Spectroscopy of transfermium nuclei using the GABRIELA set up at the focal plane of the VASSILISSA recoil separator

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Abstract. An IN2P3-JINR collaboration has launched a project called GABRIELA at the Flerov Laboratory for Nuclear Reactions (FLNR) at the Joint Institute for Nuclear Research (JINR) in Dubna (Russia). The goal of the project is to perform gamma-ray and internal conversion electron spectroscopy of heavy nuclei produced in fusion-evaporation reactions and transported to the focal plane of the recoil separator VASSILISSA. During five experimental campaigns of GABRIELA, the detection system has gained in sensitivity and new spectroscopic information has been obtained for ^{249}Fm, ^{251}Fm, ^{253}No and ^{255}Lr.

Keywords: gamma-ray spectroscopy, electron spectroscopy, alpha-decay, nuclear energy levels, nuclear structure
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1. MOTIVATION

The heaviest elements provide a unique laboratory to study nuclear structure and nuclear dynamics under the influence of large Coulomb forces and large mass. Super Heavy Elements (SHE) are nuclei with vanishing liquid-drop fission barrier and are therefore entirely stabilised by quantum shell effects. Due to the large density of single-particle levels and strongly polarising Coulomb field, theoretical predictions of magic numbers are extremely model dependent. Furthermore, shell closures for one nucleon species depend strongly on the number of the other species. The extra binding from shell effects is not localised like in lighter mass regions but rather spread over all the shell closures. Finally, semi-bubble proton and neutron density profiles lead to anomalies of the spin-orbit splitting, which may disappear or even be reversed for certain orbitals. For all these reasons, only a systematic study of the structure of heavy nuclei can help in the development of better interactions and provide discriminating tests of models. The last synthesised elements (Z>110) have extremely small production cross-sections (pico barn to sub pico-barn) and the identification of a handful of events requires long irradiation times (many months). Luckily, equally important information on the structure of SHE can come from the study of lighter deformed transfermium nuclei ($Z \sim 100$–106). The cross-section for the population of these nuclei is many orders of magnitude higher so that detailed spectroscopy becomes possible.

2. THE GABRIELA SET-UP

GABRIELA (Gamma Alpha Beta Recoil Investigation with the ELectromagnetic Analyser VASSILISSA) is a multi-detector array placed at the focal plane of the separator VASSILISSA at the Flerov Laboratory for Nuclear Reactions in Dubna. The original system is described in detail in ref. [1]. It consisted of four multichannel plates to detect the secondary electrons emitted due to the passage of separated evaporation residues (ER) through C foils thus providing an identification flag and a time-of-flight measurement. The ERs are then implanted in a position–sensitive 16–strip silicon detector (60×60 mm^2) providing an energy and time measurement of these residues and their subsequent decay (α or fission). A tunnel of four silicon strip[1] detectors 50×50 mm^2, 500 μm thick with preamplifier[2] gains tuned for the detection of internal conversion electrons and escape alphas was placed on the upstream side of the implantation detector. Around the focal plane is a ring of six EUROGAM Phase-I Germanium detectors from the French-UK loan-pool, encased in BGO shields for Compton suppression. A seventh unsuppressed Germanium detector, placed in a collinear geometry with respect to the beam line, completes the array.

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[1] four strips
[2] The preamplifiers were provided by GANIL

3. EXPERIMENTAL CAMPAIGNS

2004. The first full-scale focal plane experiments were carried out in a commissioning run in September 2004. The aim was to produce already studied isotopes [2, 3, 4] with a ^{48}Ca beam and ^{207,208}Pb and ^{209}Bi targets in order to validate the experimental set-up.

