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Proposal to the ISOLDE Committee

High-resolution spectroscopy of Sr and Y nuclei near N = Z line

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Abstract

We propose a high-resolution study of *Rb*, *Sr* and *Y* nuclei near $A = 80$. In particular, we propose to study beta decay of ^{75}Sr and ^{78}Y using beta-delayed proton and gamma spectroscopy. In addition to the decay spectroscopy, we propose to measure the masses of $^{76,77}Sr$ and $^{79\text{-}85}Y$ using the *ISOLTRAP* spectrometer. These measurements will extend the mirror decay systematics into the region of high deformation and probe the role of proton-neutron interaction in the odd-odd $N = Z$ nucleus ^{78}Y. In addition, the mass measurements will provide new data and allow more precise local adjustment of microscopic-macroscopic mass models for rp-process flow modelling. The total beamtime request is 24 shifts.

1. Introduction

Nuclei in the $A = 80$ region close to the proton drip line are known to be rich in variety of deformations. A unique shell structure together with $N \sim Z$ leads to pronounced shape variations and shape-coexistence as a function of the particle number and spin [1, 2, 3]. Proton-neutron interaction has an important role in defining nuclear properties since in these nuclei protons and neutrons occupy the same single-particle orbitals. Furthermore, increasing Z gives rise to a larger breaking of isospin symmetry. Insight into these effects can be obtained by studying systematic trends of the properties of nuclei along the $N = Z$ line, especially in the *fp* shell.

Beta decay experiments are necessary to obtain information on nuclei near $A = 80$ to compare with various nuclear models. The determination of transition strengths in these nuclei requires accurate measurements of the beta-decay half-life, branching ratios and the decay energy. The Gamow-Teller (*GT*) strengths of the individual transitions are useful in extracting the properties of the low-lying states [4]. In addition, it has been shown that beta decay experiments can be used also for studying the role of the proton-neutron interaction in the odd-odd $N = Z$ nuclei [5].

In addition to probing individual states the beta decay measurements can provide information on total Gamow-Teller strength in a region of high level density. Deformation has been predicted to have an influence on the distribution of the *GT* strength in these nuclei [6]. The position and the shape of the *GT* Resonance might even be considered as a signature of a particular deformation.

In addition, the knowledge of decay energies or masses can be used to test mass models and, furthermore, when combined with experimental half-lives these data form an important basis for astrophysical *rp*-process modelling. This process has recently been predicted to continue as high up as $A = 100$ under high temperature and density conditions [7]. Isomerism due to the close-lying $1g_{9/2}$ orbital in combination of complicated β-feeding patterns have impeded the mass measurements via decay spectroscopy and have in some cases led to clearly wrong results [8].

This proposal consists of two types of measurements. Mass measurements using the *ISOLTRAP* mass spectrometer give very accurate information on atomic masses. High-resolution beta-delayed gamma and proton spectroscopy will be carried out using the existing set-up used in the *IS351* and *IS353* experiments for ^{71}Kr [9] and ^{58}Zn [10], respectively. A firm ground for these studies is laid by highly selective production of *Sr* and *Y* isotopes at the *ISOLDE* On-line Mass Separator from the same target/ion source. This proposal introduces a complementary approach to study the properties of nuclei close to the $N = Z$ line in comparison with the already accepted proposal (*IS370*) based on total-absorption gamma-ray spectrometry (*TAGS*) [11]. Together with the *TAGS* measurements and large number of existing in-beam and laser spectroscopy experiments this effort will shed new light on the role of deformation and nucleon-nucleon interaction on the nuclei near the $A = 80$. In addition, these measurements will update our knowledge on masses and half-lives in the region where isomerism is very common and in some cases has distorted previous attempts for better understanding.

2. Physics motivation

In this proposal decay spectroscopy will be applied to ^{75}Sr and ^{78}Y. Mass measurements using *ISOLTRAP* will be performed for $^{79\text{-}85}Y$ and $^{76,\,77}Sr$. In the following we point out the reasons to study these cases.

2.1. Mass measurements on $^{76,\,77}$Sr

Mass measurements of $^{76,77}Sr$ would be an extension of the studies already performed for the *Sr* isotopic chain down to ^{78}Sr previously at *ISOLDE* using the *ISOLTRAP* mass spectrometer [12, 13]. Masses of ^{76,77}Sr are known only with accuracies of 300 and 170 keV/c^2, respectively [14]. Improvement in the mass values to 10 keV/c^2, as obtained in ref.

