Mass excess of ^{69}Br and the *rp* process

M. S. Antony[1;1)] J. -B. Bueb[2]

[1] Résidence Einstein, Strasbourg - Cronenbourg 67200, France
[2] 11 rue de Klingenthal, Strasbourg - Cronenbourg 67200, France

Abstract: The proton separation energy *Sp* of −786.07±11.49 keV has been evaluated for ^{69}Br from a least squares fit of mass difference of analog states versus $\alpha/A^{1/3}$, where α is the average charge of the mirror nuclei and A is the mass number. The extracted *Sp* value is indicative of the rapid proton-capture process *rp*, and subsequent Type I X-ray bursts.

Key words: proton separation energy, rapid proton-capture, type I X-ray bursts, analog levels

PACS: 21.10.Dr, 26.30.Ca, 26.60.Hj **DOI:** 10.1088/1674-1137/39/9/094103

1 Introduction

In a binary system, hydrogen-rich material from a companion star accretes on the surface of a neutron star [1]. When the temperature and density of the accreted material becomes high enough to allow a breakout of the CNO cycle, Type I X-ray bursts are generated by fast burning of hydrogen along a chain of rapid proton capture and subsequent beta decay. This sequence known as the *rp* process continues until the proton drip-line is reached. Thereafter, the *rp* process can continue by bridging $2p$ capture, only if the beta decay of the waiting point nucleus is long and the proceeding nucleus is proton unbound. These conditions are satisfied by the long beta decay lifetime of 35.5 s for the waiting point nucleus ^{68}Se and the proton unbound nature of ^{69}Br [2].

2 Methods and data analysis

Rogers et al. [2] deduced an experimental proton separation energy Sp=−785(+34−40) keV=−788.8±37.1 keV, corresponding to a mass excess (ME) of −46111.6±37.1 keV for ^{69}Br. Sp=ME of (^{68}Se+p)-(^{69}Br).

Pape and Antony determined (−46030±30) keV for the mass of ^{69}Br via the Isobaric Multiplet Mass Equation [3]. Based on the Skyrme Hartree–Fock model of Coulomb Displacement Energies (CDE), using the CDE of mirror nuclei combined with experimental masses of the neutron-rich nuclei, Brown et al. obtained ME of −46130 (110) keV and Sp is −770±110 keV for ^{69}Br [4]. Coulomb Displacement Energy $CDE = MD + \Delta_{\rm nH}$, where MD is the mass difference of analog states and $\Delta_{\rm nH}$ is the mass difference between neutron and hydrogen, which is equal to 782.4 keV [5].

Analog levels have the same mass number A, isospin T and nuclear spin J^{π}. Table 1 provides examples of analog states for the pairs ^{18}F-^{18}O and ^{51}Mn-^{51}Cr [5].

For spherical nuclei, CDE versus $\alpha/A^{1/3}$ follows a linear equation [6]:

$$CDE = p(\alpha/A^{1/3}) + q, \tag{1}$$

where p and q are the constants of the linear equation, α is the average charge of the analog pairs and A is the mass number.

By removing the constant 782.4 from CDE,

$$MD = a(\alpha/A^{1/3}) + b. \tag{2}$$

Lists of CDEs have been compiled by Antony et al [5, 7].

In the present investigation, we have made a weighted least squares fit to the MD of analog levels versus $\alpha/A^{1/3}$. The fit for 130 data points shows non-negligible

Table 1. Examples of analog states T is isospin J^{π} is nuclear spin ME is mass excess g.s. is the ground state $E_{\rm x}$ is the excitation energy of analog states and M is mass.

nucleus	T	J^{π}	ME of g.s./keV	$E_{\rm x}$/keV	M of analog states/keV
^{18}F	1	0^+	873.1 (5)	1041.55 (6)	1914.65 (50)
^{18}O	1	0^+	−782.8156 (7)	0.0	−782.8156 (7)
^{51}Mn	3/2	$7/2^-$	−48243.5 (9)	4451. 0 (20)	−43792.5 (22)
^{51}Cr	3/2	$7/2^-$	−51451.1 (9)	0.0	−51451.1 (9)

