Recent Results from Heavy Element Research at JYFL

M. Leino*
University of Jyväskylä, Department of Physics, P.O. Box 35, FIN-40351 Jyväskylä, Finland

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The gas-filled recoil separator RITU in conjunction with germanium detector arrays and the SACRED conversion electron array has been used for studies of nuclear structure in the region around ^{254}No. Rotational spectra have been extracted using in-beam measurements with recoil gating or recoil decay tagging. Results from completed in-beam γ-ray studies of ^{252,254}No as well as preliminary data from in-beam conversion electron measurements of ^{253,254}No and γ-ray studies of ^{250}Fm are presented. These measurements give strong support to the prediction that nuclei in this region of the nuclear chart are quadrupole-deformed in their ground state with $\beta_2 \sim 0.27$. There are indications of an upbend occurring in the moment of inertia of ^{252}No and ^{250}Fm at a frequency around 180 keV. Future prospects for these studies as well as for focal plane decay spectroscopy in the transfermium region using RITU are discussed.

1. Introduction

Almost 20 years ago, the surprising experimental result was obtained that the even-even nuclide ^{260}Sg has a much longer spontaneous fission half-life than expected.[1,2] Soon afterwards, α decay of the even-even nuclide ^{264}Hs was also observed.[3] These results were incompatible with predictions based on calculations which reproduced rather well the lifetime systematics of lighter nuclei (see e.g. Reference 4).

A long standing prediction is that a region of spherical superheavy nuclei which are stabilised by shell effects should exist. It has also been known for a long time that a deformed shell closure at neutron number $N = 152$ has an effect on spontaneous fission half-lives of the actinides.[5] However, such deformed shells were not expected to have a strong enough effect to stabilise superheavy nuclei. It was only after the above mentioned experimental findings that the idea of deformed superheavy nuclei emerged.[6] Many detailed calculations have been performed, and it is now a well established theoretical result that, in particular in the region surrounding the "doubly magic" nuclide ^{270}Hs, deformed superheavy nuclei should exist.[7,8]

For many years after the synthesis of ^{260}Sg and ^{264}Hs, among others, there was only little experimental evidence of the deformation. In even-even nuclei, some of the lowest-lying levels were known from α- or β decay. Examples are ^{248,250}Cf, in which the 2^+, 4^+, and 6^+ levels of the ground state rotational band were observed in α decay of ^{252,254}Fm (Ref. 9). In both daughter nuclei, also the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ γ rays were observed. Another example is ^{256}Fm where the low-lying level structure was studied via β decay of the 7.6 h high-spin ^{256}Es isomer.[10] In this case, the ground state rotational band could be observed up to the 8^+ state. The measured excitation energies of the 2_1^+ states for the isotopes ^{248}Cf, ^{250}Cf, and ^{256}Fm are 41.5 keV, 42.8 keV, and 48.3 keV, respectively. These excitation energies are indicative of strong deformation of these nuclei. One should note that total internal conversion coefficients for E2 transitions are high in this region of nuclei and at these transition energies.[11] For example, for a $2^+ \rightarrow 0^+$ E2 transition with an energy around 50 keV, the total conversion coefficient is on the order of 1000 for Fm ($Z = 100$). Thus, in Reference 10, the energy of the 2^+ level was extracted as the difference between energies of less converted transitions.

The heaviest nuclide for which Coulomb excitation measurements have been performed is ^{248}Cm which was studied via the bombardments ^{58}Ni, ^{136}Xe + ^{248}Cm (Ref. 12). Levels of the ground state band were observed up to 22^+, and the diagonal E2 matrix elements were measured up to spin $20\hbar$. These matrix elements provide the most direct and unambiguous evidence and quantitative data on quadrupole collectivity in nuclei.[12]

