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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

NICOLE Collaboration Status Report

25 September 2019

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Abstract

We present the status report of the NICOLE facility, starting with the overview of its history since 2010, and showing the latest result confirming that a sub-1K temperature has been reached during the last run in August/September 2019. Cooling to down to mK temperature was prevented by the unexpected (?) malfunctioning of an electrical connection to the ^{3}He diffusion pump which is now is being repaired. The fridge is now leak free and all its parts, including the dilution unit, are now operational. We plan another run in the second part of October to cool down to mK temperature with the repaired diffusion pump. The result will be reported in the presentation at the Collaboration meeting in November.

Next presented are details of the current proposals IS460 and IS575, high-lighting new developments since they were originally approved. Future experiments on fundamental symmetry violations testing, as an extension of IS460, new detection technique used of beta-delayed neutron experiments for IS575, and a new initiative in medical physics are outlined.

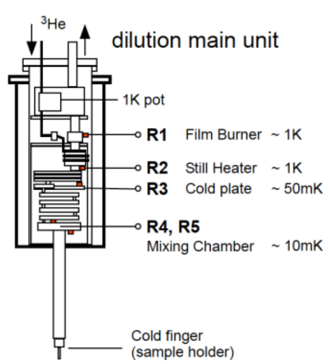
Finally overview of the personnel and financial support is given.

1. Overview of activities at NICOLE since 2010 – present

NICOLE is an on-line low temperature nuclear orientation experiment at ISOLDE, CERN that has been in operation since the 1980s. NICOLE has in the past produced a lot of impressive measurements of nuclear ground state properties, essential for better understanding of nuclear structure. NICOLE at ISOLDE provides a unique combination of beam and device, not available in any other facility worldwide. The intensity and diversity of ISOLDE beams and very high level of polarization achieved with at NICOLE enables experiments, which cannot be performed anywhere else. This continues to be the case in the foreseeable future for number of cases presented here. The NICOLE collaboration is responsible for over 50 publications and over 15 PhD and Master Thesis [1]. The experiment operation was stopped in 2011 due to a leak that could not be repaired locally, and by the major construction work happening at the ISOLDE hall. The recovery of NICOLE after the ISOLDE Hall upgrade was challenging. There was damage done to the instrument itself and a lot of hardware lost, including: power and water connections; air and He recovery lines; and control electronics and the vacuum systems. The structures for filling the fridge with nitrogen and liquid helium as well as for top-loading sample holders and off-line samples had to be rebuilt due to the mezzanine being now shared with the HIE-ISOLDE project.

The NICOLE dilution refrigerator ***has been restored to its previous functionality at the cost of over 20K EUR.*** The major leak that stopped the NICOLE operation in 2011, was fixed by ICE Oxford. Systematic tests of the vacuum and cooling functions started in 2016, happening 2-3 times a year until present. A steady but slow progress was made dependent on the limited availability of Takashi Ohtsubo and Stephanie Roccia, who at that time were the only members of the group with the expertise to lead these operations. Many previously undiagnosed problems were found in the intervening years, overall extending the repair period beyond the original plans. The group from Novi Sad led by Jovana Nikolov is now taking responsibility for operations of the instrument. The most recent runs were led by Taka Ohtsubo and attended mainly by PhD students Andrej Vranicar and Milos Travar from Novi Sad who are now trained to operate the fridge independently.

Table 1. Results of the fridge test in September 2019. RT=room temperature, LN2=liquid nitrogen temperature, LHe=liquid He temperature, SC=start circulation. The drawing shows schematically their distribution in the fridge.



R1	R2	R3	R4	R5	Date	condition
August 2009						
367	338	341	338	365	31/7/2009	RT
371	429	342	336	380	1/8/2009	LN2
421	637	385	375	1241	2/8/2009	LHe
518	576	469	423	1418	2/8/2009	SC
445	593	1498	1033	>1600	2/8/2009	~10 mK
September 2019						
414	375	355	342	389	2/9/2019	RT
435	377	355	348	388	4/9/2019	LN2
462	424	392	360	895	5/9/2019	LHe

Finally, during the last run in August 2019, fridge was cooled down to sub-1K temperatures, after a successful test of the vital part of the cooling system, the 3He+4He circulation line. This was achieved using the 3He rotary pump as there was a problem with electrical connection of the 3He diffusion pump. We stress that the pump is independent of the fridge and the repair is under way. Based on prior experience and the measurements (see Table I), we believe that once this pump is operational, a target temperature of ~10mK will be achieved. The next run, planned for October 2019, will provide data on the final cooling down of the fridge, which will be included in the presentation by Jovana Nikolov at

the INTC committee meeting in November. The fridge will be then connected to the beam line, ready for stable beam tests.

