2%). The branching is not known.

The β^- ground state decay branch populates the ground state of ^{128}Xe (80%), the first 2^+ state at 442.9 keV (11.6%) and the second 2^+ state at 968.5 keV (1.5%).

K-shell X-ray energies involved are:

^{128}Te: 27.5 keV
^{128}Xe: 29.8 keV (negligible)
^{128}I : 28.6 keV (absent)

The present EC decay can be used as a standard for calibration and for proof of principle in much the same way as the previous ^{110}Ag case. The long half-life is, however, somewhat disadvantageous, as present trapping times are only of order of tens of seconds.

^{128}I is a medium to high priority item on our project list: **(priority ^{128}I: ** +)**

The case ^{76}As

In Fig. X7 the decay scheme ^{76}As is presented

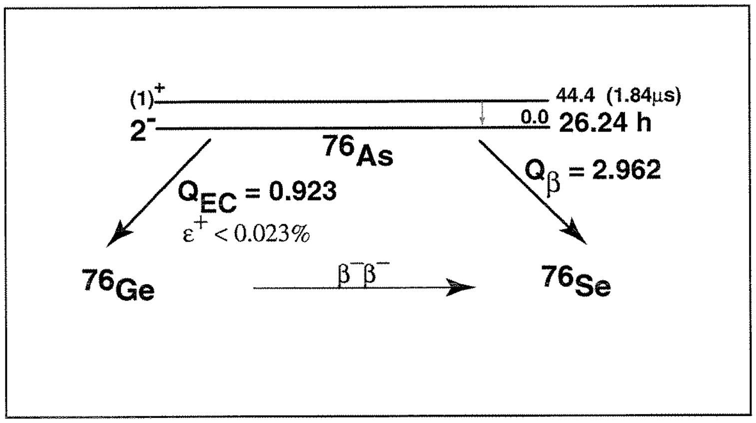

Fig. X7: Decay scheme of ^{76}As

^{76}Ge is presently considered the most important ββ decaying nucleus. This is the only nucleus, for which a signature for 0νββ decay has so far been reported. That report has prompted a massive effort in Europe (Gran Sasso) in order to put this observation to a serious test. The new experiment GERDA expects to lower the background levels by about 2 orders of magnitude compared to the previous experiment. Clearly, if a positive result is being found, one wishes to extract the mass of the Majorana neutrino with as little theoretical uncertainty as possible. The intermediate nucleus ^{76}As provides the opportunity to directly measure the matrix element for the intermediate 2^- excitation and thereby allows a sensitive test for the theoretical model. This is especially true, if there is a single-state dominance. Further, as indicated before, the first 1^+ level, which is only 44 keV above the ground state, is another key test candidate, which is presently being looked at by the Münster group using charge-exchange reactions like (d,^{2}He) and (^{3}He,t) at the KVI and at RCNP. Measuring the EC rate, and complementing this with GT transitions to 1^+ states would provide a rather complete knowledge about the properties of the intermediate states in the ββ decay of ^{76}Ge.

The β^- decay of ^{76}As to the ground state of ^{76}Se is a first order unique forbidden $2^- \rightarrow 0^+$ decay (branch of 51%) with a *log ft=9.7,* which is exceptionally large. The β^- decay also populates the first 2^+ state at 559.1 keV with a branch of 35.2 % (*log ft* = 8.1). The rest of the decay is distributed over many levels.

Presently, only an upper limit of the EC rate is known, $\varepsilon < 0.023$ %. The value originates from a 1957 measurement [SCO57]!! Clearly, the tools available at that time were moderate compared to today's standard, and, further, some unknowns remain about how this value was deduced. The Q-value of the decay allows a transition to the first excited 2^+ state at 562 keV and it could be important to distinguish this transition from the ground state transition. This would require an additional γ-ray detector.

Taking a *log ft* for the EC process similar to the one from β decay, one could estimate the branching ratio to be between about $\varepsilon = 0.01\%$ (*log ft* = 9.1) and $\varepsilon = 0.002\%$ (*log ft* =9.7), which is not too far off from the present upper limit.

