

MASS MEASUREMENTS OF NEUTRON-RICH NUCLEI AT JYFLTRAP*

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(Received January 14, 2008)

The JYFLTRAP mass spectrometer was used to measure the masses of neutron-rich nuclei in the region of $28 \leq N \leq 82$ with uncertainties better than 10 keV. The impacts on nuclear structure and the r-process paths are reviewed.

PACS numbers: 21.10.Dr, 07.75.+h, 27.50.+e, 27.60.+j

1. Introduction

Penning trap mass spectrometer is an important device for experimental physics [1]. The confinement of ions in space by the combination of a homogeneous magnetic field and an electrostatic quadrupolar potential [2] provides an ideal environment for performing mass measurements [3] of nuclei far from the valley of stability. This offers a new opportunity for studying nuclear structure [4-7], stellar nucleosynthesis [5, 8, 9] and weak interaction tests [10, 11] in nuclei.

The existence of nuclear shell structure as well as so called magic numbers have been experimentally verified among nuclei close to the valley of stability. However, it is natural to raise a question of whether the observed shell structure is influenced by the number of nucleons of opposite kind. A direct answer to this question remains open as masses of the most exotic nuclei are not yet known precisely. In low mass region the vanishing magicity of the magic neutron numbers 20 and 28 has already been shown in Refs. [12, 13]. JYFLTRAP moves forward and has given considerable efforts over the years to measure the masses of neutron-rich nuclei in the region of $28 \leq N \leq 82$.

* Presented at the XXX Mazurian Lakes Conference on Physics, Piaski, Poland, September 2–9, 2007.

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These mass measurements have contributed to a better understanding of the neutron shell gap at $N = 40, 50$, the proton shell gap at $Z = 28$ and a large deformation around the $N = 59$ region. These have been studied via the two-neutron separation and shell gap energies [4-8].

Another obvious focus for mass measurements at JYFLTRAP is to provide accurate mass values for a better understanding of the nucleosynthesis pathways. Nuclear masses are one of the key input parameters for nucleosynthesis calculations. Along the rapid neutron capture process (r-process) paths neutron separation energies are rather low, typically 2 to 3 MeV [14]. The precise masses and hence well defined neutron separation energies will help to pin down the location of the paths. Furthermore, in order to estimate the neutron capture rates, the masses and excitation energies should be known to better than 10 keV. Our precise mass results will substantially improve the r-process network calculations to minimize the models ambiguity.

The combination of the JYFLTRAP [15,16] and the Ion Guide Isotope Separator On-Line (IGISOL) [17] facility offers an unique opportunity to investigate neutron-rich nuclei including isotopes of refractory elements. The limiting factors are the half-lives and the production rates of the interesting nuclei. So far approximately 170 masses have been measured employing the JYFLTRAP setup. In this article nuclear structure effects revealed by these measurements are discussed.

2. The JYFLTRAP setup

The experimental setup consists of a radiofrequency quadrupolar (RFQ) structure following by two cylindrical Penning traps inside a superconducting magnet of a field strength of 7 Tesla. The ions of interest were produced in proton-induced fission reactions by bombarding a thin (15 mg/cm^2) natural uranium target with a 30 MeV proton beam from K-130 cyclotron at the Department of Physics at the University of Jyväskylä. The continuous 30 keV radioactive ion beam from IGISOL is first passed through a dipole magnet for isobaric mass selection and transported towards the RFQ for cooling and bunching. The bunched and cooled ion beam is then transferred to the first Penning trap for isobaric purification using the buffer gas cooling technique [18] and finally a single ion sample is transferred to the second Penning trap for cyclotron frequency measurements using the time-of-flight ion cyclotron resonance technique [19]. The mass of an ion of interest m is then determined from the cyclotron frequency ratio r of the well known reference ion ($\nu_{c,\text{ref}}$) to the ion of interest (ν_c) using the formula

$$r = \frac{m - m_e}{m_{\text{ref}} - m_e} = \frac{\nu_{c,\text{ref}}}{\nu_c}, \quad (1)$$

where m = mass of the interesting isotope, m_{ref} = mass of the known reference isotope, and m_e is the electron mass. A detailed overview of JYFLTRAP will be presented in this issue in Ref. [22].

3. Discussion

An up to date overview on the masses of neutron-rich nuclei investigated at JYFLTRAP is shown in Fig. 1 by plotting the two-neutron separation energies S_{2n} as a function of the neutron number. S_{2n} allows to observe nuclear structural changes along an isotopic chain. Generally, S_{2n} values, decrease steadily as the neutron number increases, a characteristic of the liquid-drop model. This characteristic is well demonstrated for Ru, Rh and Pd isotopic chains in Fig. 1. The magic shell closure at $N = 50$ can be seen as a sudden drop of the S_{2n} values for all nuclei with $N = 51$ and $N = 52$.