1. Current approved experiments and associated new developments

IS460: Magnetic Dipole Moments of High-K isomers in Hf Isotopes (12 shifts)

N.J.Stone, J.R.Stone, T.Ohtsubo, C.Gaulard, U.Köster, M.Madurga, J. Nikolov, S.Roccia, M.Veskovic, A.Vranicar, M.Travar and W.B.Walters.

The already published results of the first experiment reported on-line orientation measurements on two high-K isomers, the $37/2^-$, 51.4 m, 2740 keV state in ^{177}Hf and the 8^-, 5.5 h, 1142 keV state in ^{180m1}Hf using the NMR technique and gamma-ray angular distribution measurements [2]. The next experiment under IS 460 suffered from weak beams, poor delivery through the last parts of the beam line and beam interruption which greatly extended the time-scale of the experiment. NMR/ON resonance was observed as planned for ^{180m1}Hf, $I^\pi = 8^+$ implanted into nickel. However, NMR/ON of ^{177m2}Hf in Ni, required to give an accurate value for the hyperfine field for Hf in Ni and hence to yield the moment of ^{180m1}Hf, was not observed.

In the second addendum to the IS460 experiment a request was now made for a final two-part experiment under IS 460. The first part, of 6 shifts, to seek for NMR/ON of ^{177m2}Hf in nickel to complete the ^{180m1}Hf experiment. The second part, of 6 shifts, was to include (1) a first, pilot measurement of orientation in iron of the ground state of ^{169}Hf, by study of the temperature dependence of the 493 keV gamma anisotropy and (2) preparation of a weak sample of the ^{179}Hf in iron, implanted on-line, for subsequent off-line measurement, as in the original IS 460 proposal.

The remaining 6 shifts were to orient ^{169}Hf and to prepare a sample of ^{179}Hf for off-line study. However, our interest in the properties the activity of high-K isomers has reduced with retirement of Phil Walker.

As a new initiative, we propose to use the remaining shifts for further study breaking of the CPT symmetry in nuclei, using the 5.47 h isomer of ^{180m1}Hf. The main reason for such experiments is to test the CPT theorem which states that the combined operation of charge conjugation (C – changing particle to antiparticle), time reversal (T – reversing the flow of time), and parity (P reversing the orientation of space) in any order is an exact symmetry of any interaction and that under the three transformations all physical laws must be invariant. Many experiments have been devoted to proof this theorem experimentally and/or direct search for T-violation in a variety of systems, including kaon [3] and B-meson decays (see Ref. [4] and Refs. therein), neutron reactions [5,6], atomic systems [7] and a search for permanent anomalous electromagnetic moments [8]. These searches are still continuing.

Oriented nuclei play an important role in testing of symmetries of nuclear interactions [9]. The orientation axis defines a direction in space with respect to which the symmetry operation can be performed. The angular and polarization distribution of emitted radiation is sensitive to the operation. For example, in beta decay of oriented nuclei the parity violating nature of weak interaction was discovered, using a set-up analogous to NICOLE [10]. In gamma-decay, the multipole mixing ratios are sensitive to anomalous symmetry breaking admixtures in the initial state of a transition. Experiments may be designed not only for parity non-conservation, but also for T and simultaneous PT symmetry violation on the same system. The measurements can be performed at the same time if the geometry of detection system is arranged accordingly as demonstrated in Figs.1 and 2 [11,12].