[12], provides not only two additional points to experimental database for rp-process modelling but allows also more accurate local adjustment of microscopic-macroscopic mass formulas commonly used for predicting the unknown masses for flow calculations [7].

The well-known dependence of the Fermi integral *f* on the fifth power of the decay energy causes the experimentally determined Gamow-Teller strength *B(GT)* to be critically dependent on the knowledge on the decay energy. Thus, the decay energy determinations are a crucial part of this proposal. A high accuracy measurement has already been performed at *ISOLDE* for the beta-delayed gamma- and proton-decay branching ratios as well as for the half-life of ^{76}Sr [15]. These results can be used to test recent predictions for the position and the shape of the *GT* resonance in deformed nuclei [6]. Large differences in the *GT*-strength distributions were observed in these *TDA* + *HF* calculations depending on the deformation of the decaying nucleus. However, the accuracy of the experimental results and thus the quality of the conclusions are impeded by the large uncertainty in the Q_{EC} value 6090(300) keV for ^{76}Sr [14] and the model-dependent assumptions of level densities and widths [15]. The latter problem has been attacked by the proposal of measuring this decay using the *TAGS* technique at *ISOLDE* [11]. The former deficiency of the modest accuracy in the decay energy can be overcome by Penning trap mass measurements. The improvement in the accuracy of the Q_{EC} value from 300 keV to 15 keV would decrease the uncertainty induced by the decay energy in *B(GT)* at least 90%.

2.2. Mirror beta decay of ^{75}Sr

The study of the beta decay of ^{75}Sr is a continuation of mirror beta decay studies that we have performed recently on lighter isotopes [9, 16] and will extend the systematics to a region of large deformations. These decays are characterized by strong mixed Fermi and Gamow-Teller transition between the mirror states. The isospin non-conserving terms involved in the Coulomb and nuclear interactions might lead to rearranging of low-lying states in these nuclei. Such a suggestion has been made in ref. [4] based on the decay of ^{71}Kr [9] and Hartree-Fock (*HF*) calculations with Skyrme-type of interactions.

Similar type of *HF* calculations has been performed for ^{75}Sr recently [17]. Figure 1) shows the systematic trend of *GT* matrix elements for the mirror transitions up to ^{75}Sr including the calculated values for ^{71}Kr and ^{75}Sr. The calculated value for ^{71}Kr is clearly larger than measured but still within the error bars if one takes into account the global quenching of 0.7. Large prolate deformation was assumed for ^{75}Sr in the calculation [17]. This kind of collectivity tends to fragment the strength to higher excitation energies and cause the decrease of the mirror decay strength. On the other hand, results from *HF* calculations for ^{76}Sr [6] indicate that strong prolate deformation might drive large part of the *GT* strength inside the Q_{EC} window. Thus, if assuming large prolate deformation, it is not surprising that large beta-delayed proton emission probability of 6.5(33) % has been observed in the decay of ^{75}Sr [18].

HF calculations with various Skyrme-type interactions predict a positive-parity state for the ground state of ^{75}Rb [17]. In addition, Nilsson-Strutinsky calculations predict a positive parity $3/2^+$ state as the ground state [19]. Thus, this seems to be a general tendency. On the other hand, the only published beta decay work suggests a value of $3/2^-$ but the authors were not able to firmly establish the ground state spin and parity [20]. Knowledge of the possible final states for the beta decay has been recently improved by an in-beam study of ^{75}Rb [19] and by still unpublished beta decay works on ^{75}Rb [21, 22]. If the ground state spin has a value of $3/2^-$ it would indicate some systematic shortcomings in the theoretical models. Main motivation of this experiment is to shed light on these discrepancies in the low-lying level structure in ^{75}Rb by measuring the Gamow-Teller strengths present in the allowed transitions. Existing, though yet unpublished, beta decay works on ^{75}Rb will most likely provide help in determining its ground-state spin and parity.

The half-life of ^{75}Sr has been determined with modest accuracy to be 71^{+71}_{-24} ms [18]. The expected decay scheme for ^{75}Sr is shown in fig. 2). Spin and parity assignments for the states in ^{75}Rb has been taken from [19] and the beta-decay branching ratios are based on *HF* calculations for the lowest two levels [17] and fragmentation study for proton-unbound levels [18]. In addition to the strong ground state branch, the decay would proceed most likely via the first excited state at 144 keV level assigned with J^{π} of $5/2^-$, provided that the ground state spin and parity of the mirror pair ^{75}Sr-^{75}Rb is $3/2^-$. Due to these two strong transitions to the close-lying states the determination of beta-decay maximum energies would reach most likely only 150-200 keV accuracy. However, already this will allow determination of the *B(GT)* far more accurately than performed for other mirror decays above ^{59}Zn. Q_{EC} determination of ^{75}Sr by measuring its mass with *ISOLTRAP* would be difficult due to low production rate and short half-life.