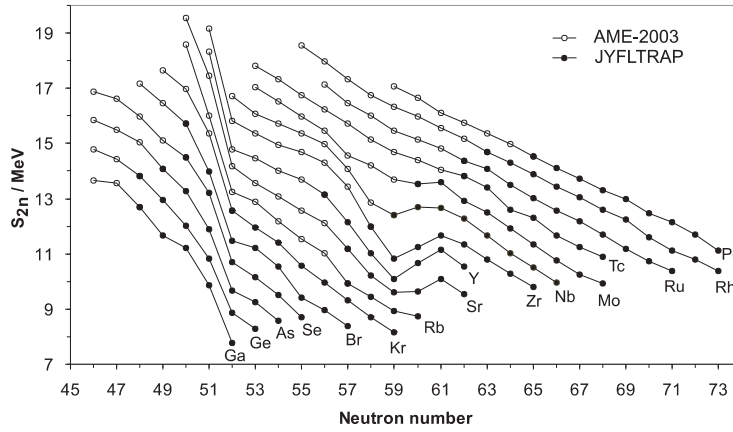


Fig. 1. Experimental S_{2n} energies as a function of neutron number for $Z = 31$ –46. The filled circles are from JYFLTRAP and the empty circles are from the AME03 mass table [20]. Kr values indicated by the filled circles are from Ref. [21].

Apart from these, a discontinuity appears in the S_{2n} values between $N = 57$ and 61 for isotopic chains from Rb to Tc. This discontinuity is strongest for the Zr isotopes and it reveals that the shell structure is undergoing a shape change from a spherical to a deformed shape. A more characteristic signature of this deformation is obtained by observing the change in the mean-square charge radii extracted from isotopic shifts measured in laser spectroscopy experiments. Fig. 2(A) shows the discontinuity in S_{2n} and mean-square charge radii as a function of neutron number for Sr, Zr and Y isotopes. At a maximum discontinuity in S_{2n} the mean-square charge radii increase suddenly. By observing the change in mean-square charge radii and subsequently in the quadrupole moments [24] the Sr isotopes below $N = 59$ were suggested to be weakly oblate and strongly prolate beyond $N = 59$.

Later similar sudden jumps in the mean-square charge radii at $N = 60$ were found in Zr and Y isotopes and a similar conclusion was drawn [25, 26].

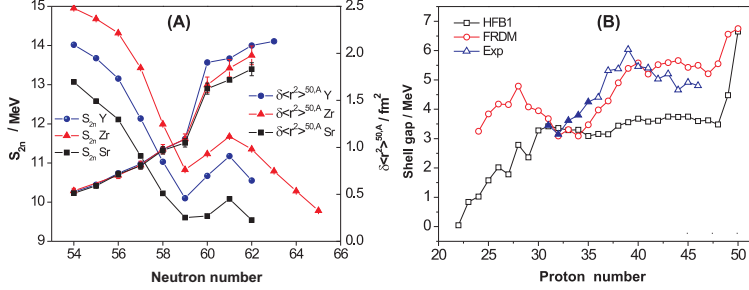


Fig. 2. (A): S_{2n} energies and mean-square charge radii as a function of neutron number for Sr, Zr and Y isotopes. (B): Experimental neutron shell gap energies [20] at $N = 50$ compared with mass models [23]. The filled triangles indicate the JYFLTRAP values.

Shell gap quenching has been experimentally observed for $N = 20$ [12, 13]. Some theoretical models [27, 28] predict a reduced neutron shell gap for $N = 50$ towards lower Z but no experimental data have been available until now. Fig. 2(B) displays the experimental neutron shell gap for $N = 50$ compared with two different models [23]. A report from JYFLTRAP [5] confirms the reduction of the shell gap energy towards $^{85}_{35}\text{Br}$. Later these measurements have been continued towards $^{81}_{31}\text{Ga}$ [29] where a further reduction in neutron shell gap energy was confirmed towards $^{82}_{32}\text{Ge}$. An increment in gap energy was observed for $^{81}_{31}\text{Ga}$ compared to $^{82}_{32}\text{Ge}$ which could be explained by the proton shell gap $Z = 28$ approaching at $^{78}_{28}\text{Ni}$. FRDM model has predicted this effect clearly whereas HFB 1 deviates from the experimental observation.

