第 33 卷 第 2 期 原 子 核 物 理 评 论 Vol. 33, No. 2
2016 年 6 月 Nuclear Physics Review June, 2016

Article ID: 1007-4627(2016) 02-0156-04

Shell Evolution Study for New Magic Number $N=32$ via Isochronous Mass Spectrometry

XU Xing(徐 星)[1], WANG Meng(王 猛)[1], ZHANG Yuhu(张玉虎)[1], SHUAI Peng(帅 鹏)[1], XU Hushan(徐瑚珊)[1], TU Xiaolin(涂小林)[1], ZHOU Xiaohong(周小红)[1], CHEN Ruijiu(陈瑞九)[1], CHEN Xiangcheng(陈相成)[1], FU Chaoyi(付超义)[1,2], GE Zhuang(葛 壮)[1,2], HUANG Wenjia(黄文嘉)[1,2], LAM Yek-wah(蓝乙华)[1], LI Hongfu(李宏福)[1,2], LIU Junhao(刘俊豪)[1,2], SUN Mingze(孙铭泽)[1,2], XING Yuanming(邢元明)[1,2], YAN Xinliang(颜鑫亮)[1], ZENG Qi(曾 奇)[3], ZHANG Peng(张 鹏)[1,2], XIAO Guoqing(肖国青)[1], ZHAN Wenlong(詹文龙)[1]

(1. Key Laboratory of High Precision Nuclear Spectroscopy and Center for Nuclear Matter Science, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China;
3. Research Center for Hadron Physics, National Laboratory of Heavy Ion Accelerator Facility in Lanzhou and University of Science and Technology of China, Hefei 230026, China)

Abstract: Recent results and progress of mass measurements of neutron-rich nuclei utilizing Isochronous Mass Spectrometry (IMS) based on the HIRFL-CSR complex at Lanzhou are reported. The nuclei of interest were produced through projectile fragmentation of primary ^{86}Kr ions at a realistic energy of 460.65 MeV/u. After in-flight separation by the fragment separator RIBLL2, the fragments were injected and stored in the experimental storage ring CSRe, and their masses were determined from measurements of their revolution times. The re-determined masses were compared and evaluated with other mass measurements, and the impact of these evaluated masses on the shell evolution study is discussed.

Key words: storage ring; isochronous mass spectrometry; nuclear mass; shell evolution

CLC number: O57 **Document code:** A **DOI:** 10.11804/NuclPhysRev.33.02.156

1 Introduction

The particular bound and enhanced stable nature of some special nuclei with certain configurations of protons and neutrons led Mayer and Jensen introduced nuclear shell model more the 60 year ago[1−2], leading to the concept of the "magic" number associated with proton numbers or neutron numbers 2, 8, 20, 28, 50, 82 and neutron number 126. In the single particle shell model, protons and neutrons are believed to occupy nuclear orbitals with different quantum numbers. When these orbitals are fully filled, nuclides are extremely bound and can be regarded as spherical. However, the traditional nuclear shell picture has been found that it is not invariable when approaching to the drip lines. How magic numbers evolve with extreme proton-to-neutron ratios from β-stable valley toward the drip lines has become one of the research frontiers of nuclear physics.

The excitation energy of the first $J^{\pi}=2^{+}$ state in even-even nuclei, which is often called $E(2_1^+)$, is inversely proportional to the quadrupole deformation parameter[3]. As a result, spherical or semi-spherical nuclei will show relatively higher $E(2_1^+)$ values compared with neighbouring even-even nuclei. The $E(2_1^+)$ value is treated as a good indicator for closed-shell or

Received date: 25 Mar. 2016;

Foundation item: National Basic Research Program of China (973 Program)(2013CB834401); National Natural Science Foundation of China (U1232208, U1432125, 11205205, 11035007); Western Light Talent Training Program of Chinese Academy Scienus

Biography: XU Xing(1986–), male, Huangmei, Hubei, Ph.D., working on nuclear physics; E-mail: xuxing@impcas.ac.cn

Corresponding author: WANG Meng, E-mail: wangmeng@impcas.ac.cn.

sub-shell nuclei.

Nuclear mass is one of fundamental properties of the nucleus and it directly reflects the total effects of strong, weak and electromagnetic interactions among the nucleons. Precise and systematic investigations of nuclear masses provide valuable information on nuclear structure. The two neutron separation energy, which is often called S_{2n}, derived from nuclear mass and representing the neutron shell gap, is another well established probe not only for even isotopic chains but also for odd ones.