2005. The second campaign of measurements was carried out in October 2005. The goal of this second campaign was to study the decay properties of ^{257}No produced by bombarding a radioactive ^{210}Pb target with a ^{48}Ca in order to confirm the recent finding [5] that the ground-state properties of ^{257}No break the N=155 systematics. This experiment suffered from problems with the target and no evaporation residues were observed at the focal plane of VASSILISSA after a beam dose of 8×10^{17} particles. This was probably due to a lack of material in the irradiated part of the target. However, radioprotection procedures were verified during the handling of this hot target. The remainder of the allocated beam time was used to collect more data on ^{255}Lr.

Preparation for 2006. Following the 2005 campaign the 37° analysing magnet was replaced by the original 8° magnet to increase the transmission of VASSILISSA. In preparation for experiments involving ^{22}Ne beams thinner emissive foils were produced in order to reduce both the energy losses and the angular straggling of the recoils of interest. In addition, one of the Germanium detectors from the French-UK loan pool was modified - reducing the distance between the Germanium crystal and the front face of the end-cap. The efficiency of the Germanium array was therefore increased by nearly a factor of 2 : the new γ–ray singles efficiency curve is shown in Fig. 1. The characteristics of the new set-up were measured during a test run in mid-September 2006. ^{22}Ne induced reaction products (from Au, Pb, W and Pt targets) were transported to the focal plane of VASSILISSA. The background conditions were considerably improved and the transmission/detection efficiency was measured to be $\sim$5% (2-3 times higher than with the old set-up).

2006. The third campaign of experiments was completed in December 2006. The aim was to use a ^{22}Ne beam and a ^{242}Pu target to study the decay properties of ^{259}Rf and ^{255}No and extend the existing systematics for the N=153 and 155 isotones. Since the cross–section for the reaction ^{242}Pu(^{22}Ne,5n)^{259}Rf is only of the order of 5 nb, the reaction ^{238}U(^{22}Ne,5n)^{255}No with $\sigma \sim 200$ nb [6] was used to set the ion optical parameters of VASSILISSA. No α particles that could be associated with the decay of ^{255}No were observed when two emissive foils of $\sim 30\mu$g/cm^2 were used for the time-of-flight measurement. This is a consequence of the important angular straggling of the ^{255}No recoils produced in asymmetric fusion-evaporation reactions induced by light projectiles and the smallness (60×60 mm^2) of our implantation detector. Extensive tests were then performed to compare the possibilities of 1) using only one emissive foil to merely flag the passage of a residue and 2) performing decay spectroscopy in the beam-off signal used to synchronise the beam on the rotating target. Finally, 1500 ^{255}No alpha-decays were observed at the focal plane of VASSILISSA and the transmission and detection efficiency of No recoils was estimated to be of the order of 1-1.5%.