It is not easy to extend such measurements to heavier elements. Lack of stable, or long-lived, target or source material prevents Coulomb excitation and decay studies. Traditionally, heavy ion evaporation reactions (HI, xn) have produced extensive data from in-beam studies on collective properties e.g. in the rare earth region. In the region of heavy elements, these studies were for a long time impossible to conduct because of the severe background arising from fission products. This problem was essentially solved with the employment of RDT (Recoil Decay Tagging) techniques.[13,14] In these measurements, an in-beam detector system is coupled to a recoil separator. Only such in-beam events are accepted for study which are accompanied by a delayed coincidence with a separated nucleus identified through its characteristic (α- or proton-) decay. A variation of this method, called recoil gating, makes use of a delayed coincidence between the in-beam event and a heavy recoil particle, identified as a fusion product through its energy and possibly also other measured parameters such as time of flight.

When the RDT or recoil gating method are used, the limitation comes from the reaction cross section. For the observation of the ground state band of heavy even-even nuclei, the present limit is on the order of 100 nb (see e.g. Reference 15). With stable targets, cross sections for (HI, xn) reactions fall below this limit around the element fermium with $Z = 100$ (see e.g. Reference 16). On the other hand, when actinide targets and very asymmetric reactions are made use of, the separator transmission is small. A notable exception comes from the use of the doubly magic ^{48}Ca projectile with targets around the doubly magic ^{208}Pb (Ref. 17, 18). For cold fusion reactions, i.e. (^{48}Ca, 1–2n) evaporation reactions, cross sections on the order of 0.1–1 μb allow in-beam measurements in the region surrounding ^{254}No. In the following, recent work on the structure of Fm and No nuclei using the methods of RDT and recoil gating at the Department of Physics, University of Jyväskylä (JYFL), is described. Finally, some future possibilities concerning both in-beam and decay spectroscopy studies will be discussed.

2. Experimental Details

All of the studies described here have been performed using the JYFL gas-filled recoil separator RITU.[19] RITU was designed for the study of the heaviest man-made elements but, mainly due to insufficient beam intensities previously available at JYFL, has mostly been used for the study of neutron-deficient nuclides in the W–Th region and for the experiments described here. In in-beam experiments, the maximum beam intensity is limited by the counting rate in the γ- or conversion electron detectors and is typically on the order of 1–10 pnA. A primary reason for using a gas-filled separator is the high transmission

*E-mail: matti.leino@phys.jyu.fi. FAX: +358-14-260 2351.

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of such devices which is based on charge and velocity focusing of the reaction products.[20]

The determination of the transmission of recoil separators is a notoriously difficult task. In-beam experiments provide an accurate method for such a determination using the ratio of the number of $\gamma\gamma$ to recoil-$\gamma\gamma$ coincidences for a particular fusion product. For the reactions described here, RITU efficiencies on the order of 25–45% have been estimated, depending on the losses caused by multiple scattering in the Time-of-Flight detector in case such a device was used in front of the focal plane.

The filling gas used in RITU is helium, and typical gas pressures are 0.5–1.0 mbar. The separator gas volume is isolated from the beam line vacuum using a gas window which is typically carbon with a thickness of around 50 μg/cm^2. The carbon window and the helium gas increase the count rate of Ge detectors used in in-beam γ-ray experiments. Partly for that reason, differential pumping has recently been installed at RITU. However, in all of the experiments described here, a gas window was still used.

3. In-beam γ-ray and Conversion Electron Experiments

The first in-beam γ-ray experiment on transuranium nuclei performed at JYFL was the study of ^{254}No, produced in the reaction ^{208}Pb(^{48}Ca, 2n).[21] The cross section for this reaction has been determined to be about 2 μb in several experiments (see e.g. References 17, 18). Slightly earlier, the same reaction had been used at Argonne National Laboratory to study ^{254}No using Gammasphere and the Fragment Mass Analyzer (FMA).[22] The main differences in these two experiments were the efficiencies of the setup. Gammasphere has a γ-ray detection efficiency of 10% at 1.3 MeV while the efficiency of the SARI array used at JYFL was 1.7%. The smaller efficiency of SARI was compensated for by the use of the highly efficient gas-filled separator at JYFL, and the overall performances of the setups were comparable in these essentially singles γ-ray experiments. In these two experiments, the bombarding energy was chosen for maximal production of ^{254}No which occurred at approximately 20 MeV excitation energy.