In the past few decades, a lot of efforts have been made on the shell evolution of pf shell, where protons(π) and neutrons(ν) $p_{3/2}-p_{1/2}$ and $f_{7/2}-f_{5/2}$ spin-orbit parters constitute a nuclide. Nuclear spectroscopy experiments of $E(2_1^+)$ in even-even nuclei have showed a strong evidence for the onset of a new neutron shell closure at $N=32$ in ^{50}Ar[4], ^{52}Ca[5−6], ^{54}Ti[7−8], ^{56}Cr[9−10]. As can be seen from Fig. 1, the unambiguous peak at $N=28$ indicates the robustness of standard magic number $N=28$, and another peak at $N=32$ reveal a new magic number. Furthermore the relative weaker peak in ^{56}Cr imply the reduction of $N=32$ shell gap when proton number evolve from 18 to 24.

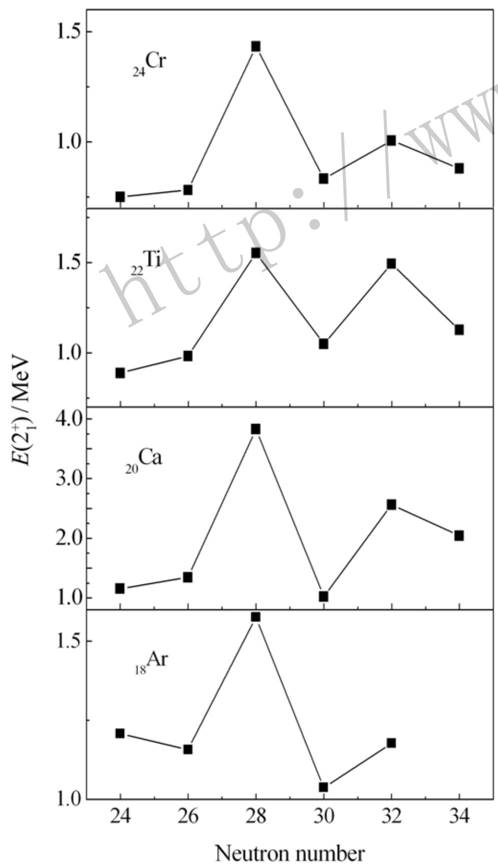

Fig. 1 The systematic behaviour of $E(2_1^+)$ in even-even nuclei as a function of the neutron number in four even-Z isotopic chains from Argon ($Z=18$) to Chromium ($Z=24$). All data taken from Evaluated Nuclear Structure Data File(ENSDF)[11].

From the aspect of nuclear mass, much progress has been made on this research. Recent high-precision mass measurements by Penning-Traps from Titan[12] and Isotrap[13] confirmed the existence of N=32 sub-shell closure in Calcium isotopes. And mass measurements by Multi-Reflection Time of Flight (MR-TOF) facility for ^{52,53}K revealed the persistence of the $N=32$ shell gap in Potassium isotopes below the proton magic number Z=20[14]. However, due to the large uncertainties of nuclear masses in the $A\sim 55$, $Z>20$ region(about several hundred keV), it is difficult to give a definitive conclusion of $N=32$ shell evolution above $Z=20$. It is quite worthy to re-measure nuclear mass for these nuclides and improve the precision.

2 Experiment and data analysis

The experiments were conducted at the HIRFL-CSR accelerator complex consisting of a main cooler storage ring (CSRm) operating as a heavy-ion synchrotron, an experimental storage ring CSRe, and a radioactive beam line RIBLL2 connecting the two rings and operating as an in-flight fragment separator. The CSRe was set into an isochronous mode with a transition energy $\gamma_t=1.395$[15]. In order to make the $\gamma=\gamma_t$, which is often called isochronous condition, for the nuclide of interest, the primary beams of ^{86}Kr^{28+} ions were accelerated to an energy of 460.65 MeV/u by the CSRm, and then were fast extracted and focused on a $\sim$15 mm beryllium target placed at the entrance of the RIBBL2. The secondary ions were produced via projectile fragmentation and were separated by the RIBLL2. The cocktail beam of secondary ions within an Bρ-acceptance of about $\pm$0.2% were injected into the CSRe for further investigations.

A dedicated time-of-flight detector[16] installed in the CSRe aperture was used to generate the timing signals of every stored ion when passing through the detector at every revolution. Giving the fact that the typical rising time of the signals is about 450 ps[16], the time resolution, which is about 50 ps, is good enough to accurately determine the time stamps of signals. The detection efficiency varies from $\sim$ 20% to $\sim$ 70% depending on the proton number and the total number of stored ions in this injection. In this experiment, in a typical injection, there were 5 ions stored simultaneously. For nuclide with proton number about 20, the detection efficiency is about 50%, in other words, about 150 timing signals were recorded. Since the energy loss in the TOF detector at every revolution slightly changed the revolution time, a second order polynomial were utilized to describe the relationship between flight time and revolution turns. The revolution time at the 35th turn of all stored ions were used in further analysis.