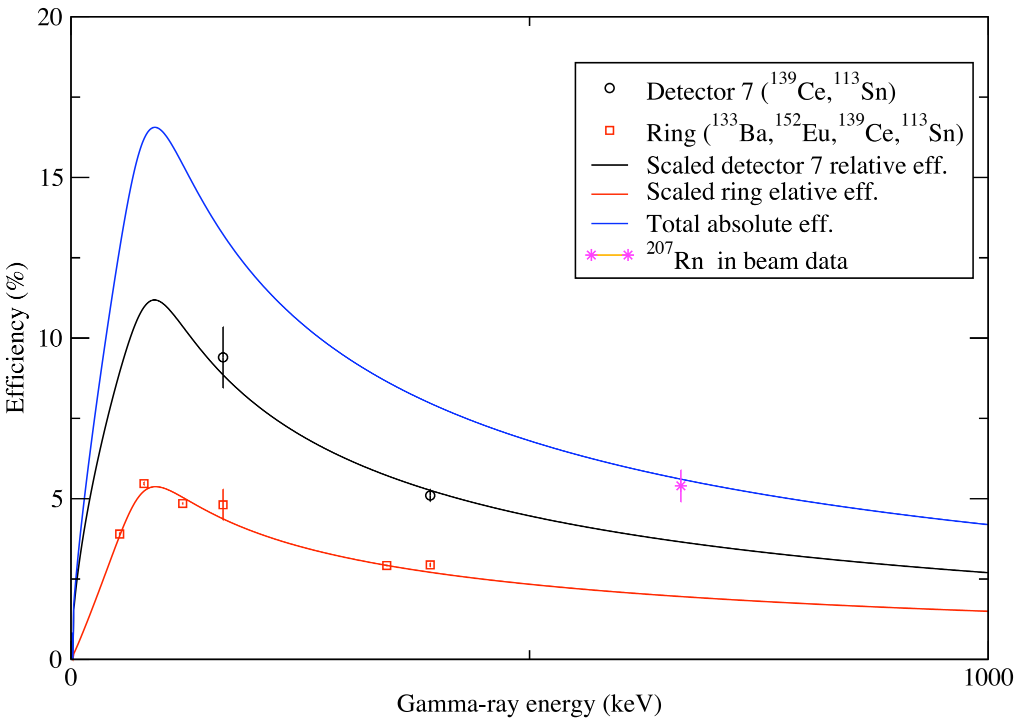

FIGURE 1. [color online] Points : Absolute efficiencies measured with standard sources or from in-beam data. Lines : relative efficiency curves, obtained using ^{133}Ba and ^{152}Eu sources, scaled to the absolute efficiency data points.

The remaining beam-time was used to study the decay of ^{217}Pa via the ^{181}Ta(^{40}Ar,4n) reaction. From the calibration data ^{174}Yb(^{40}Ar,xn) the decay from an isomeric $13/2^+$ state in ^{209}Ra was observed for the first time [7].

2008. During February/March 2008 we performed our 4th one-month long campaign. Our initial plan was to study ^{259}Rf following the bombardment of a ^{242}Pu target with a ^{22}Ne beam. In order to achieve this goal the emissive foils used in the time-of-flight measurement were again reduced in thickness, this time to $15-20\ \mu$g/cm^2. The distance between the emissive foils and the distance from the last foil to the implantation detector were further reduced. Tests were performed using ^{22}Ne+^{197}Au and a transmission of over 6% was achieved. The next incremental step was to tune the separator parameters using the ^{22}Ne+^{238}U reaction since it has approximately 40 times the cross-section of ^{22}Ne+^{242}Pu. Surprisingly we were unable to detect ^{255}No alpha decay at the focal plane, despite the aforementioned modifications. We have therefore abandoned the program of light beams on actinide targets until the upgrade of VASSILISSA has been completed (see SHELS in Section 6). Changing to a ^{40}Ar beam we then performed ^{208}Pb(^{40}Ar, 2n and 3n) excitation function measurements in preparation for the thesis data of Svirikhin [8]. In addition the decay properties of ^{245,246}Fm were studied with these data. Complementary statistics for the decay of ^{217}Pa and, in preparation for isomeric studies in ^{218}U, isomers in ^{214}Th were searched for.

2009. During February/March 2009 the 5th one-month long campaign was performed. For this campaign new electronics [9] had been designed for the new focal plane implantation Si detector. The detector is now a 48×48 Double Sided silicon Strip Detector. A resolution of 17 keV for the sum of the 48 front face strips was obtained. This face of the detector was equipped with 3 pre-amplification ranges, which allows it to be sensitive to low-energy electrons (100 keV) as well as high-energy fission events ($\sim$ 150 MeV). In the future, we hope to equip both faces of the detector with such preamplifiers so that low energy electrons may be properly position correlated to alpha particles or evaporation residues. More details of the new DSSD can be found in the contribution of Isaev to this conference [10]. We had envisaged to study ^{256,257}Rf via the reaction ^{208}Pb(^{50}Ti,xn) but problems with the beam preparation forced us to revert to the detailed study of the isomeric- and alpha-decay properties of ^{253}No using a ^{48}Ca beam. These data allow for a direct comparison with those taken in 2004 and Fig. 2 shows the fruits of the cumulative improvements made to the VASSILISSA + GABRIELA system as a whole.