The result of these experiments, and of one more study performed at Argonne, using a slightly higher excitation energy (approximately 23 MeV) to enhance the population of high-spin levels[23] was the following: The ground state rotational band was observed up to spin 20$\hbar$ showing that ^{254}No can sustain at least this amount of angular momentum without fissioning. The observation of the rotational band was clear evidence of ground state nuclear deformation. A quantitative estimate of the degree of deformation was extracted as follows: Due to large conversion coefficients of low-energy γ-ray transitions in No nuclei, the lowest transitions $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ could not be seen in the γ-ray spectra. By making a Harris parameter fit to the observed transition energies, the excitation energy of the 2^+ level was extracted. The result was 44.2(4) keV.[21] By using global systematics of 2^+ energies of even-even nuclides,[24,25] the value of the quadrupole deformation parameter $\beta_2 = 0.27(3)$ was determined.[21]

After these pioneering experiments, the main experimental goals were the following: (i) Extension of the knowledge of even-even systems. (ii) Study of odd-mass cases to gain information on single-particle properties. (iii) Observation of conversion electrons to determine excitation energies of low-lying states. Some of the progress made at JYFL along these lines will be discussed in the following.

3.1. Gamma-ray RDT Experiment on ^{252}No. A straightforward extension of the study of even-even No isotopes was the in-beam γ-ray RDT measurement[26] on ^{252}No, produced with a cross section of 300 nb in the reaction ^{206}Pb(^{48}Ca, 2n). This experiment was performed using the JUROSPHERE II array which consisted of 15 Eurogam phase I detectors, 5 Nordball and 7 TESSA detectors (all Compton-suppressed) with an efficiency of 1.7% at 1.3 MeV γ-ray energy. The spectrum quality was much better than with the SARI array which consisted of four unshielded clover detectors, and thus the ground state rotational band could again be observed up to spin 20$\hbar$ in spite of the significantly reduced reaction cross section as compared to the ^{254}No experiment.

3.2. Gamma-ray RDT Experiment on ^{250}Fm. The most recent investigation in this field performed at JYFL was an in-beam γ-ray RDT experiment on the structure of ^{250}Fm. This isotope was produced in the reaction ^{204}Hg(^{48}Ca, 2n)^{250}Fm for which a peak cross section on the order of 1 μb was measured at an excitation energy of 23 MeV. The targets were ^{204}HgS and had a thickness of 300–600 μg/cm^2. Prompt γ rays from the target were detected using the JUROSPHERE IV germanium detector array which was similar to the JUROSPHERE II array described in sect. 3.1. At the focal plane there was, in addition to the usual position sensitive stop detector, a Time-Of-Flight detector[27] for the identification of fusion products. The combined Time-Of-Flight and energy gate (for the signal in the stop detector) provided very clean conditions for separating fusion products from other heavy particles. Thus, decay tagging was only used to confirm the identification of the origin of γ rays. Preliminary results from this experiment[28] are given in the following.

In Figure 1 the preliminary recoil gated total γ-ray spectrum is shown. In addition to γ-ray peaks, Fm X-ray peaks around 100 keV energy can be seen in the spectrum. A cascade of E2 γ-ray transitions in the ground state rotational band has been tentatively identified as shown. As in the cases of ^{252,254}No (Ref. 21, 26), the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions are too weak to be seen due to internal conversion. The spin assignments shown are the only ones which lead to a meaningful Harris parameter fit of the transition energies.