Following the successful measurement of the P symmetry violation through measurement of an irregular E2/M2 mixing ratio in the 8^- -> 6^+, highly K-forbidden, 501 keV gamma transition in an oriented 5.47 h isomer of ^{180m1}Hf [13], we wish to use the remaining 6 shifts to test a set-up for investigation of the T and PT symmetry breaking using the same system. The decay of the ^{180m1}Hf isomer is uniquely suited for symmetry breaking experiments as can be seen in the level scheme in Fig. 3. The 8^- (K=8) isomeric state decays to the 6^+ level of the K= 0 ground-state rotational band via of the 501 keV transition, which is of mixed E3/M2 multipolarity. The parity non-conserving interaction is expected to admix a small 8^+ component into the 1.142 MeV 8^- level. Assuming that this admixture can be treated as a perturbation, close spacing between the 8^- level and the 8^+ level at 1.084 MeV tends to magnify the admixture. In addition, the parity conserving E3 and M2 components of the 501-keV transition will be strongly hindered, resulting in a relative enhancement of any possible irregular (parity violation) component – a signal of parity mixing in the 8^- 1.142 MeV isomeric state [13].

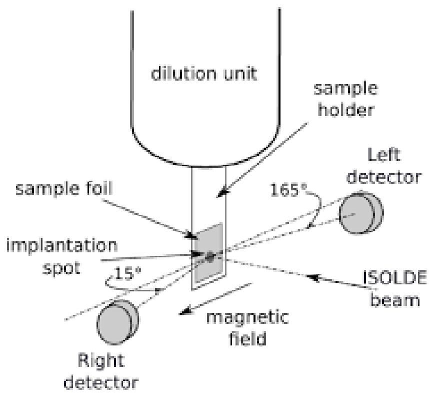


Fig.1 Geometry for parity non-conservation test.

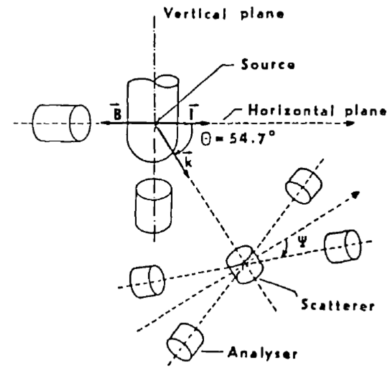


Fig.2 Geometry for the time-reversal invariance test.

To study T and PT reversal violation in nuclear gamma-decay, detection of the linear polarization of gamma-rays from oriented nuclei is required. Pioneering experiments were performed in 1980's [9,11,13], but the geometry and handling of the systematic errors produced by the Compton polarimeters assembled of 4+1 low efficiency GeLi detectors, available at that time, were the main obstacle to pursuing this research. Today these experiments could be performed using highly efficient segmented clover detectors as Compton polarimeters [14]. All currently available Compton polarimeters use the recoil photon as a signal which limits its efficiency.

The parity non-conserving interaction is expected to admix a small 8^+ component into the 1.142 MeV 8^- level which would lead to an anomalous E2 component in the 501 keV transition. Assuming that this admixture can be treated as a perturbation, close spacing between the 8^- level and the 8^+ level at 1.084 MeV tends to magnify the admixture.

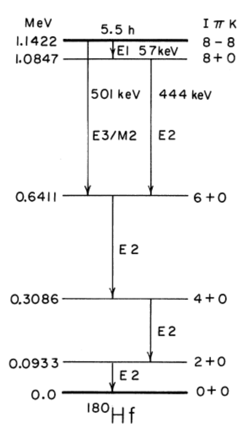


Fig. 3 Level scheme of $^{180}Hf^{m1}$

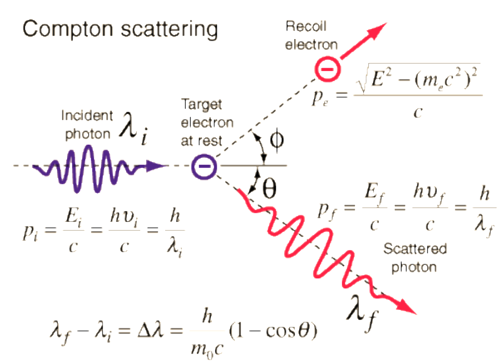


Fig.4 A sketch of the Compton scattering

We plan to explore a new design of a polarimeter which would be sensitive to the energy and position of the recoil electron as well as to the scattered photon (see Fig.4). When such a device could be developed, its polarization detection efficiency would increase considerably, and the proposed experiment will be in the forefront of the symmetry breaking in nuclear systems searches.