Received 17 November 2014

1) E-mail: antonymariasusai@yahoo.fr

residuals, except for 20 of them which encompass experimental errors. The groups of the 20 mirror nuclei are ^{52,53,56}Mn-Fe, ^{57}Fe-Co, ^{56,57,58,59,60,63,65}Co-Ni, ^{62}Ni-Cu, ^{59,61}Cu-Zn, ^{67}Zn-Ga, ^{81}Se-Br, ^{87}Kr-Rb, ^{88}Rb-Sr, ^{88}Sr-Y and ^{89}Y-Zr. Ground state MEs are from Ref. [8] and excitation energies of analog levels are from Ref. [9].

For nuclei with quadrupole deformation β_2, CDE is expressed as [10]

$$CDE(\text{experimental}) = CDE(\text{fit})(1-4\beta_2^2/45). \quad (3)$$

From the β_2 values, 110 out of 130 nuclei are classed as deformed. The deformation alters the linear dependence of CDE on $\alpha/A^{1/3}$ [11].

3 Results and discussion

For ^{69}Se-^{69}Br, α=34.5 and $\alpha/A^{1/3}$=8.411433409. The linear expression determined from the least squares fit to Eq. (2) is:

$$(1432.87\pm4.26)(\alpha/A^{1/3}-6.0)+(6865.09\pm4.89)\ \text{keV}, \quad (4)$$

and the normalized χ^2 value of the fit is 0.29. From Eq. (4), the MD of the analog pair ^{69}Br-^{69}Se is (10320.36±11.38) keV. As the ME of ^{69}Se is (−56434.7± 1.5) keV [8], the ME of ^{69}Br is (−46114.34±11.48) keV.

The proton separation energy Sp of ^{69}Br is obtained from the equation ^{68}Se+p->→^{69}Br. As the mass of ^{68}Se is (−54189.4±0.5) keV [4], the Sp of ^{69}Br is (−786.07±11.49) keV. Systematic errors of the data and of the fit have been included in estimating the fit value of MD. Fig. 1 is a plot of MD of analog states versus $\alpha/A^{1/3}$, and Fig. 2 is a plot of residuals versus $\alpha/A^{1/3}$.

The evaluated values of MD ^{69}Br-Se, ME ^{69}Br, and Sp ^{69}Br from the fit and those from Ref. [2] are compared in Table 2.

The most recent value of Sp for ^{69}Br is −641 (42) keV [12]. The Sp of ^{69}Br from the fit is in agreement with that of Rogers [2]. Since the linear fit from MD stems from spherical mirror nuclei, ^{69}Br is in the category of sphericity.

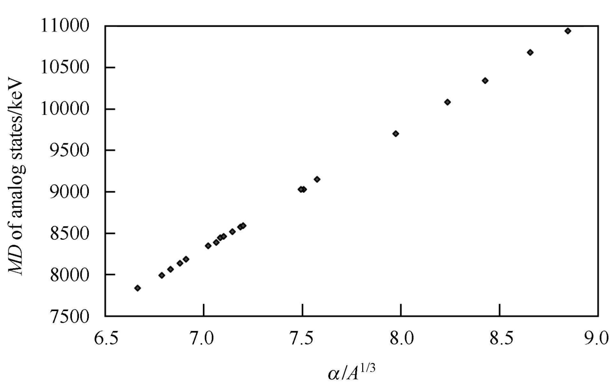

Fig. 1. MD of analog states versus $\alpha/A^{1/3}$.

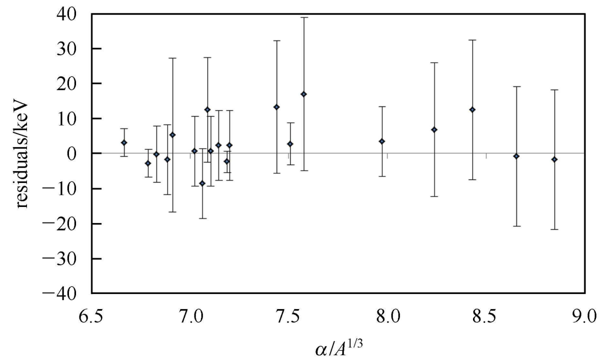

Fig. 2. Residuals versus $\alpha/A^{1/3}$.