2.3. Mass measurements on $^{79\text{-}85}$Y

Accuracies of 10 keV/c^2 would lead to considerable improvements in the mass values of $^{79\text{-}85}Y$ isotopes. These improvements would be crucially important for modelling of the *rp*-process path especially in the region of $A = 79\text{-}83$ where these nuclei are predicted to participate in the process path [7].

The case of ^{80}Y shows clearly the need of accurate mass determinations in the region. In the recent experiment at *SARA*, Grenoble, it was possible to determine the mass of ^{80}Y within 180 keV/c^2 accuracy [8]. The new result is differing from the result based on beta-decay endpoint-energy measurements about 2.2 MeV/c^2 [8]. The difference is partly due to complicated feeding patterns faced in the beta decay experiments and the non-separable components of isomeric and ground state masses in the case of cyclotron frequency determination at *SARA*.

As a by-product of these mass measurements, question of isomerism in ^{82}Y could be solved. Discrepancies in the measured half-lives and transition rates have been observed for ^{82}Y [23] and this might be due to isomerism that is supported also by systematics of neighbouring nuclei. Production rates for *Y* isotopes measured at *SC-ISOLDE* might indicate isomerism as well since a clear discontinuity can be seen in $A = 82$ (Fig. 4b). In the neighbouring even-even *Y* nuclei the energies of the isomeric states are between 200-500 keV [24]. The clear separation of the 464 keV isomer in ^{84}Rb [12] and, especially, the 175 keV in ^{141}Sm [25] shows the power of trapping techniques over decay spectroscopy in certain cases where complicated feeding patterns makes the separation difficult. A mass resolution (*FWHM*) of about 100 keV can be obtained with *ISOLTRAP* by increasing the *RF*-excitation time [26]. Thus, the separation would be possible for ^{82}Y as well provided that the energy of the isomeric state follows the systematical trend.

2.4. Role of p-n interaction in odd-odd N = Z nucleus ^{78}Y

First observation of the beta decay of odd-odd $N = Z$ nucleus ^{78}Y was reported recently [5]. In that work, it was possible to measure the decay of a ($J^{\pi} = 5^{+}$, $T = 0$) state with a half-life of 5.8(6) s. In these odd-odd $N = Z$ nuclei, the ground-state properties are determined by a competition of ($J^{\pi} = 0^{+}$, $T = 1$) and ($J^{\pi} = \text{odd}^{+}$, $T = 0$) states. Indeed, the 0^{+} state was observed in projectile fragmentation experiment [27] and the half-life was deduced to be 55(12) ms which is in agreement with the value for a pure Fermi beta emitter. Uusitalo et al. [5] could not determine the ordering of these levels. Based on beta detection efficiency considerations, Longour et al. [27] found weak evidence for the ($J^{\pi} = 5^{+}$, $T = 0$) state being above 0^{+} state in energy and thus isomeric. The ordering of these states is determined by the strength of residual proton-neutron interaction. Figure 3) shows the results from a *TQRM* calculation for the low-lying states in ^{78}Y by Uusitalo et al. [5] performed with and without proton-neutron interaction V_{pn}. When no proton-neutron interaction is included the 0^{+} state is always lower than the 5^{+} state at prolate deformations of $\varepsilon_2 = 0.3 - 0.45$. The proton-neutron interaction could lift the 0^{+} state up even 700 keV higher in energy compared to the 5^{+} state.

Experience from the *SC-ISOLDE* shows that production mechanism used at *ISOLDE*, spallation of *Nb* target nuclei, produces both ground- and isomeric states (Fig. 4b). Even $J^{\pi} = 8^{+}$ isomer in ^{86}Y is produced in high amounts. This gives possibility to observe both states in the same experiment and determine the ordering of the states using the beta-decay energy as a signature. Distinction between 0^+ and 5^+ states in ^{78}Y will be carried out based on the half-lives and beta-delayed gamma decay of the 5^+ state into levels of ^{78}Sr. The separation of these states would give information on the role of the proton-neutron interaction in defining the properties of the low-lying states in ^{78}Y.