3.3. Conversion Electron RDT Experiments on ^{253,254}No. As mentioned above, internal conversion coefficients are large for low-energy transitions in the transfermium region. As an example, the total conversion coefficients for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in ^{254}No are around 1000 and 30, respectively. Thus, it is highly desirable to measure conversion electrons in-beam for these nuclei. Several problems, foremost of which is the very intense background of delta electrons coming from the target, have prevented such measurements. This problem was recently overcome at JYFL by using a high voltage barrier electrode in conjunction with the SACRED electron spectrometer[29] and RITU. Details of the setup are discussed in a forthcoming publication.[30] Briefly, the current version of SACRED makes use of a segmented 25-unit electron detector which is located almost collinearly upstream from the RITU target, i.e. at 177.5 degrees from the beam direction. Conversion

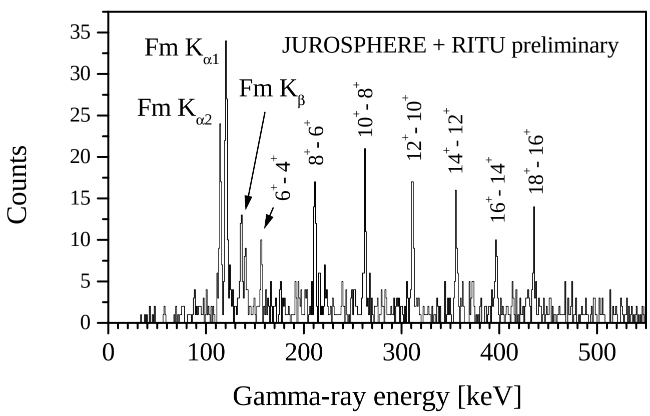

Figure 1. Preliminary recoil-gated singles γ-ray spectrum of ^{250}Fm produced in the reaction ^{48}Ca + ^{204}Hg and measured using RITU in conjunction with the JUROSPHERE IV Ge detector array.[28] The spin assignments are tentative.

electrons from the target are guided to SACRED by using a set of four solenoidal coils. The efficiency of the device was measured to be approximately 8% for electrons with energies around 200 keV. A high voltage electrode with typically 40 kV negative potential prevents the passage of low-energy delta electrons to the SACRED silicon detector. In order to achieve high vacuum in the barrier region, two gas windows with additional pumping in the space between the two foils was employed.[30]

Two measurements on No isotopes were performed with this setup. In the first one, RDT conversion electrons from ^{254}No were collected using the reaction ^{208}Pb(^{48}Ca, 2*n*) at 20 MeV excitation energy.[31] The target thickness was 430 μg/cm^2 and the beam intensity, limited by the count rate in the SACRED silicon detector, was 2 pnA. Altogether around 2400 ^{254}No nuclei were collected in a 70 h bombardment. The total recoil gated electron spectrum is shown in Figure 2. The low-energy part of the spectrum is affected by the -40 kV high voltage barrier. The conversion electron peaks corresponding to the E2 transitions have been identified as shown. In particular, a triplet of peaks identified as arising from the $4^+ \rightarrow 2^+$ transition gives a transition energy of 101.72(15) keV, confirming the result from the γ spectroscopy measurements where an energy of 102.0(3) keV was determined by extrapolation. The $2^+ \rightarrow 0^+$ transition still remains unobserved due to the effect of the high voltage barrier.