Fig. 2 shows the final results of the experiments. The left picture illustrates the revolution time spectrum associated with nuclides used in the mass calibration. The right picture shows the standard deviations of revolution time spectrum of all well-resolved nuclides, and a clear dependence with the isochronous condition can be seen from this picture.

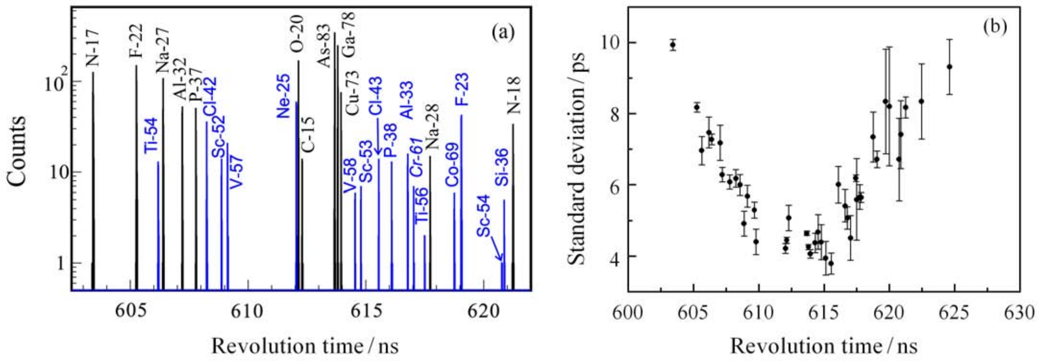

Fig. 2 (color online) (a) Part revolution time spectra of ^{86}Kr fragments. Nuclei with masses determined in this experiment and those used as references in the mass calibration are indicated with blue bold and black italic letters, respectively. (b) Standard deviation of revolution time spectrum of all well-resolved nuclides.

A third order polynomial was used to calibrated the mass to charge ratio m/q and the revolution time T. Twelve nuclides with accurately known masses[17] (little than the foreseen systematic error) were used as references to calculate the freely fitted parameters of the polynomial. The masses of nuclide of interest were obtained by interpolation with corresponding revolution time.

3 Results and discussion

Since several mass measurements have been conducted in this mass region[18–22], a careful atomic mass evaluation have been made combine these results with our results(see details in Ref. [23]). The re-evaluated mass values of $^{52-54}$Sc were $-40\,450(85)$, $-38\,895(76)$ and $-34\,535(180)$ keV, which were more bound by 280, 785, and 935 keV compared with corresponding evaluated values in AME12[17], respectively.

With our new mass values of Scandium isotopes, the systematic behaviour of $S_{2\mathrm{n}}$ with increasing neutron number of Scandium isotopic chain is completely changed. As can be seen from Fig. 3, the $S_{2n}(^{52}\mathrm{Sc})$ as well as $S_{2n}(^{53}\mathrm{Sc})$ shift up, and consequently, a significant kink at $N=32$ become visible. This behaviour is in line with the ones recently established in Calcium[13] and Potassium[14] isotopic chains. The pronounced decrease reveals the persistence of new magic number $N=32$ in Scandium isotopes.

The emergence of new shell closure is due to the change of the single particle order caused by the variation of nuclear forces. In the tensor-force-driven-shell evolution framework, the tensor force exist between protons in $j_{<,>}=l\pm\frac{1}{2}$ and neutrons in $j'_{<,>}=l'\pm\frac{1}{2}$, where l and l' represents orbital angular momenta of protons and neutrons, respectively. In this mass region, as Otsuka *et al.* pointed out[24–25], the valence protons, occupying the $\pi f_{7/2}$ orbital, have an attractive tensor force with valence neutrons, occupying the $\nu f_{5/2}$ orbital in the standard shell model picture. As protons are moved out from the $\pi f_{7/2}$ orbital, *i.e.*, from ^{60}Fe to ^{54}Ca, the strength of the attractive $\pi-\nu$ tensor force will decrease and result in a consequently shift up $\nu f_{5/2}$ orbital. At last the two valence neutrons of ^{54}Ca occupy the $\nu d_{1/2}$ orbital instead of $\nu f_{5/2}$ orbital