3. Experimental details

3.1. Target and ion source

A large amount of information on producing *Sr* and *Y* using a *Nb* foil target and *W* surface ionisation at *ISOLDE* is available. The production of clean beams of radioactive *S*r and *Y* nuclei as SrF^+ and YF_2^+ ions using CF_4 addition has been also demonstrated at *ISOLDE* [28]. We would take advantage of this and produce $^{75,76,77}Sr$ as SrF^+ from the above mentioned target-ion source combination. The chemical selectivity of this sideband technique will thus remove the contaminant activities $^{75,76,77}Rb$ that are intensively produced in these masses. The use of a *Nb* target is also supported by the fact that the mass number $A = 93$ of the target material prevents $^{94,95,96}Rb$ as contaminants. These might be present in the case of *Zr* target material.

In the case of *Y* making use of its known property of forming YF_2 molecules provides background free conditions in mass $A + 38$ [28]. Estimated yields for *Sr* and *Y* isotopes are shown in figure 4. For *Sr* the data points marked with black squares have been determined from the calculated cross sections [29] and by normalising the decay-loss corrected cross section to the known production rate of ^{76}Sr [14]. For *Y* the decay-loss corrected cross sections have been normalised to the known yield of ^{79}Y from *SC-ISOLDE* after scaling it to correspond to the present production rate of ^{76}Sr. Yields of both ^{79}Y and ^{76}Sr were measured by Grawe et al. at *SC-ISOLDE* [28].

It should be noted that the possibility of separating isomeric and ground states using laser ionisation (*LIS*) has been recently established [30]. In the case of *Y* isotopes, however, the use of *LIS* would destroy the chemical selectivity obtained by CF_4 addition.

3.2. Measurement set-ups

Masses of $^{76,77}Sr$ will be measured using the *ISOLTRAP* that provides relative accuracy in the mass determination of about 10^{-7} [13]. This Penning trap mass spectrometer was recently improved by the installation of a new *RFQ* ion cooler, which should increase the overall efficiency of the apparatus by orders of magnitude.

The measurement set-up for the decay studies has been already used successfully several times at *ISOLDE*, for example, in studies of ^{71}Kr and ^{58}Zn [9, 10]. It consists of a large 70 % *Ge* detector for γ-rays, a thin plastic scintillator for positrons, a large 20 mm thick planar *Ge* detector for *X*-rays and high-energy positrons and a gas-silicon telescope detector for protons [31]. The scintillator and the planar *Ge* detector can be used as a beta telescope to measure endpoint energies. The thickness of the detector allows observation of positrons up to nearly 20 MeV. The determination of the β-decay end-point energies would be performed using the technique described in ref. [32]. This technique would need several well-known reference points for calibration.

3.3. Calibrations

Necessary calibrations for the set-ups will be performed partly with existing off-line sources and with on-line sources.

The relative efficiency calibration between β- and proton detection as well as between β- and γ detection can be performed using ^{20}Na. Its decay is well-known [33] and it also provides a high-energy calibration point for the beta telescope i.e. E_{max} = 11232(7) keV for the transition to the 1633 keV level in ^{20}Ne. This high-energy reference value would be needed for determining the end-point energy of ^{75}Sr and for ^{78}Y. Production rate can be estimated to be ~ 900 at/μC for ^{20}Na [34] based on the observed production rate of 1.8 x 10^5 at/μC for ^{21}Na at *SC-ISOLDE* from *Zr*-foil target [35].

Additional calibration points can be obtained by measuring the decay of ^{64}Ga. The production rate for ^{64}Ga is about 10^5 at/μC and no contaminants will be present provided that this run is performed first without CF_4 addition. Addition of CF_4 may produce radioactive $^{45}Ca^{19}F$ what should be avoided. The two most intense transitions have endpoint energies of 6143(4) and 4756(5) keV.

3.4. Beamtime request

In addition to calibrations mentioned above that require **4 shifts**, we request the following.

Mass measurements of $^{76,77}Sr$ using *ISOLTRAP* can be carried out in **2 shifts**. The expected production rates for $^{76,77}Sr$ are 3×10^3 at/μC [14] and 10^5 at/μC, respectively.

The production rate of ^{75}Sr is estimated to be 1.5 at/μC. Accuracy for the ground-state GT matrix element for ^{71}Kr shown in Fig. 1 was obtained in 3 shifts [9]. To reduce the uncertainty in the *B(GT)* values we request **6 shifts** for ^{75}Sr.