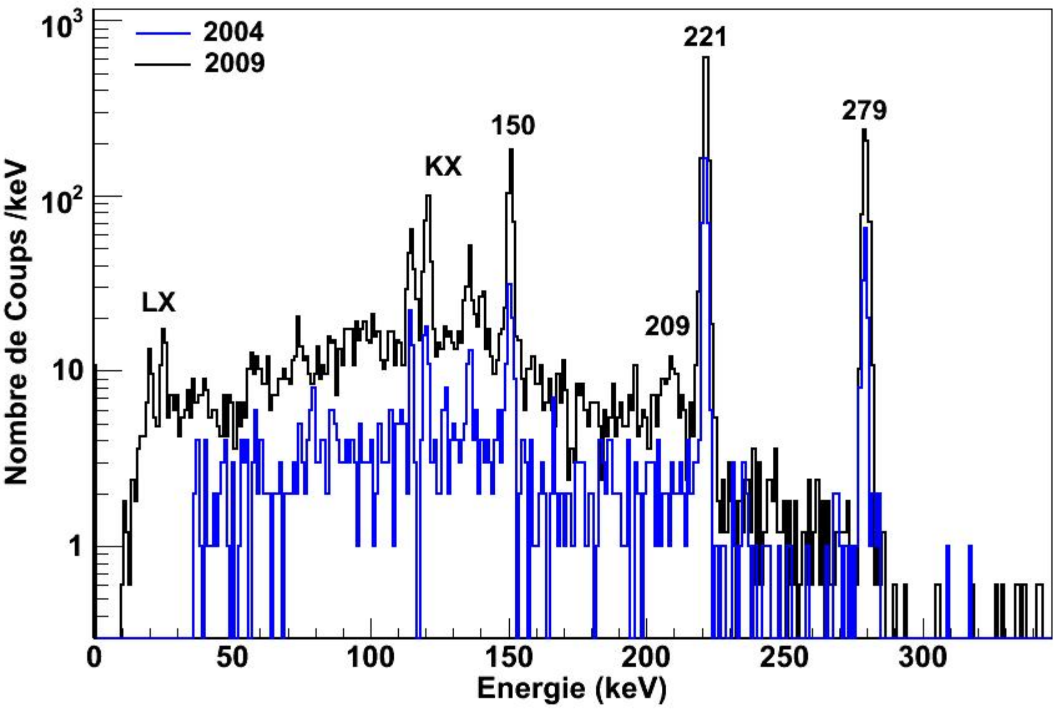

FIGURE 2. [color online] A beam dose normalised comparison of the γ–ray spectrum observed in prompt coincidence with the α–decay of ^{253}No.

4. RESULTS

In this talk results from ^{249}Fm, ^{253}No and ^{255}Lr will be discussed.

4.1. Detailed spectroscopy of ^{249}Fm

Excited states in ^{249}Fm were populated in the α-decay of ^{253}No, which was produced in the reaction ^{207}Pb(^{48}Ca,2n)^{253}No. The spectra of $\gamma-$rays and electrons emitted by the excited ^{249}Fm nucleus are shown in Figure 3. It was shown that the 279, 221 and 150 keV lines are emitted from the same nuclear state at an excitation energy of 279 keV and that they populate the lowest members of the ground state rotational band. From the measurement of a positive gyro-magnetic factor, the ground state configuration was firmly established to be based on the $7/2^{+}$[624] Nilsson neutron orbital. The 279 keV state, favourably populated in the $\alpha-$decay of ^{253}No, was assigned the $9/2^{-}$[734] configuration as the three transitions which de-excite it are of E1 character. These observations are consistent with the results of Herzberg [2] and Hessberger [3] and gave us confidence that our new experimental set up was performing correctly. However, there remained a problem of an observed excess X-ray intensity suggesting that the level schemes in [2, 3] were incomplete. From a careful analysis of the $\alpha-$electron coincidence matrix combined with GEANT4 [11] simulations, the presence of a 5/2+ state, which decays to the ground state by a highly converted 211(2) keV M1 transition was inferred [12]. The existence of this M1 transition was recently confirmed by the observation of a weak 209 keV line in an experiment performed at SHIP [13].