IS575: Beta-delayed neutrons from oriented ^{137,139}I, and ^{87,89}Br nuclei (18 shifts)

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The NICOLE collaboration is preparing for a new experiment, for ***the world first*** study of the angular distribution of beta-delayed neutrons emitted by nuclei oriented at low temperatures.

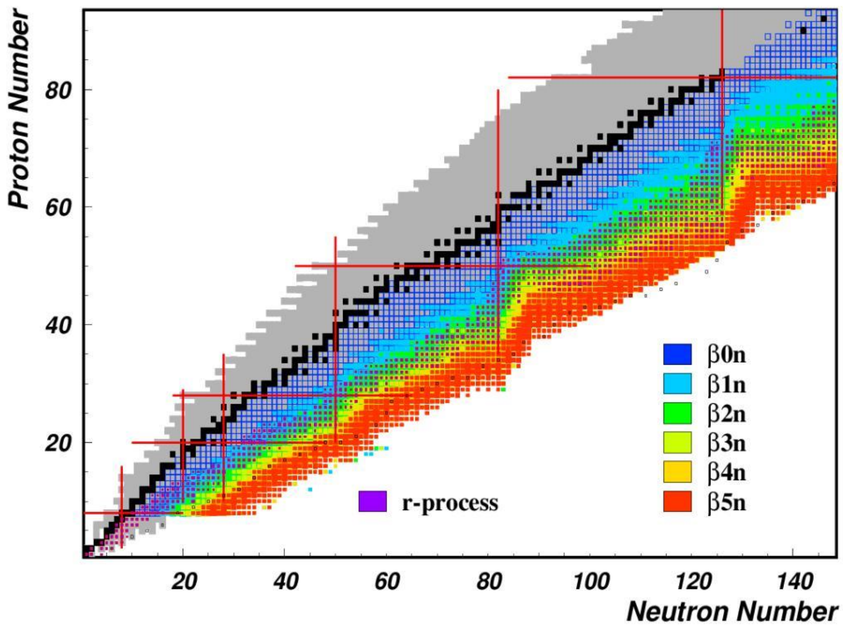


Fig.5 r-process path [32] and the multi-neutron emitters [33].

Beta-delayed particle emission processes are predominant as the drip-lines are approached Importantly, all the r-process nuclei are delayed neutron emitters (see Fig.5) and any nuclear model used in astrophysical simulations must account correctly for beta-delayed neutron emission. Conventional spectroscopy provides overall information concerning energies, level structures and transition probabilities. Recently obtained interesting results [15-17] show clearly the first stage of this process, when the beta-decay is driven by the Gamow-Teller mechanism, while the neutron emission seem to be dominated by the compound nucleus decay, at least in the heavier nuclei. This makes the neutron emission only sensitive to spin and parity of the excited nucleus [18-20]. This hypothesis has been supported by several observations in the past and in more recent experiments but it is not universally proven due to experimental limitations. The spins and parities in the emitter, see Fig 6, were never measured. In particular, the contribution of different partial waves to the neutron emission remains unknown. The study of the angular distribution of the beta-delayed neutrons from nuclei, with a high degree of controlled polarization, provides on the angular momentum composition of the emitted neutron waves. Considering that the beta-delayed neutron emission is a dominant decay mode for majority of the neutron-rich nuclei, neutron spectroscopy may become one of the dominant technique for future decay measurements and the NICOLE measurement will be critical to shape the future directions of this research.

The proposed experiment is to measure the angular distribution of beta-delayed neutrons from ^{137,139}I and ^{87,89}Br nuclei, polarized at the NICOLE facility. The aim is to make direct observation of the magnitude and sign of the departure from spherical symmetry of the beta-delayed neutron spectrum and establish whether the observed anisotropy of the angular distribution and its dependence upon neutron energy is consistent with theoretical predictions based on the best existing models (see Ref. [18-20] and Fig.7) which comprise the QRPA or shell-model of the beta-decay and the statistical Hauser-Feshbach model of the neutron emitting states.