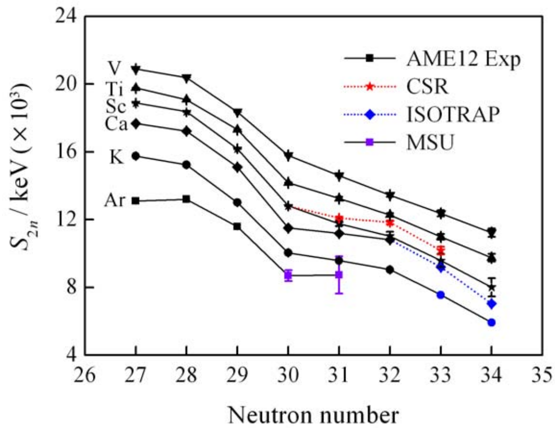

Fig. 3 (color online) Experimental two neutron separation energy S_{2n} as a function of neutron number N for isotopic chains from Argon to Vanadium. Black points represent values based completely on data from latest evaluation AME12, while colour ones derived from recent mass measurements.

leading to the substantial shell gaps between $\nu d_{1/2}$ and $\nu d_{3/2}$ as well as $\nu d_{3/2}$ and $\nu f_{5/2}$, in other words, the formation of new magic number $N=32$ and $N=34$.

It is noteworthy that the up boundary of the new magic number $N=32$ is still controversial. As can be seen from Fig. 3, the rather smooth systematic behaviour in Titanium and Vanadium reveals no significant indication of $N=32$ shell gap, while the aspect of $E(2_1^+)$ shows a strong evidence of the persistence of $N=32$ shell gap up to Chromium isotopes. This somehow conflict call for more accurate measurement for both nuclear mass as well as $E(2_1^+)$ in this mass region or a unified description of this exotic phenomena.

References:

[1] MAYER M G. Phys Rev, 1949, **75**: 1969.
[2] MAYER M G, JENSEN J H D. Elementary Theory of Nuclear Shell Structure, Wiley, New York, 1955.
[3] STEPHENS F S, DIAMOND R M, LEIGH J R, *et al.* Phys Rev Lett, 1972, **29**: 438.
[4] STEPPENBECK D, TAKEUCHI S, AOI N, *et al.* Phys Rev Lett, 2015, **114**: 252501.
[5] HUCK A, KLOTZ G, KNIPPER A, *et al.* Phys Rev C 1985, **31**: 2226.
[6] GADE A, JANSSENS R V F, BAZIN D, *et al.* Phys Rev C 2006, **74**: 021302(R).
[7] JANSSENS R V F, FORNAL B, MANTICA P F, *et al.* Phys Lett B, 2002, **546**: 55.
[8] DINCA D C, JANSSENS R V F, GADE A, *et al.* Phys Rev C, 2005, **71**: 041302(R).
[9] PRISCIANDARO J I, MANTICA P F, BROWN B A, *et al.* Phys Lett B, 2001, **510**: 17.
[10] BÜRGER A, SAITO T R, GRAWE H, *et al.* Phys Lett B, 2005, **622**: 29.
[11] http://www.nndc.bnl.gov/ensdf/
[12] GALLANT A T, BALE J C, BRUNNER T, *et al.* Phys Rev Lett, 2012, **109**: 032506.
[13] WIENHOLTZ F, BECK D, BLAUM K, *et al.* Nature, 2013, **498**: 346.
[14] ROSENBUSCH M, ASCHER P, ATANASOV D, *et al.* Phys Rev Lett, 2015, **114**: 202501.
[15] XIA J W, ZHAN W L, WEI B W, *et al.* Nucl. Instrum. Methods in Phys Res A, 2002, **488**: 11.
[16] MEI B, TU X L, WANG M, *et al.* Nucl Instr Meth A, 2010, **624**: 109.
[17] AUDI G, WANG M, WAPSTRA A H, *et al.* Chin Phys C, 2012, **36**: 1287.
[18] MATOS M, Ph.D. thesis, Justus-Liebig-Universitat Giessen, 2004.
[19] TU X L, ZHOU X G, VIEIRA D J, *et al.* Z. Phys A Atomic Nuclei, 1990, **337**: 361.
[20] SEIFERT H L, WOUTERS J M, VIEIRA D J, *et al.* Z. Phys A Atomic Nuclei, 1994, **349**: 25.
[21] BAI Y, VIEIRA D J, SEIFERT H L, *et al.* AIP Conf. Proc, 1998, **455**: 90.
[22] ESTRADE A, MATOS M, SCHATZ H, *et al.* Phys Rev Lett, 2011, **114**: 172503.
[23] XU X, WANG M, ZHANG Y H, *et al.* Chin Phys C, 2015, **39**: 104001.
[24] OTSUKA T, SUZUKI T, FUJIMOTO R, *et al.* Phys Rev Lett, 2005, **95**: 232502.
[25] STEPPENBECK D, TAKEUCHI S, AOI N, *et al.* Nature, 2013, **502**: 207.