In another experiment, conversion electrons were measured from the reaction ^{207}Pb(^{48}Ca, 2*n*)^{253}No. A preliminary spectrum of recoil gated electrons is shown in Figure 3 (top panel). While the data do not allow detailed interpretations, some preliminary conclusions may be drawn: The ground state and three predicted lowest single-particle states in ^{253}No according to Reference 7 are $9/2^-$[734], $7/2^+$[624], $5/2^+$[622], and $1/2^+$[620]. If it is assumed that the quadrupole moment of ^{253}No is identical to that of ^{254}No, rotational model calculations can be performed to produce a level scheme for ^{253}No. Figure 3 shows the results of simulations[32] based on such a calculation. The intrinsic g_K factor of an individual state depends sensitively on the single-particle configuration and determines, on the other hand, the nature of the transitions to be observed. Here in particular, negative g_K values favour M1 intra-band transitions while positive g_K values enhance the cross-over E2 transitions. The E2 transitions are less converted than the M1 transitions which may allow their observation in a γ-ray investigation. Of the four band heads mentioned above, the only one leading to a large positive g_K value ($+0.28$) is the $7/2^+$ state. The predicted $9/2^-$[734] ground state leads to the negative g_K value of -0.25. As can be seen from the two simulated spectra in Figure 3, the converted M1 transitions from the band based on the $9/2^-$ state are in much better qualitative agreement with the experimental data than the transitions from the band based on the $7/2^+$ state. This observation is complementary with results from a γ-ray experiment performed at Argonne using Gammasphere and the FMA which shows evidence for a rotational band built on the $7/2^+$ single-particle state.[33]

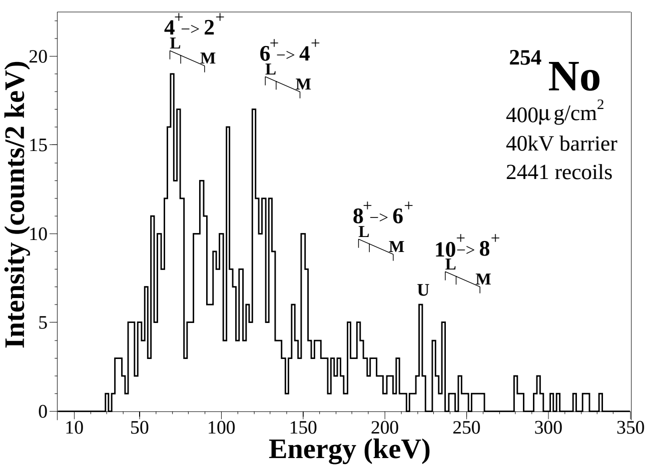

Figure 2. Recoil-gated singles conversion electron spectrum of ^{254}No produced in the reaction ^{48}Ca + ^{208}Pb and measured using RITU in conjunction with the SACRED spectrometer.[31]

4. Discussion

The extraction of the quadrupole deformation parameter β_2 on the basis of extrapolated 2_1^+ excitation energies and the global systematics[24,25] certainly involves uncertainties. Nevertheless, by using the same method for a set of isotopes, some systematic trends can be discussed. Scrutiny of the 2^+ energies directly, which appear to be quite reliable also when extracted by extrapolation, should already be fruitful. For example, according to Sobiczewski et al.,[8] ^{254}No should have the lowest 2_1^+ energy among all nuclei in this region. This expectation is based on the effect of the closed $N = 152$ shell which should reduce the effect of pairing correlations and thus increase the moment of inertia for this nuclide. The extracted 2_1^+ energies are the following (calculated values[8] are given in parentheses): ^{250}Fm, 43.5 keV (43.9 keV); ^{252}No, 46.5 keV (44.5 keV); ^{254}No, 44.2 keV (41.6 keV). These values lead to the following β_2 deformation parameters: ^{250}Fm, 0.273; ^{252}No, 0.260; ^{254}No, 0.264. The relative uncertainty of all values is approximately 10%.[21] (The value given here for ^{252}No differs from that given in Reference 26 where somewhat different systematics were used. For the sake of consistency, the same method which was also employed in Reference 21 is used here for all nuclides.) The excitation energies are in good agreement with those calculated by Sobiczewski et al.[8] although the difference between energies of ^{250}Fm and ^{254}No is smaller than predicted. If the same method is used to extract the β_2 values for Cf isotopes with $N = 150$ and $N = 152$ for which the 2^+ energies have been directly measured,[9] the results are 0.280 (^{248}Cf) and 0.274 (^{250}Cf). In this case there is also no significant effect seen at $N = 152$. For No isotopes, the experimentally determined deformation values are in good agreement with results calculated using the macroscopic-microscopic method[7,34,35] which typically yields values of $\beta_2 \sim 0.25$.

