Mass measurement of neutron-deficient nuclei close to the N = Z line

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The masses of neutron-deficient nuclei close to A=80 are important for modeling the astrophysical rapid proton capture process (rp process) [1]. The rp process occurs as a sequence of β^+-decays and proton captures in various astrophysical sites, such as on the surface of an accreting neutron star. The rp process flows close to the N = Z nuclei up to ^{56}Ni. At higher masses, the path will broaden and shift by about one or two units towards stable nuclei.

The decay properties of several neutron-deficient nuclei near A=80 have been studied at the IGISOL facility in a series of experiments [2]. These investigations are now extended to precision mass measurements of the nuclei. The masses of ^{79,80,81,82,83}Y, ^{83,84,85,86,88}Zr, ^{85,86,87,88}Nb and ^{96,98}Mo have been measured in the precision trap of the JYFLTRAP Penning trap at IGISOL. The mass of ^{84}Zr has been measured for the first time. The accuracy of the Q$_{EC}$ values and proton separation energies, which are important for the rp process, could be improved significantly for the studied neutron-deficient nuclei.

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1. Introduction

The rp process is mainly determined by nuclear masses and β^+-decay half-lives of the nuclides on its path [3]. The theoretical mass predictions for the nuclides in the A = 80 region give too high uncertainties for the rp process calculations and therefore, reliable experimental data on masses are needed. The rp process models depend critically on the Q values for proton captures which drive the path towards the proton drip line until a waiting-point nucleus is reached. In order to estimate the proton capture rates, the masses and excitation energies should be known better than 10 keV [4]. Recently, 13 neutron-deficient isotopes of Y, Zr and Nb approaching the Z = N line were measured using the JYFLTRAP Penning trap setup at the IGISOL facility. These data will provide important contribution to more reliable predictions of binding energies at main rp-process nuclei.

2. Experimental method

The neutron-deficient isotopes were produced by a ^{32}S beam from the Jyväskylä K-130 cyclotron impinging on an enriched ^{54}Fe or ^{nat}Ni target. The reaction products were stopped in a gas cell and extracted as singly-charged ions, which were mass separated in a 55° bending magnet [5]. The beam was cooled and bunched in an RFQ-cooler/buncher [6] and transferred into the first of two Penning traps housed in a 7 T magnet. After isobaric purification [7], the ions were injected into the second trap, where the actual mass measurement was performed by scanning the ions' cyclotron frequency and using the time-of-flight technique [8]. The RFQ and the two traps are shown schematically in fig. 1.
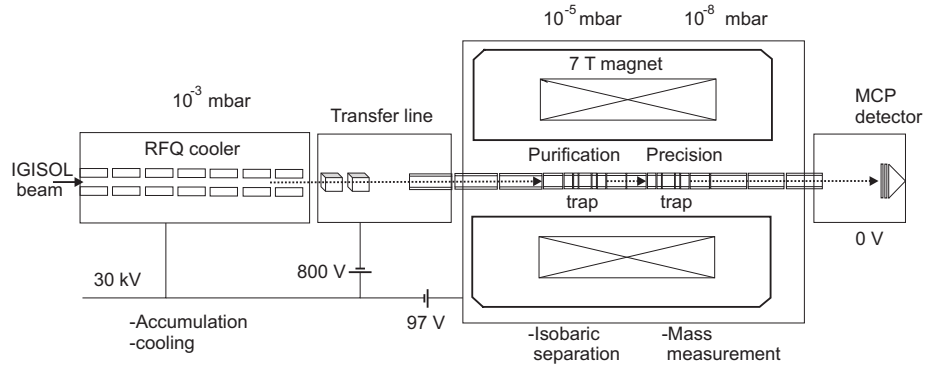

Figure 1: The RFQ-cooler/buncher and the 7 T magnet housing the two Penning traps.

3. The rp process

The rp process occurs in a sequence of proton captures and β^+-decays in various astrophysical sites, such as on the surface of an accreting neutron star (see, e.g., [3]). The flow of the rp process follows a path close to the N = Z nuclei up to ^{56}Ni. At higher masses, the path broadens and shifts by about one or two units towards stable nuclei. The path is wider for steady state burning (e.g., in X-ray pulsars) than for X-ray bursts. Regardless of the burning type, the rp process can proceed up
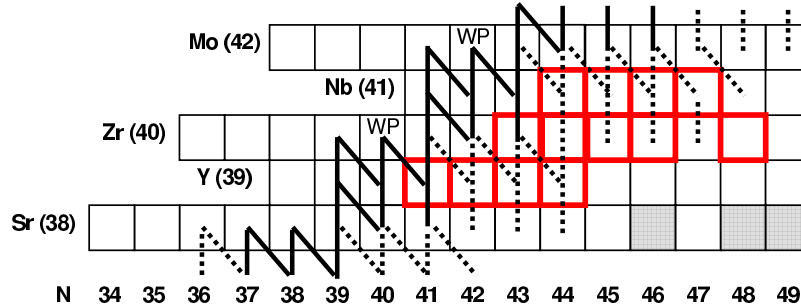
Figure 2: The rp process path for relevant nuclei in steady-state burning conditions

to A≈100 ending in a closed SnSbTe cycle [9].