In the original proposal, the neutron detection was going be done using the Versatile Array of Neutron Detectors at Low Energy **(**VANDLE**)** in conjunction with high purity Ge detectors for neutron–gamma coincidence and fast beta detection to allow time-of flight determination of neutron energy [21-23]. This detector measures time-of-flight between the neutron origin and a plastic scintillator, placed in a fixed distance, in which the neutron is stopped and produces a visible signal which is position sensitive (left part of Fig. 8).

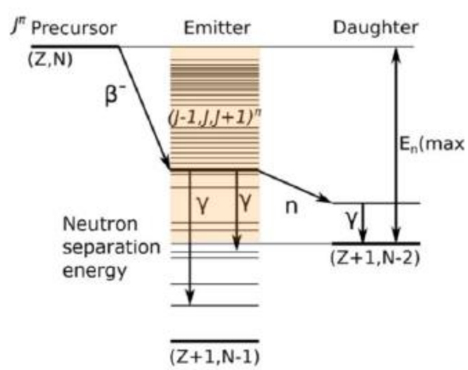


Fig.6 Illustration of the beta-delayed neutron process

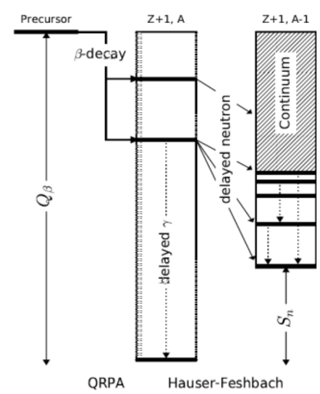
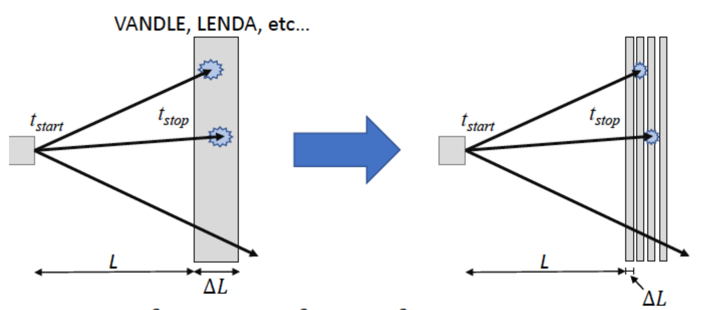


Fig.7. Application of theoretical models to different phases of the decay.

As a new development, a more efficient neutron detector Neutron dEtector with X-neutron Tracking (NEXT) [24] has been developed beta-delayed neutron experiments in which the scintillator is segmented as shown in the right part of Fig. 8. This design aims for improving timing and position resolution without decreasing detection efficiency and adds neutron-gamma discrimination capability. These features are particularly important in measurement of angular distribution of the delayed neutrons.



$$\left(\frac{\Delta E_n}{E_n}\right)^2 = \left(\frac{2\Delta(ToF)}{ToF}\right)^2 + \left(\frac{2\Delta L}{L}\right)^2 \qquad \text{Eff.} \propto \Delta L \times n_{segmen}$$

Fig.8 Schematic features of the VANDLE and NEXT detectors (taken from [24]).

The proposed experiment ***is to prove the method in principle*** and measure the angular distribution of beta-delayed neutrons from ^{137,139}I and ^{87,89}Br nuclei, polarized at the NICOLE facility before getting to more exotic cases.

3. Future experiments at NICOLE

With NICOLE becoming operational, the collaboration will be able to strengthen its scientific case with the funding agencies and in time recover the full strength of the scientific program, with the unique beams of radioactive isotopes available at ISOLDE.
We will propose to the INTC new the time-reversal experiment and further investigation of the beta-delayed neutrons from relevant targets. The latter is an uncharted territory and even the proof-of-principle experiments may provide surprises. For beta-delayed neutron spectroscopy we are somewhat limited by two factors, the need to go as far from stability towards the neutron drip-line as possible and the decrease in life-time and beam intensity. While the studies iodine and caesium isotopes have been identified as primary goals for the demonstration experiments, there are other cases which can be delivered at ISOLDE, such as heavy Cu, Sb and Y.