The dynamic moments of inertia deduced for ^{250}Fm and ^{252,254}No are shown in Figure 4. The data for ^{250}Fm are based

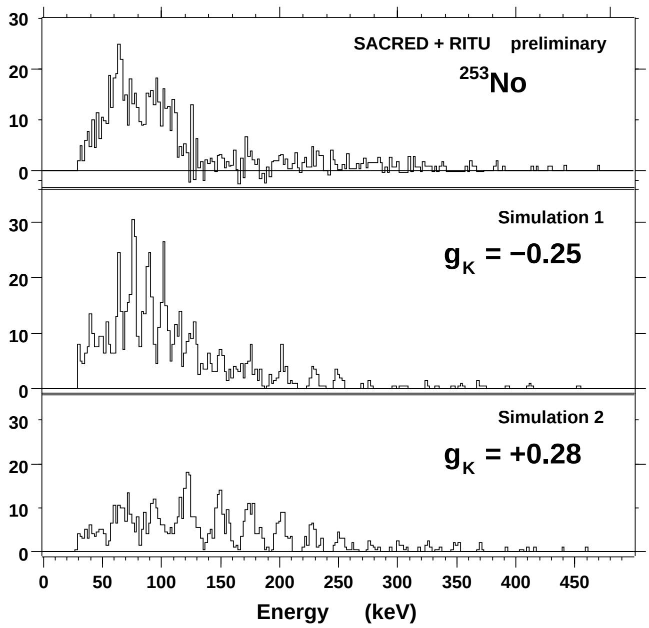

Figure 3. Top panel: Preliminary recoil gated conversion electron spectrum of ^{253}No produced in the reaction ^{48}Ca + ^{207}Pb and measured using RITU in conjunction with the SACRED spectrometer. Middle panel: Simulated spectrum (Reference 32, see text for details) using an intrinsic g_K factor of -0.25 for the band head state. Bottom panel: Simulated spectrum using $g_K = +0.28$.

on preliminary results and are only tentative. Perhaps the most striking feature of the data is the upbend which occurs for ^{252}No at approximately 0.18 MeV rotational frequency but is absent, or occurs at higher frequency, for ^{254}No. The last data point for ^{250}Fm corresponds to the $18^+ \rightarrow 16^+$ transition, i.e. two $\hbar$-units lower than for the two No nuclei. Qualitatively, the behaviour of the dynamic moment of inertia of ^{250}Fm is closer to ^{252}No than to ^{254}No at high spin values while the opposite is true at the lowest data points. The fact that ^{254}No is more deformed than ^{252}No can also be seen from the relative magnitudes of the moments of inertia at low frequencies.

Several theoretical studies utilising Hartree-Fock-Bogoliubov (HFB) calculations have been performed to explain the experimental observations for ^{254}No (Ref. 36–38). In Reference 37, where the agreement with experimental γ-ray energies and kinematic moments of inertia is very good, an upbend and a backbend are predicted at $I \sim 30\hbar$ and $\sim 38\hbar$, respectively. These changes are due to the alignment of $\pi i_{13/2}$ and $\nu j_{15/2}$ orbitals, respectively. The theoretical deformation value is $\beta_2 = 0.29$. In Reference 36, the dynamic moments of inertia have been calculated for ^{252,254}No. The calculations reproduce the fact that the moment of inertia increases faster for ^{252}No than for ^{254}No above a rotational frequency of 200 keV although experimentally, the difference between the two isotopes is more pronounced. The obtained deformation parameter[36] is 0.264 for ^{254}No. In Reference 38, using another parametrisation of the Skyrme interaction, a somewhat improved description, as compared with Reference 36, of the dynamic moment of inertia is found for ^{254}No.