^{76}As is therefore a high priority item on our project list: **(priority ^{76}As: ****)**

2. Description of the experiment

Measurements of EC branching ratios are usually carried out in a conventional method using a tape-station technique. This technique has a number of drawbacks. There is always the issue of X-ray absorption of the backing-material onto which the radio-isotope was implanted. In addition, one always has to deal with an intense background from the associated β decay, and furthermore, the purity of the sample is quite often not guaranteed. In our case we propose an entirely novel approach. An isotopically pure sample is stored in the backing free environment of the EBIT trap and then the X-rays following EC are observed with a high resolution detector perpendicular to the axis of the magnet. Electrons from the associated β^- decay are guided on the magnetic field lines and focused to the center of the magnet near the exit. Because of the high field (6T), they will never reach the X-ray detectors. Further, the TITAN facility allows preparation of a clean sample, which is then stored in a Penning trap. Another and rather unique advantage of the trap is its open access for X-ray detectors. A total of 7 detectors can be mounted subtending 2.1% of the 4π solid angle in the present configuration.

In the following, the experimental procedure will be described in detail.

The TITAN experimental setup consists of initially three ion traps in series; an linear RFQ cooler and buncher trap, an electron beam ion trap (for charge breeding) and a Penning trap, where in general mass measurements are carried out (Fig. 2.1)

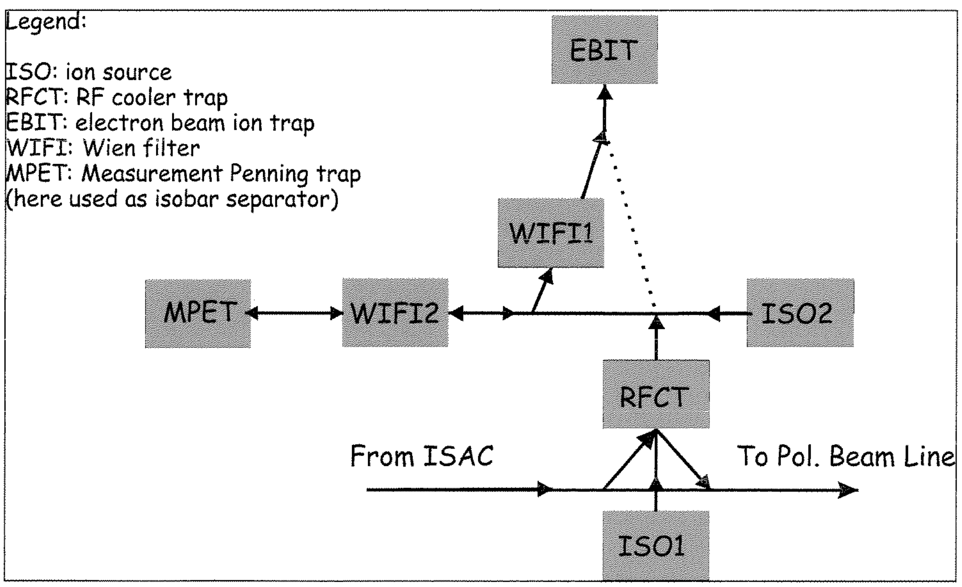

Fig. 2.1 The TITAN set-up. Note, that the proposed configuration for the present project is slightly different from the one used for mass measurements. The beam preparation sequence is indicated with arrows.

The continuous 60 keV ISAC beam enters the gas-filled RFQ, gets cooled and bunched and transferred to the next component. In the present case, the beam will be transferred to the Measurement Penning Trap (MPET), where mass selective buffer gas cooling will be carried out. This well established technique can be used to produce an isotopically pure sample [SAV91, KOH04] and a mass resolving power of $R=M/\Delta M \sim 12{,}000$ has been demonstrated. Figure 2.2 shows a mass scan figure from the ISOLTRAP collaboration, where an on-line cocktail beam could be separated and identified.