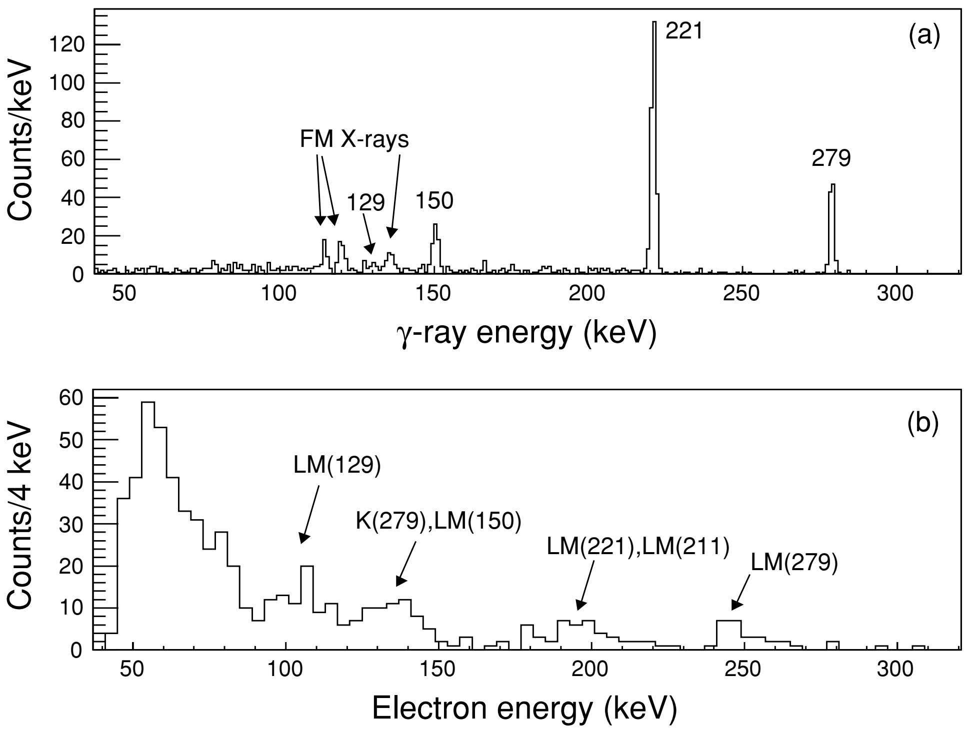

FIGURE 3. Spectrum of a) γ-rays and b) conversion electrons detected in prompt coincidence with the α-decay of ^{253}No

4.2. Isomeric states in ^{253}No

4.2.1. The $5/2^{+}$ isomer in ^{253}No

At the time of running the first campaigns there was a discrepancy between the Table of Isotopes [14] and published data [15] with regards to the excitation of the $5/2^{+}[622]$ state in ^{253}No. The half-life of the isomer was determined from delayed K x-rays [16] and is quoted to have an excitation energy of 296-keV in the Table of Isotopes. A subsequent paper by GSI places this level below the K binding energy at an excitation energy of 124-keV from the α–decay of ^{257}Rf, albeit from very low statistics. Therefore the question to be addressed is: Are they seeing the same thing ? A search for isomeric decays following the implantation of recoils was performed using the same data discussed in 4.1. Figure 4 presents the logarithm of the time between recoil implantation and subsequent isomeric decay as a function of (a) $\gamma-$ray and (b) conversion electron energy. The boxes highlight the decays from an isomeric state. The corresponding projections of γ rays and conversion electrons detected between 8 - 128 μs after a recoil implantation are shown in Figs. 4 (c) and (d), respectively. In Fig. 4 (c) one can clearly see Nobelium K X-rays. The difference in energy between the two large conversion electron peaks in Fig. 4 (d) is consistent with the difference between the L- and MN binding energies in Nobelium and corresponds to a transition of 167-keV, also seen in the γ–ray spectrum. The M2 nature of the transition has been deduced from measured conversion coefficients and a comparison of the intensity of the 167-keV line with the K X-rays. Since the ground state of ^{253}No has been assigned $9/2^{-}[734]$ (see section 4.1) we can assign the configuration of this isomer as $5/2^{+}[622]$. The measured half-life of $t_{1/2}$=31.1(2.1) μs is in agreement with that measured by Bemis [16], but not with recent data measured at SHIP [17].