Mass measurements of $^{79\text{-}85}Y$ will need **5 shifts.**

The production rate of ^{78}Y is estimated to be 3 at/μC. To collect statistically sufficient 10^5 counts in the beta spectrum following the decay of the 0^+ state requires **5 shifts.** The yield of the 5^+ state is most likely larger due to a smaller decay loss factor.

In addition, we ask for **2 shifts** to perform detailed production rate tests for more neutron-deficient ^{74}Sr, ^{73}Sr and ^{77}Y for future purposes using the same target/ion source combination.

4. Summary

We propose high-resolution measurements on beta decays of deformed ^{75}Sr and ^{78}Y. In addition to decay spectroscopy, we propose direct mass measurements of $^{76,77}Sr$ and $^{79\text{-}85}Y$ using the *ISOLTRAP* mass spectrometer.

These planned measurements will give insight into the level structure of ^{75}Rb and improve the understanding of the effects on the Gamow-Teller strength distribution in this region of high deformation. Beta decay of odd-odd $N = Z$ nucleus ^{78}Y provides a way to probe the role of the proton-neutron interaction in forming the low-lying level structure. Additional mass measurements will improve the quality of the input for the modelling of the *rp*-process path and provides a key to more accurate Gamow-Teller strength studies. All the experiments using beta-delayed proton and gamma detection could be performed with the existing and very flexible measurement set-up that was successfully used in several experiments at *ISOLDE* before.

Table 1. Requested shifts and used set-ups.

Measurement	Set-up	Shifts
^{20}Na calibration	*GPS* + *LA1* + $\beta p, \beta\gamma$	3.5
^{64}Ga calibration	*GPS* + *LA1* + $\beta p, \beta\gamma$	0.5
Masses of $^{77,76}Sr$	*GPS* + *ISOLTRAP*	2
Masses of $^{79\text{-}85}Y$	*GPS* + *ISOLTRAP*	5
Spectroscopy on ^{75}Sr	*GPS* + *LA1* + $\beta p, \beta\gamma$	6
Spectroscopy on ^{78}Y	*GPS* + *LA1* + $\beta p, \beta\gamma$	5
Production rates of $^{74,73}Sr$ and ^{77}Y	*GPS* + *LA1* + $\beta p, \beta\gamma$	2
TOTAL		24

The total beamtime request is **24 shifts** (see Table 1). The suitable target/ion source would be *Nb*-foil target + *W* surface ionisation + CF_4 addition. The experimental set-up for the decay measurements would be preferably installed in the *LA1* beamline due to its low background conditions.

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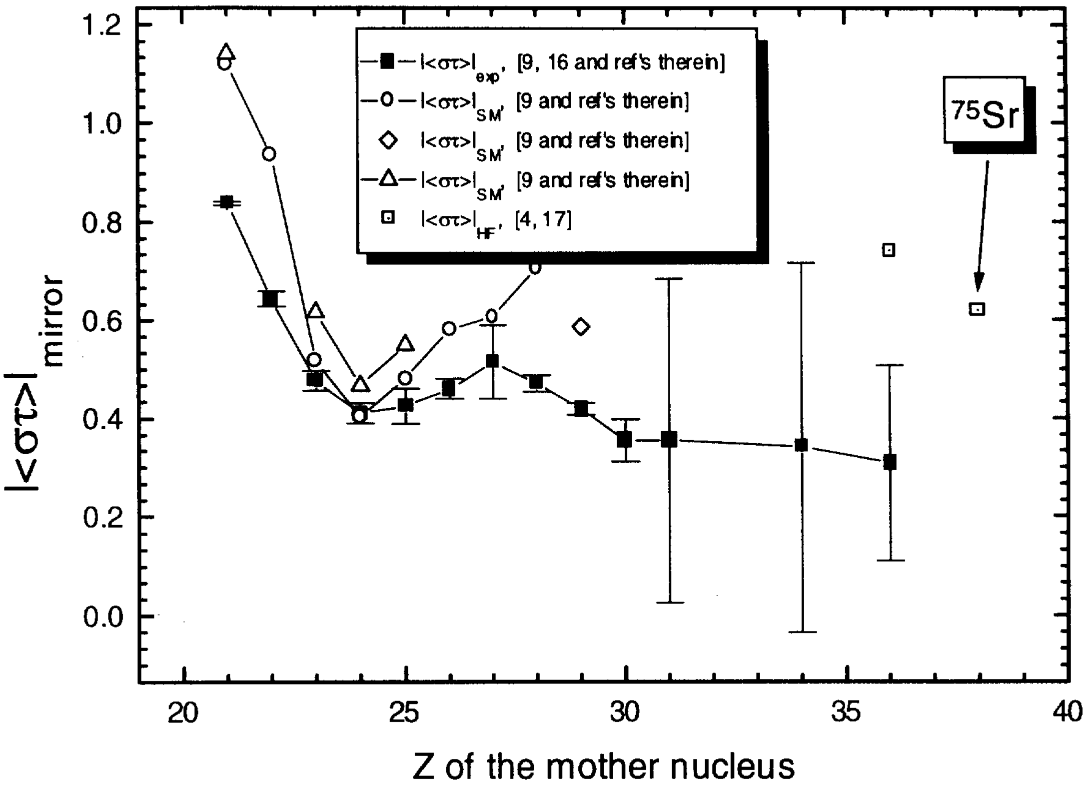