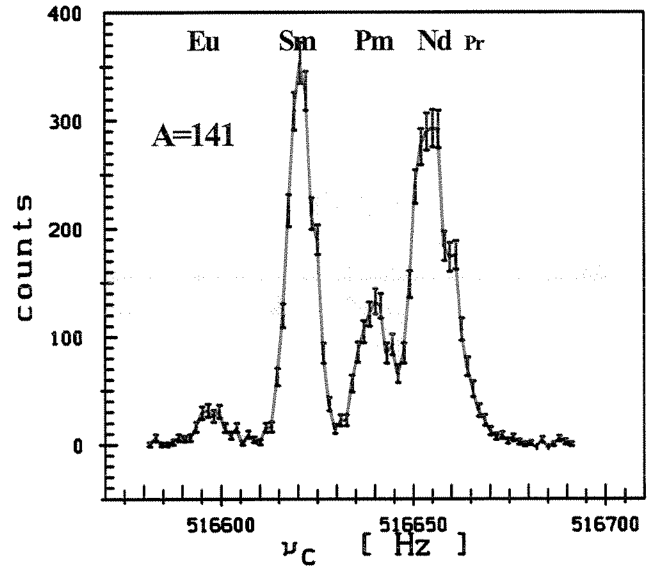

Fig. 2.2: Mass scan example from the ISOLTRAP experiment [RAI97]. The individual elements are cleanly resolved. The quoted resolving power was R > 10000.

In the proposed experiment, the purified sample will be transferred to the EBIT. The EBIT will be used in a so-called Penning-trap mode, i.e. without the application of the electron beam!! The charged ions will be trapped and stored by the super-conducting 6T magnetic field and by the electrostatic potentials applied to the trapping electrodes. The EBIT is operated in a 'cold-bore' configuration, i.e. providing LHe temperature onto the electrodes. The vacuum in the system is then good enough to reach trapping times on the order of minutes ($P_{EBIT} \approx 1 \cdot 10^{-11}$ mbar). The magnet system used for the EBIT is a double Helmholtz coil configuration and provides easy access to the center of the trap. The geometry of the EBIT is shown in figure 2.3. The EBIT will provide ideal storage conditions for the radioactive sample. The geometry is versatile enough to allow for X-ray detectors to be mounted close to the center of the trap. This is a rather unique characteristic of the system, and the present proposal takes full advantage of this. An additional β-counter can be inserted in the vacuum cross, because once the electron gun (E-gun) is fully retracted, this space is available. The E-gun is conveniently mounted on a linear feed-thru, and can be pulled back sufficiently far as to not interfere with the rest of the set-up anymore.