Table 2. MD, ME and Sp from the fit and the experimental results of Ref [2].

	from the fit/keV	from rogers et al. [2]/keV
MD ^{69}Br-Se	−10320.36±11.38	−10323.1±37.1
ME ^{69}Br	−46114.34±11.48	−46111.6±37.1
Sp ^{69}Br	−786.07±11.49	−788.8±37.1

The subshell closures of 32 and 34 neutrons in ^{52,54}Ca have been demonstrated by Steppenbeck et al. [13]. The MD_{exp} are comparable to MD_{fit} for the groups, ^{140}Ce-La and ^{139}La-Ba, indicating the role of the neutron shell closure N=82, resembling that of ^{69}Br with N=34. Though the initial list of 130 groups of mirror nuclei range from ^{28}Al-Mg to ^{116}Sb-Sn, MD can be evaluated by the fit from ^{3}He-H up to ^{239}Np-U.

4 Conclusions

From the analog levels of mirror nuclei, the mass of ^{69}Br and its proton separation energy have been evaluated. Similar to CDE, MD is a linear function of $\alpha/A^{1/3}$. Since the MD of the 20 mirror groups lie on a straight line and that of ^{69}Br-Se fits into Eq. (2), ^{69}Br is a homogeneously charged sphere. The subshell closure N=34 indicates that $_{35}$Br$_{34}$ is spherical, similar to ^{54}Ca. The Sp of ^{69}Br is in agreement with the experimental value of −788.8±37.1 keV obtained by the group of Rogers [2] at the National Superconducting Cyclotron Laboratory of the Michigan State University, USA. The new generation of radioactive ion beams endowed with high resolving power and adequate efficient selective fragment separations at RIKEN (Tokyo), NSCL (Michigan), and JINR (Dubna) will permit production of exotic nuclei at the borders of nuclear territory. Masses obtained from the fit of analog levels of mirror nuclei may be helpful to explore the nuclear landscape and probe the limits of nuclear stability. An international Facility for Antiproton and Ion Research, FAIR at Darmstadt, Germany will be operational within the coming years. Over 6000 nuclei that exist in nature are expected to be produced. Some of them are assigned to the rapid proton-capture, *rp*. They run through areas far from the stable nuclei and reveal the nucleosynthesis phenomena.

We are grateful to Florent Dietrich of Gambsheim, Jean Ehrhart and ChalounVesaphong for their encouragement.

References

1 Wallace R K, Woosley S E. Astrophys. J. Suppl. Ser., 1981, **45**: 389
2 Rogers A M, Famiano M A, Lynch W G et al. Phys. Rev. Lett., 2011, **106**: 252503
3 Pape A, Antony M S. Atomic Data and Nuclear Data Tables, 1988, **39**: 201
4 Brown B A, Clement R R C, Schatz H et al. Phys. Rev. C, 2002, **65**: 045802
5 Antony M S, Britz J, Bueb J B et al. Atomic Data and Nuclear Data Tables, 1985, **33**: 447
6 Janecke J. Isospin in Nuclear Physics. Wilkinson, Oxford, 1969
7 Antony M S, Pape A, Britz J. Atomic Data and Nuclear Data Tables, 1997, **66**: 1
8 Audi G, Kondev F G, WANG M et al. Chinese Physics C, 2012, **36**: 1157
9 National Nuclear Data Center, ENSDF, BNL, 2013
10 Seitz H, Zaidi S A A, Bigler R. Phys. Rev. Lett., 1972, **28**: 1465
11 TU X L, SUN Y, ZHANG Y H et al. J. Physics G, 2014, **41**: 025104
12 Santo M Del, Meisel Z, Bazin D et al. Physics Letters B, 2014, **738**: 453
13 Steppenbeck D, Takeuchi S, Aoi N et al. Nature, 2013, **502**: 2074