4.2.2. A second, longer lived isomer in ^{253}No

In these data evidence of a longer–lived isomeric state in ^{253}No was also observed and half-life of 0.97(20) ms was obtained for this state [18]. The limited statistics meant that no spectroscopic information concerning the decay properties of this state could be obtained. Following the instrumentation of the new 48×48 strip DSSD in February 2009 we can now employ the Jones method [19] of searching for the calorimetric signal associated with the decay of a high-lying isomer. Using the reaction ^{207}Pb(^{48}Ca,2n) of the order of 10 000 decays were observed from the isomer following the implantation of ^{253}No recoils. These data are currently being analysed.

4.3. Isomer search in ^{255}Lr

A search for isomers in ^{255}Lr was carried out following the reaction ^{209}Bi(^{48}Ca,2n). The known low-lying α-emitting spin–isomer [20] was confirmed. A new isomer with a half–life of $t_{1/2}$=1.4(1) ms was observed using conversion electron spectroscopy and

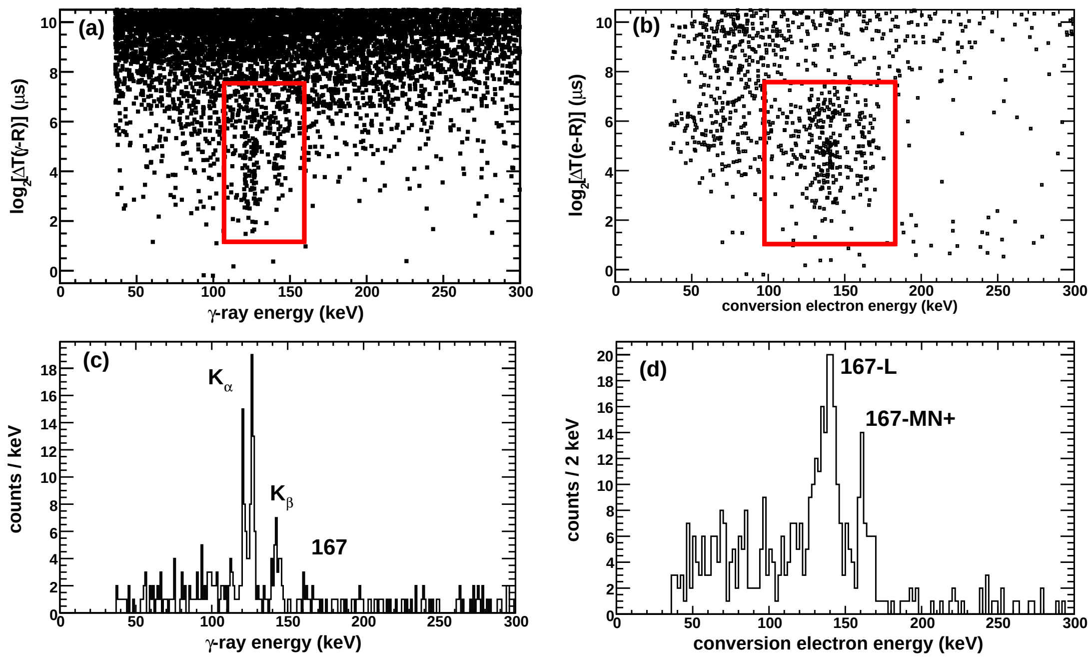

FIGURE 4. [color online] Energy spectra of (a) γ−rays and (b) conversion electrons as a function of $\log_2(\Delta T)$, where ΔT is the time difference between the detection of recoils and γ−rays or electrons. The corresponding projections onto the energy axis for (c) γ rays and (d) conversion electrons observed within 8-128 μs of a recoil implantation. Energies are in keV.