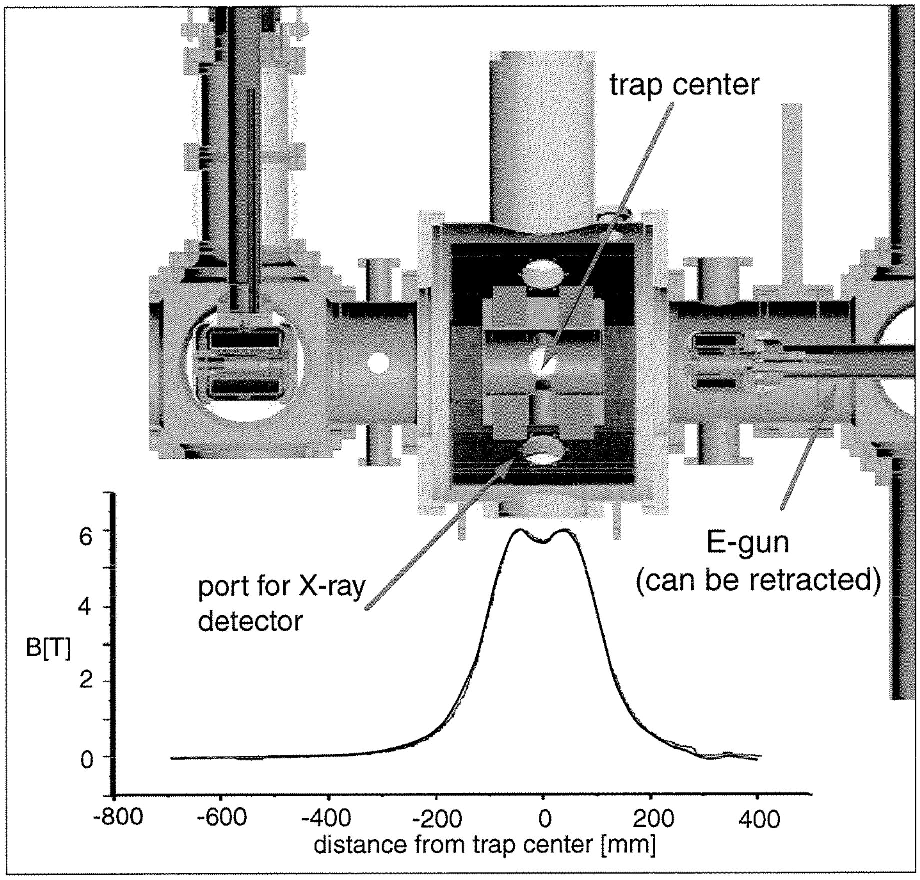

Fig. 2.3: EBIT schematic set-up together with magnetic field distribution. The E-gun head will be retracted to make room for a β-counter.

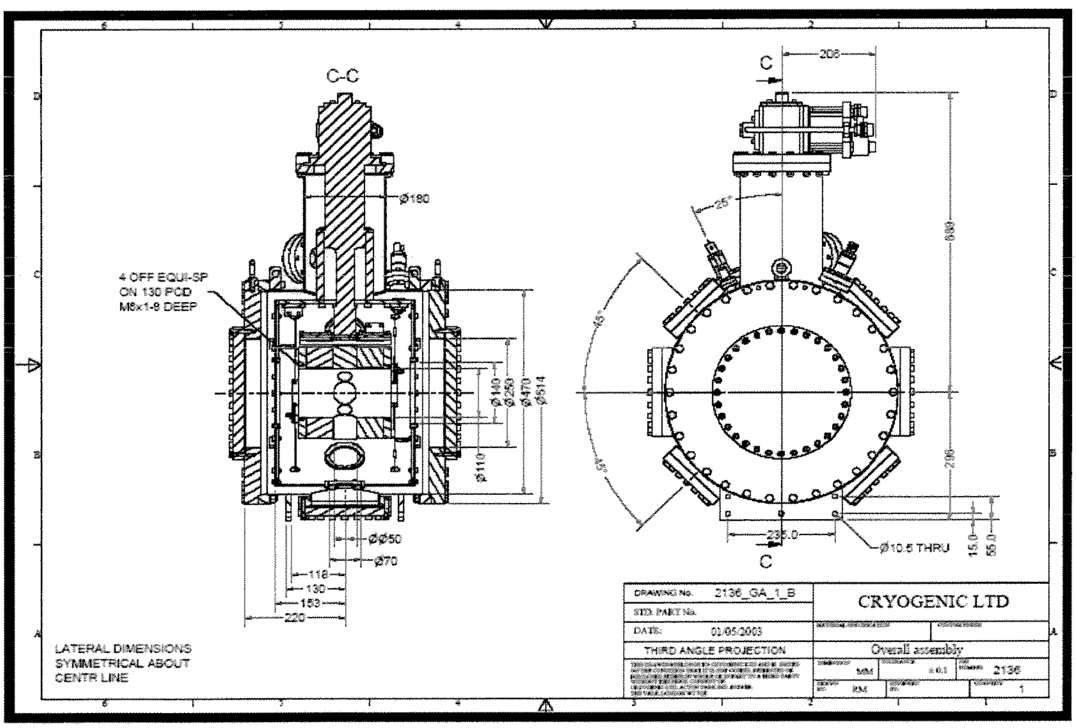

Fig.2.4: Drawing of EBIT magnet with magnet coils and ports.

The 7 ports (see figure 2.4) are located around the trap at 45°, 90°, 135°, 180°, 225°, 270° and 315° perpendicular to the beam axis. The zero degree port is occupied by the cold finger system of the super-conducting magnet. The individual ports have a diameter of 50mm and are located on a sphere around the trap axis on a radius of 225 mm (presently restricted by the extra thermal shield). Hence, in this configuration, the subtended solid angle would be 2.1% of 4π. This assumes an active surface area for each detector of $A = \pi\ (25\ \text{mm})^2 = 1963\ \text{mm}^2$. A modification of the Be-window sealed access port, which allows a larger solid angle is under discussion. A cross sectional view of the trap showing the position of the window is shown in fig. 2.5. The beam estimates will, however, use the number of the present design.