Figure 1) Systematics of the Gamow-Teller matrix elements for mirror transitions in fp shell nuclei. Large error bars in the case of ^{61}Ga, ^{67}Se are due to large uncertainties in $T_{1/2}$, Q_{EC} and branching ratio. In the case of ^{71}Kr, only the uncertainty in the Q_{EC} value contributes significantly [9]. All the theoretical values have been calculated without quenching factor 0.7. The result of the HF calculation for ^{71}Kr [4] agrees with the experimental value within the error bars if the quenching is taken into account.

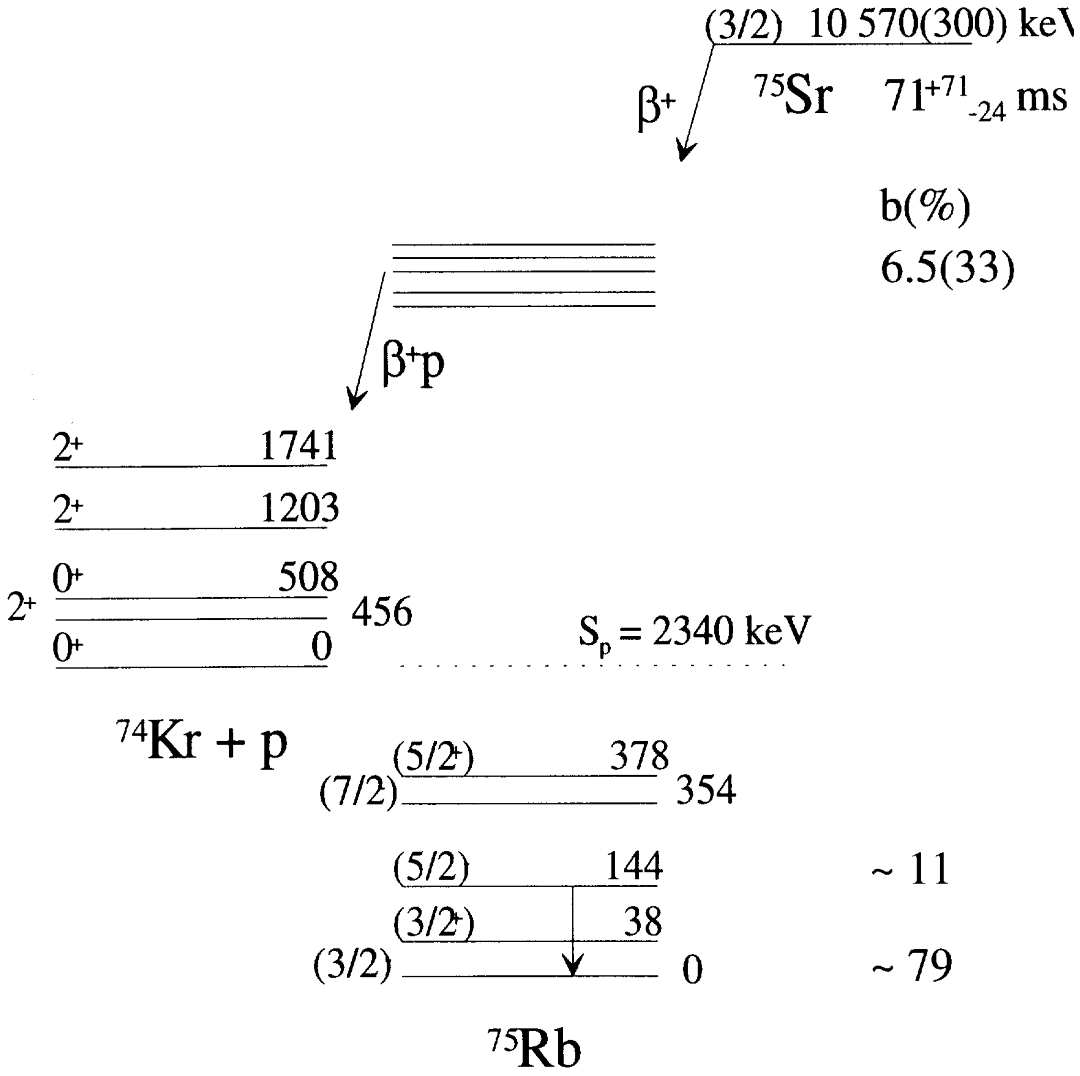

Figure 2) Expected decay scheme of ^{75}Sr.

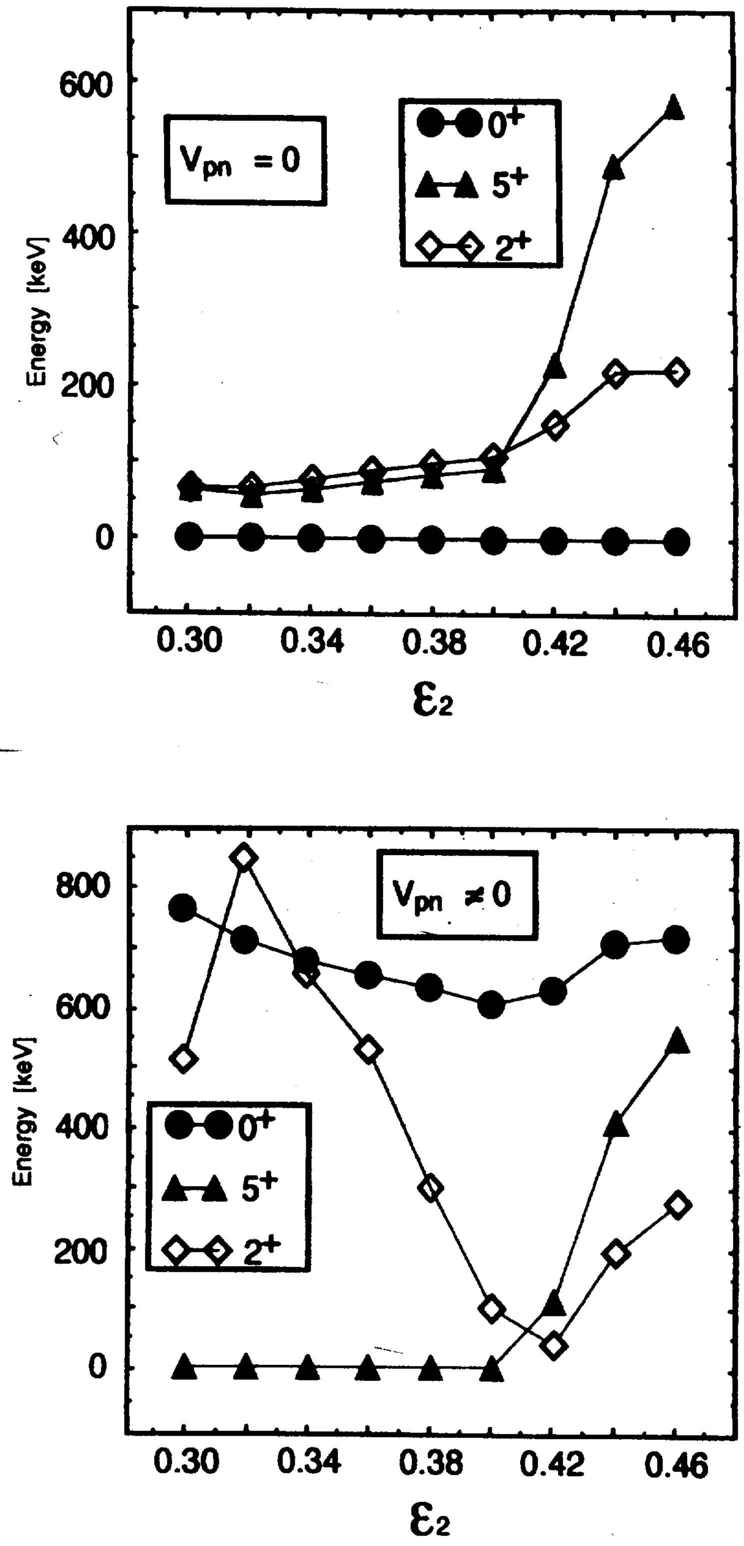

Figure 3) Positions of the low-lying levels in ^{78}Y calculated without (upper) and with (lower) residual proton-neutron interaction [5].