was assigned to ^{255}Lr following isomer–tagged recoil–α correlations. γ-electron coincidences established a correlation between a 588 keV γ ray and 100 keV electron. Assuming LM–conversion accounts for the 100 keV electron, then, the excitation of the isomeric state of at least 720 keV. For K-conversion this becomes $E_x \geq 850$ keV. In this heavy, highly fissile, deformed nucleus the only plausible explanation for the observation of a metastable state at such an excitation energy is K–isomerism[3]. Based on calculated K-forbiddeness values, the state is most probably formed by coupling the valence proton to a two quasi-particle neutron excitation. More details are given in Ref [21].

5. SUMMARY

Since 2004 five experimental campaigns have been carried out using GABRIELA to perform spectroscopy in the transactinides. During these studies we have seen the importance of being able to perform conversion electron spectroscopy and the need to have realistic GEANT4 simulations to aid with the interpretation of measurements. We have

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[3] K, the projection of angular momentum on the symmetry axis, is an approximate quantum number in deformed nuclei and transitions between states are governed by selection rules. For an allowed transition $\Delta K \leq \lambda$, where ΔK is the change in K between initial and final states and λ is the multipolarity of the transition. The degree of K forbiddeness ν is defined as $\nu = \Delta K - \lambda$

also seen that it is important to repeat experiments, particularly those performed in the 90's which, while cutting edge at the time, do not hold up to today's standards of high statistics and combined $\alpha-$, $\gamma-$ and conversion electron spectroscopy. There still exist many inconsistencies in the published data to resolve - some of which are recent and indicate the difficult nature of these studies. Our initial goal of performing spectroscopy in less neutron deficient nuclei using light beams (e.g. ^{22}Ne and ^{18}O) has been hampered by the combination of the relatively low transmission of VASSILISSA for asymmetric reactions coupled with our rather small implantation detector. To remedy these short-comings requires an upgrade of the VASSILISSA separator to increase the transmission.

6. PERSPECTIVES : SEPARATOR FOR HEAVY ELEMENT SPECTROSCOPY (SHELS)

A grant was obtained from the French Agence Nationale de la Recherche (ANR) in 2006. This grant will cover part of the necessary funds to modernise VASSILISSA and its detection system, the remaining funds will be provided by the FLNR. A memorandum of understanding between the IN2P3 and JINR was signed in in 2008.

The modernisation of VASSILISSA has two purposes:

- to increase the transmission efficiency for very asymmetric combinations, like ^{22}Ne + ^{238}U or ^{16}O + ^{244}Pu by a factor of ∼2–3
- to increase the detection efficiency of transported recoils by about a factor of 2 by using a larger Si detector (100×100 mm^2)
- to extend the region of accessible reactions to symmetric combinations like ^{136}Xe + ^{136}Xe

It is planned to replace the central part of the separator, consisting of 3 electrostatic deflectors (E), by a combination of two electrostatic deflectors and two dipole magnets (D) creating a velocity filter instead of an energy one. The modernised separator will therefore be of (Q-Q-Q)[4]-(E-D)-(D-E)-(Q-Q-Q)-D type and will operated in vacuum mode. More details can be found in the contribution of A. Yeremin to these proceedings [9].

This upgrade will take place during the refurbishment of the U400 cyclotron. We therefore look forward to the opportunities that will be provided by the combination of increased beam intensities, greater control of beam energies and improvements in VASSILISSA and GABRIELA.

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[4] A quadrupole lens triplet for focussing

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