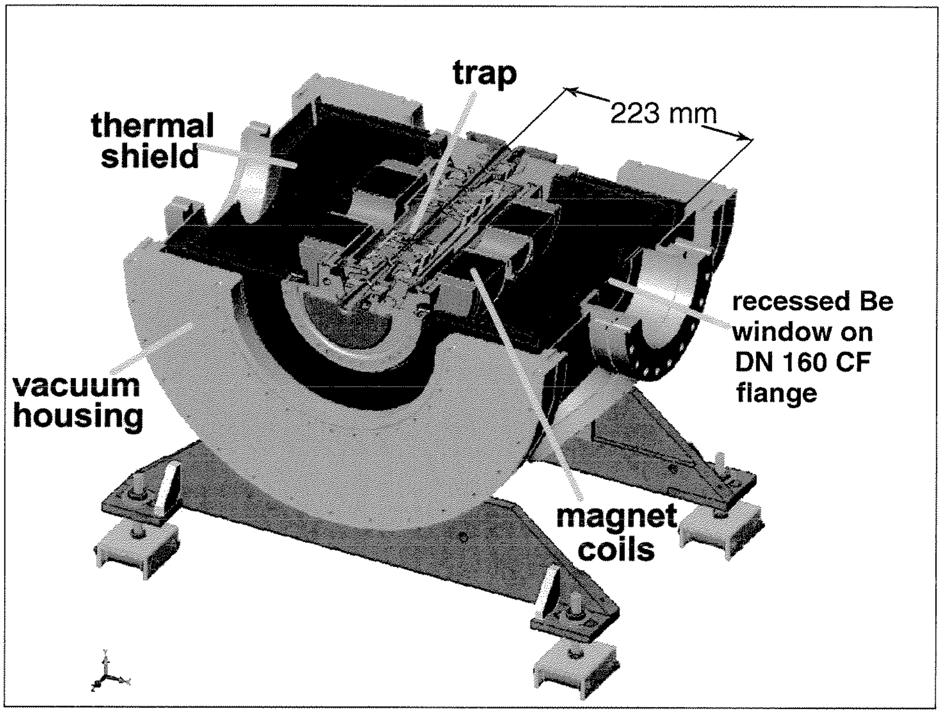

Fig. 2.5: Cross sectional view of the trap showing the position of the Be-windows. A modification to re-position the windows further inside to increase the solid angle is mechanically possible, but requires also a modification of the cryogenic part. This part is presently under discussion..

The seven detectors can detect the emitted X-rays without interference from electrons emitted by the much more intense β decay. The β decay electrons will be guided by the magnetic field lines away from the detectors and focused to the axis of the magnet at the exit. There they can also be observed with a suitable detector placed on axis, though still within the high field region of the magnet. The detection would operate in anti-coincidence in order to gate on possible X-rays which are associated with the β decay. This could be for example an MCP detector, or a channeltron, both of which are known to operate in high magnetic fields [FRA90,TRE96].

For an absolute branching ratio measurement, the total number of ions in the sample need to be determined. This can be done in batch-mode operation. A first batch will be prepared as an isotopically pure sample, trapped in the EBIT and expelled onto an ion detector (or the same β detector) for counting. This determines the number of ions per spill. The following number of on-line produced ions in each batch can then be monitored via the detected electrons.

A measurement of well established EC rates will be used to measure the total detection efficiency.

3. Beam time estimates

- Transfer efficiency of the ions into the RFQ (20 %),
  into the isobar separator Penning trap (10%),
  into the EBIT (50 %)

- Ratio of 'good-to-bad' ions that can be dealt with in the Penning trap $\sim 1:10^4$

- Total number of ions in the Penning trap per spill: $\sim 10^5$

<u>Example case:</u>

Step-1: ^{100}Tc will be laser ionized, and a clean beam will be transferred to TITAN. Additional mass selective buffer-gas cooling will lead to isobar separation of spills with ~10.000 ions. The ^{100}Tc atomic mass is known with an accuracy of 2.3keV. Therefore, mass separation can be done selectively and efficiently via the excitation of off-resonant ions (cyclotron frequency is mass dependent.)

Step-2: Accumulation of 10 spills in EBIT.

Step-3: Start counting at 100 000 ions in EBIT trap.

With a ^{100}Tc a half-life of $T_{1/2}$ =15.8 ±0.1, an EC branch $\varepsilon \sim 0.0018$ % (1.8×10^{-5}) and a detection time of 15 s (~ 1 half-life), one calculates 50.000 β^- decays and ~ 0.9 EC decays.