5. Future Possibilities

The study of man-made elements has progressed to a region where the production cross sections are on the order of 1 pb. The production of spherical superheavy elements may require even more sensitive measurements. In such experiments, spectroscopic information to be gained is scarce. However, even at the level of 10 pb, important data for example on isomeric states can be collected.[39] Very efficient and versatile detector configurations are then needed. An extensive collaboration has been funded in the U. K. to develop a data acquisition and detector system called GREAT[40] to be used at the focal plane of the RITU separator. GREAT comprises two Double-sided Silicon Strip Detectors (DSSD) covering an area of 40 mm by 120 mm to be used as a stop detector and 32 PIN diodes for detection of conversion electrons and escaping α particles. A segmented planar Ge detector in combination with a large-volume segmented Ge detector, both behind the DSSD detector, will be used for the detection of low- and high-energy γ rays, respectively. This system provides unsurpassed capability for the detection of α-γ, α-e$^-$, and also β-γ coincidences. The system is expected to be commissioned in the year 2002. First experiments will concentrate on the study of α-decay fine structure and isomeric α decays as well as γ rays from high-*K* isomers[41] in the region around ^{254}No.

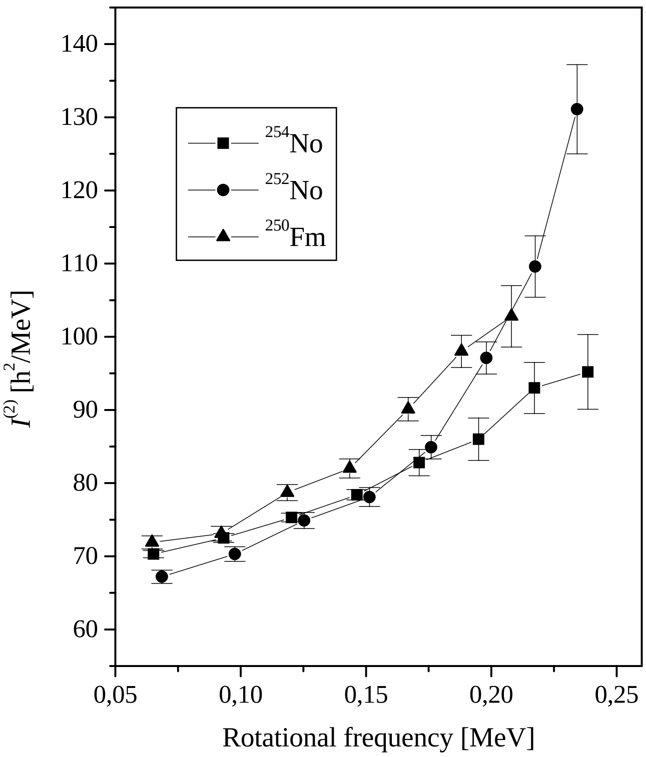

Figure 4. Dynamic moments of inertia determined for ^{250}Fm (preliminary data[28]) and ^{252,254}No (Ref. 21, 26).

The study of odd-mass nuclei in the No region may provide crucial information on single-particle properties, especially regarding predictions concerning the exact location of the next closed spherical proton shell. In-beam conversion electron spectroscopy is expected to be an important method complementing γ-ray spectroscopy and focal plane studies. At JYFL, emphasis will be placed on improving the energy resolution of the SACRED spectrometer and on optimising the electron transport efficiency.

Finally, it is expected that a Ge γ-ray detector array will be available at JYFL in the year 2003, providing an order of magnitude improvement in the detection of γγ coincidences in RDT studies. This will significantly increase the capability to extend the ground state rotational band of ^{254}No to higher spin values which should shed light on the nature of the quasi-particle alignment properties of this nuclide. It may also be possible to observe the β and γ bands. Tentative evidence of the linking transitions was already seen in the previous measurement.[21]

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