The part of the rp process relevant here is depicted in fig. 2

4. Analysis and results

4.1 Isomeric states

Several of the measured nuclides have isomeric states. The observation of these isomers is experimentally limited by the half-life, the excitation energy and by their relative production rate (isomer ratio). With typical production rates in this experiment, isomers with a half-life of less than 500 ms could not be measured due to the excitation time of 900 ms in the precision trap and a total cycle time of ~ 1.5 s. The FWHM of the time-of-flight resonance was about 1.2 Hz, or about 100 keV in this mass region. Due to these limitations, only the isomeric states of ^{80}Y, ^{85}Zr, ^{85}Nb could have been observed. Larger frequency ranges were scanned to find a second resonance. Since in all of these cases only one state was observed, it is not possible to determine whether the measured nucleus was the ground state or the excited state. From previous decay spectroscopy ([2] and [10]) at HIGISOL, the isomers ^{80m}Y, ^{85m}Zr and ^{85m}Nb are less produced than the ground state. These production ratios support the conclusion that we have really measured the ground state masses.

4.2 Results

The obtained mass excesses of the studied nuclei are shown in fig. 3 as the difference of the new value and the literature value.

5. Conclusions

Almost all of the studied nuclides lie on the path of the rp-process and are involved in the proton captures. The masses of these nuclides have been measured with uncertainties of less than 10 keV required for detailed rp-process calculations [4]. Large deviations (several hundreds of keV) to the adopted AME values have been found except for ^{80}Y, ^{84,85,88}Zr and ^{88}Nb which all agree with the AME values. The proton separation energies S_P also differ from previous values; for the Nb isotopes they are smaller than predicted by up to 800 keV. The Q_{EC} value for ^{84}Zr and S_P values for ^{84}Zr and ^{85}Nb have been determined experimentally for the first time.
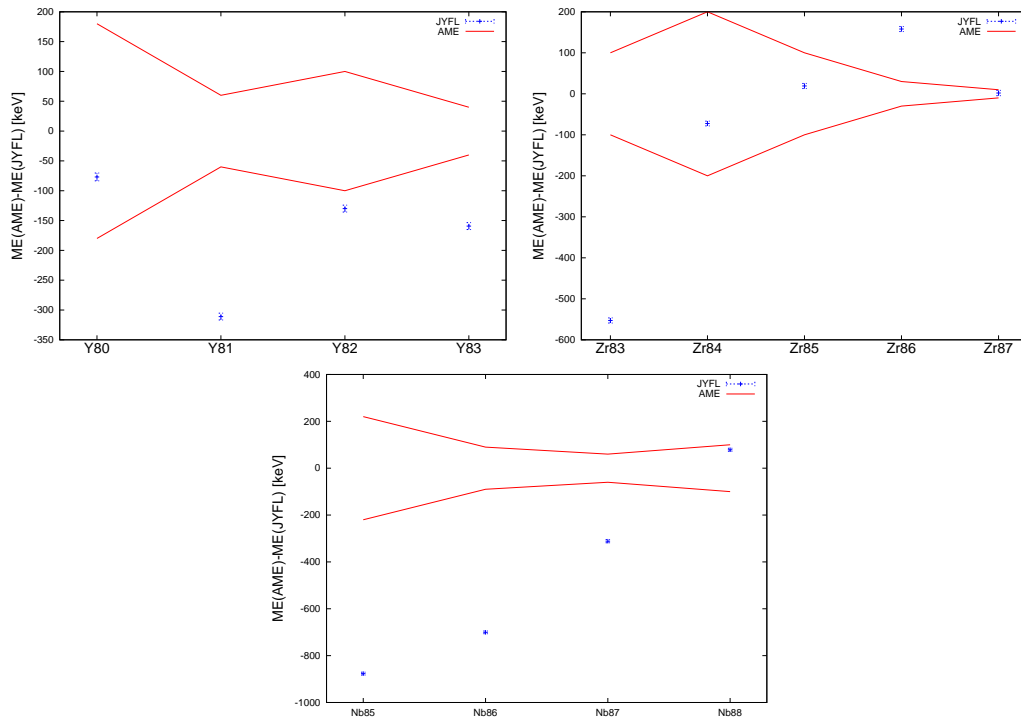
Figure 3: Results as the difference of the mass excess as measured by JYFLTRAP and the literature value.

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