Solid angle acceptance:	2.1 %
X-ray-detection efficiency (assumed):	30 %

Total number of detected EC events per 15 seconds: 5.6×10^{-3}

For 100 detected events, ~ 17.637 EBIT trap fills needed =	74 h of operation (6 shifts)
Overhead (~20%)	<u>14 h (1.2 shifts)</u>
Total number of hours/shifts:	88 h (11 shifts)

The beam time estimate for the other isotopes scales approximately with the ratio of the EC branches ($\varepsilon_{100}/\varepsilon_x$) and the ratio of the partial β-decay life-times for the ground state transitions (τ_x/τ_{100}), assuming that in all cases ~ 100.000 ions are being brought into the trap. Further, a 10% statistical accuracy is assumed. (For 3% statistical accuracy, scale by another factor 10.)

Scaling factors: (^{100}Tc: 1.00 (~ 88 h, 11 shifts) per definition)

^{110}Ag: 0.01 (~ 1 h) for 3% statistics → 10 h
^{114}Cd: 0.02 (~ 2 h) for 3% statistics → 20 h
^{116}Cd: 0.08 (~ 7 h) (using EC rate 0.023 %)
1.2 (~ 13 shifts) (using EC rate 0.0015 %)
^{82m}Br: deferred
^{128}Te: 0.4 (~ 37 h, 5 shifts) for 5% statistics → 20 shifts
^{76}As: 473 (~ 41.650 h) (using EC rate 0.01% (*log ft* = 9.1), no overhead!)

The measurements on ^{76}As are in the present configuration not doable. Yet, the solid angle in the EBIT trap could be increased by moving the detectors closer to the trap center. At present, the radius of the detector position is limited to r = 225 mm (see fig. 2.5). It is given by the Be-window of the second stage thermal shield of the super-conducting magnet. It is possible to move this window further inwards by recessing the shield, but this modification would probably have to be carried out by the magnet manufacturer. The shield can then be placed on a radius of r =150 mm, thereby bringing all seven detectors closer and increasing the solid angle by a factor of 2.25.

The maximum possible number of stored ions also needs to be investigated in detail. The presently assumed number of 10^5 is a conservative estimate. Experiments with REXTRAP [AME05] at ISOLDE/ CERN have shown that when additional dipole-forces are applied, for example with the so called rotation wall technique [BOL93, DUB99], storage capacities of 10^6 and 10^7 can be reached.

With the increase in solid angle and an increase of the storage capacity to (a conservative) $5 \cdot 10^6$, the beam time needed for a 10% measurement would decrease to a more realistic value of about 50 shifts (including a 10% overhead).

Backgrounds

The level of background in the X-ray detectors cannot be reasonably well estimated at the present time. There are various scenarios of possible background sources one may have to consider in a situation of low counting rates. These could be Bremsstrahlung-photons accompanied with EC (of order 10^{-2}-10^{-3}), X-rays from possible ion-wall interactions, induced X-rays after β^- decay (although the anticoincidence will partly discriminate), Compton-scattered γ-rays, cosmic induced backgrounds, neutron induced γ-ray backgrounds etc. The high-resolution of the X-ray detectors ($\Delta E < 1$ keV) will certainly be an advantage for the signal to background ratio.

The present proposal will therefore ask for test beams to evaluate:

Storage capacities,
Storage times,
Isobar separation,
Capabilities of measuring absolute values,
Background levels under different conditions.

4. Readiness

The experiment can be started as soon as the TITAN-facility including the EBIT trap are operational, which is presently foreseen for the 1st half of 2006. The radioactive beams will have to be provided by ISAC. It may require the operation of the actinide target, although the presently requested intensities are low and could be provided with an alternative Ta target.

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The spokesperson published about 40 papers in refereed journals over the last 5 years on the following topics:

High-energy physics (neutrino physics)
Nuclear physics (charge-exchange reactions)
Double beta decay matrix elements
NIM articles on detectors and developments

Journals:
Phys. Rev. C,
Phys. Rev. Lett.
Phys. Lett. B
Nucl. Phys. A
Nucl. Instr. & Meth.