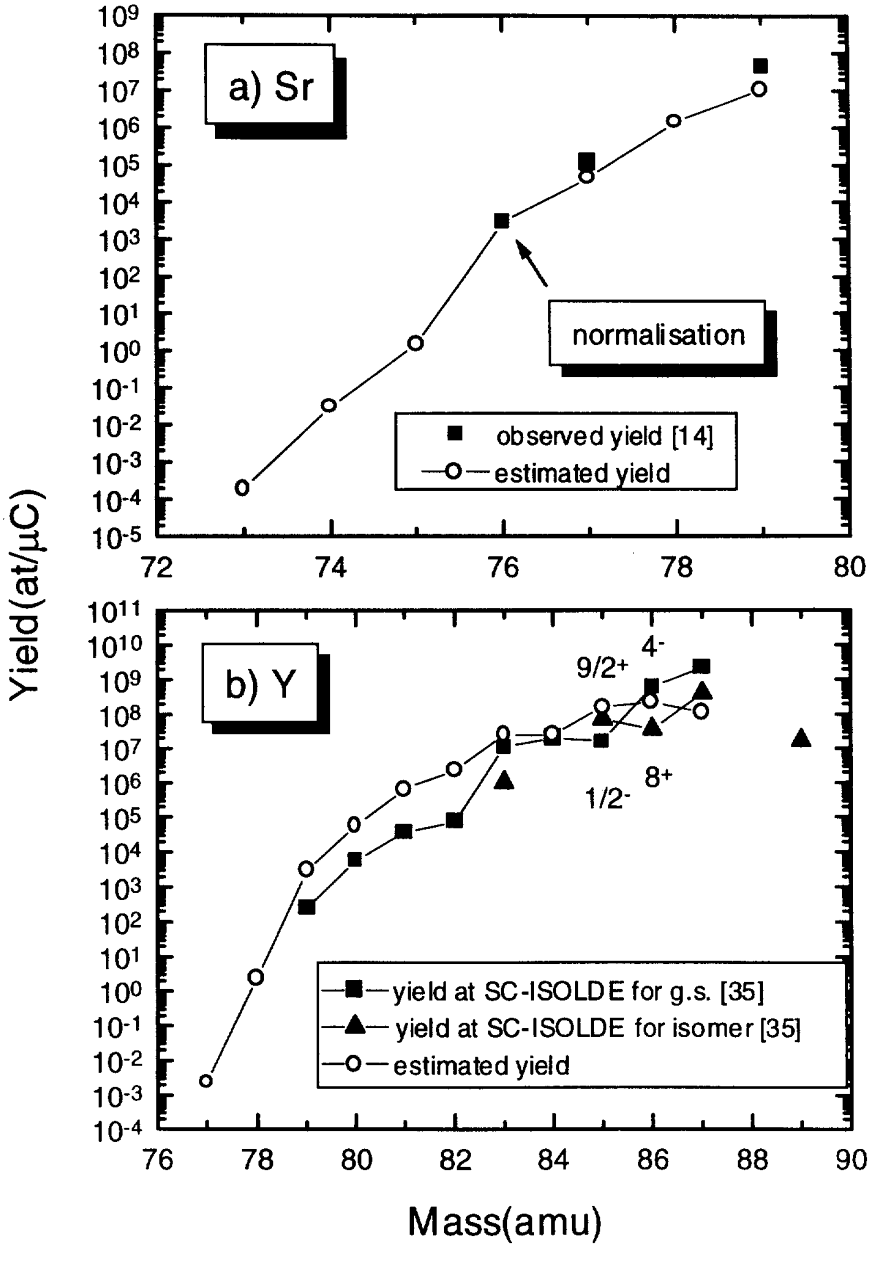

Figure 4) Estimated yields for Sr and Y isotopes as SrF and YF_2 from Nb foil target equipped with W surface ion source.