As the third line of development, we wish to make a proposal to obtain nuclear structure data on isotopes used for medical applications. ***This area of research, lead by Ulli Koester, is of a particular interest to the Novi Sad group. The University of Novi Sad has a strong medical physics school and there will be a several PhD students recruited and supported to join these experiments.***

Targeted radionuclide therapy is a powerful method to treat serious diseases such as cancer. Nuclides emitting short-range radiation such as α particles, low energy β, conversion or Auger electrons are linked to a biomolecule, called vector, that can selectively target cancer cells. Ultimately the best targeting could be achieved with Auger electrons due to their very short range [25]. Thus, isotopes that emit conversion electrons followed by cascades of Auger electrons are of great interest. Preclinical experiments study the therapeutic effects and side effects of different radionuclides as function of activity [26, 27], but eventually this activity has to be converted into dose for direct dose/effect comparisons. This requires precise knowledge of the intensities of all conversion electrons and the resulting Auger cascades. Experimentally it is very difficult to measure precisely low-energy conversion electrons, but it might be easier to approach the problem indirectly: measure precisely the mixing ratios, then calculate the conversion electron yields. Such measurement would involve measurement of rather low energy gamma-rays, requiring special detectors, to be placed inside the NICOLE cryostat. We have a considerable experience with such detectors [28-30] and take advantage of current progress in technology.

A major technological innovation in construction of dry ^{3}He dilution systems for cooling samples to mK temperatures has been recently accomplished, although the principle has been known for some time (see Fig.9). These systems do not require liquid refrigerants, the operation can be considerably automated and operate down to temperatures < 10 mK. Details can be found, for example, in [31]. Although these instruments are not yet fully ready for on-line nuclear orientation experiments as there may be issues with side access to the beam line, top-loading of the sample, cooling power and vibrations, we envisage them as a future for further 'new" NICOLE physics at ISOLDE.

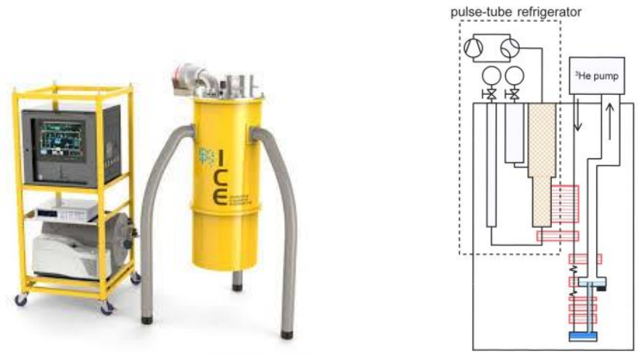


Fig.9 Over-all picture (left) and a schematic diagram of a cryogen-free, or dry, dilution refrigerator precooled by a two-stage pulse tube refrigerator, indicated by the dotted rectangle (right). Taken from [31].

5. Funding available for the NICOLE project in the partner institutions

The Novi Sad group has at present a yearly income from the Serbian government of **10K CHF** dedicated to the NICOLE activity. There is all expectation that this money will continue for foreseeable future when NICOLE starts to produce results. A new application for the Serbian governmental grant supporting Milos Travar's long term presence at CERN, in case he does not get a CERN fellowship, is being prepared.

The University of Tennessee (UTK) made a commitment to provide, using SC grant which ends 08/15/2020 (after that a 3 year renewal will be asked for). The NNSA grans started 06/04/2019 and will support experiments with UTK neutron arrays for 3 years.
1. VANDLE or NEXT/v5D neutron detector arrays in the configuration required for studies with oriented beta-delayed neutron emitters as outlined in the proposal. This also includes the development of the trigger detector attached to the 4K window necessary for the time-of-flight measurements. The construction of about 50 more NEXT detector modules has been recently funded at $910k by NSF through the Major Research Instrumentation program.
2. Digital data acquisition system, which can support all NICOLE experiments.
3. Mechanical workshop support, to machine parts for NICOLE and related experimental systems.
This technical support, depending on a configuration, is worth between 200-300k USD.
4. Personnel support for the detector systems during preparation and experiment itself, up to 3 persons per experiment 2-3 times a year (~5 k USD per person per trip). PhD student cost is about 50k USD a year.