The $N = 40$ subshell closure in $^{68}_{28}\text{Ni}$ has been observed to be weaker than the $Z = 40$ subshell closure in $^{90}_{40}\text{Zr}$. Experimental results are contradictory for the shell closure at $^{68}_{28}\text{Ni}$ [30-33]. The first excited state in $^{68}_{28}\text{Ni}$ is a 0^+ state observed at much higher energy than the first excited states in neighboring even-even nuclei. Also the 2^+_1 state in $^{68}_{28}\text{Ni}$ has a large excitation energy and the $B(E2, 0^+_{\text{gs}} \rightarrow 2^+_1)$ value is quite small supporting a semidoubly-magic character of this nucleus [33]. This conclusion, however, is not supported by recent JYFLTRAP measurement. Fig. 3(A) shows S_{2n} as a function of the proton number for even neutron numbers. The neutron shell gap energy is defined as $\Delta(N) = S_{2n}(Z, N) - S_{2n}(Z, N + 2)$ which is characterized by the vertical distance between two consecutive isotones in Fig. 3(A). A small enhancement of the neutron shell gap energy at $N = 40$ for $Z = 28$ is observed which can be explained by considering $N = 40$ as a weak subshell closure [7].

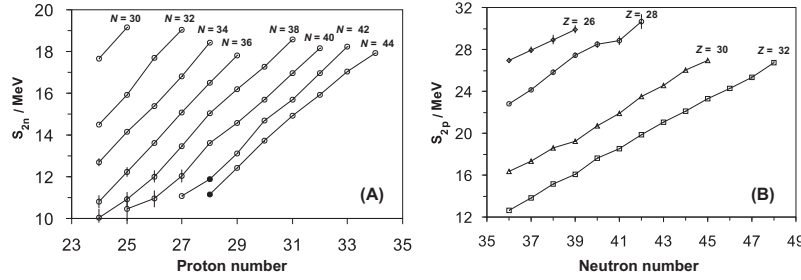


Fig. 3. (A): S_{2n} plotted as a function of the proton number for even neutron chains. The filled circles are from JYFLTRAP and the empty circles are taken from Ref. [20]. A weak irregularity is observed for $N = 40$ and 42 at $Z = 28$. (B): S_{2p} plotted as a function of the neutron number for even proton chains. See text for details.

The two-proton separation energies S_{2p} are plotted as a function of the neutron number in Fig. 3(B) for even- Z isotopic chains from $Z = 26$ to 32 . In this plot the gap between the $Z = 28$ and $Z = 30$ chains gives the proton shell gap energy for $Z = 28$. A tendency of decreasing proton shell gap energy is noticed for $Z = 28$ at $N = 41$. It is in agreement with the tensor force calculations which explained that with increasing number of neutrons ($N = 40$ to 50) occupying the $\nu 1g_{9/2}$ orbit, the $\pi 1f_{7/2}$ and $\pi 1f_{5/2}$ orbits come closer to each other [34, 35] resulting in a reduction of the proton shell gap energy. However, the next point at $N = 42$ has a larger shell gap energy but it is based on extrapolated ^{68}Fe mass. Therefore, more experimental mass data are required, in particular precise masses of n -rich Fe isotopes to ascertain the observed trend.

4. Conclusions and outlook

More than 100 neutron-rich mass values in the vicinity of the astrophysical r -process paths have been determined at JYFLTRAP. A discontinuity in the S_{2n} values has been observed around $N = 59$ reflecting a change in the deformation. This effect was seen in $Z = 37$ – 43 isotopic chains being strongest at $Z = 40$. The $N = 50$ neutron shell gap has been observed to decrease towards $Z = 32$ and increased again at $Z = 31$. A small enhancement of the neutron shell gap energy has been noticed at ^{68}Ni suggesting that there is a weak subshell closure. A reduction of the $Z = 28$ proton shell gap energy is observed at $N = 41$ which is in agreement with the tensor force prediction. However, more experimental masses are needed to study the trend towards $N = 50$. JYFLTRAP will continue mass measurements of neutron-rich nuclei in order to understand the issues related to nuclear structure and astrophysics addressed in this paper.

This work has been supported by the TRAPSPEC Joint Research Activity project under the EU 6th Framework program “Integrating Infrastructure Initiative — Transnational Access”, the contract number: 506065 (EURONS) and by the Academy of Finland under the Finnish center of Excellence Program 2006–2011 (Nuclear and Accelerator Based Physics Program at JYFL and project number 202256 and 111428).

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