University of Niigata is preparing a new application for travel and NICOLE related expenses and a support for a graduate student dedicated to NICOLE.

It is important to realize that it has been difficult to seek new funding for NICOLE in the past with the fridge not operating. When the facility is working, new applications for funding will be launched.

6. Personnel:

The group of the **University of Novi Sad**, led by **Jovana Nikolov**, has been a prime mover in training **Andrej Vranicar** and **Milos Travar**, PhD students in running the NICOLE fridge, thus releasing Takashi Ohtsubo from his sole responsibility for the fridge. Nevertheless, we hope that Taka will remain an important member of the NICOLE team in future. **Miroslav Veskovic** is also a senior member of the team currently working in Brussels.

Takashi Ohtsubo of the **University of Niigata** became the central figure in the fridge work over the years. Although subject to his availability due to his duties at his home institute, he still keeps a strong connection with the NICOLE collaboration.

University of Tennessee researchers (**R. Grzywacz , M. Madurga, N.J.Stone and J.R.Stone)** have a strong interest in the success of NICOLE. **Robert Grzywacz** and **Miguel Madurga** lead the proposal IS575. **Miguel Madurga** is an integral member of the VITO collaboration which has similar goals and is leading nuclear orientation studies at UTK. UTK researchers have a very strong interest in investigating and modeling beta-delayed neutron emission and provide expertise in calculations using shell-model and statistical model. The latter is done in collaboration with Toshihiko Kawano from Los Alamos National Laboratory.

The **POLAREX group in CSNSM, Université Paris Sud, Carole Gaulard**, her student and **Stephanie Roccia** (currently at ILL), are seen as an essential part of the NICOLE team. We view NICOLE and POLAREX as mutually complementary operations, being the only facilities which will work on-line with radioactive beams. Thus, the most productive way forward is seen as planning joint experiments and sharing their conduction, data analysis and publications. It is essential to realize that there is a difference in beams available at ISOLDE and ALTO. For example, heavy beams such as Hf, which are needed for our proposed future experiments will never be available in Orsay, as well as proton rich nuclei and some rare earths for the medical physics studies. These beams are readily available at ISOLDE. It may take a long time before negative ion beams such as I and Br, needed for the beta-delayed neutron studies, will be produced. Also, POLAREX would benefit from an increasing manpower which would be achieved if the NICOLE team joined in when the physics program is known. In the same way, we consider the Orsay team as an important part of the NICOLE team. The combination of radioactive beams available at ISOLDE and ALTO will make accessible to study a wide range of nuclei, both in the neutron rich and neutron deficient sides of the nuclear chart.

Ulli Koester of **ILL, Grenoble**, has been a long-term member of the collaboration responsible for beam and target related issues.

W.B.Walters, Professor of Chemistry at the **University of Maryland** has been associated with NICOLE for many years contributing to nuclear model related interpretation of the results.

6. Summary

We have reported current status of the NICOLE facility illustrating that all the components of the fridge are in working order. After a technical issue outside the fridge is repaired, we will cool down the fridge to mK temperature and show the data during the oral presentation to the INTC in November.

The current experiments IS460 and IS575 have been discussed and physical and technical developments since their approval presented. Proposals for future experiments include (i) fundamental symmetries violation test, (ii) beta-delayed neutron emission from polarized precursors experiments on precursors with the aim to provide data relevant to astrophysics and to better understanding of the process itself, and (iii) measurement relevant to medical applications. Further development in cryogenic technique to "dry" ^{3}He dilution refrigerator, which would bring the experiments to the next level of sophistication, is outlined.

NICOLE is currently the only facility on-line to isotope-separated radioactive beams. It extends the already rich and diverse physics program of ISOLDE in the direction which cannot be followed any other way. In combination with the POLAREX at ALTO (when it gets on-line) the low-temperature-nuclear-orientation technique will provide unique data with a wide application across low energy nuclear structure and theory.

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