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# 2 - 4 Research Progress in the CSRe Fine Nuclear Spectroscopy Group

Zhang Yuhu and Wang Meng

The research group of CSRe fine nuclear spectroscopy has been working on the precision mass measurements of short lived nuclei based on the isochronous mass spectrometry. The research activities are mainly focused on two aspects. One is the improvements of detection techniques and data analysis methods, the other is the investigations on nuclear structures and nuclear astrophysics based on the new mass values from the experiments.

We have installed two time-of-flight detectors in the straight section of CSRe in order to measure the velocity of stored ions in the ring. The distance between the ultra-thin foils of two ToF detectors has been measured using a laser range-finder Leica Nova MS60 Multi-Station. On the other hand, un-synchronicity of the timing signals from the two ToF detectors is also measured. These two parameters are crucial in the precise determination of ion's velocity. Test experiments have been performed using $^{40}$Ar and $^{58}$Ni primary beams and great efforts are devoting to develop a new method to deduce the ion's velocity using the experimental data of two-ToF isochronous mass spectrometry.

Concerning the conventional IMS experiments using $^{58}$Ni, $^{112}$Sn primary beams and single ToF detector, main parts of the data analysis has been completed yielding new mass values which are shown in Table 1 together with those in AME12[1] for comparisons. Most of our ME values are compiled in the latest atomic-mass evaluations 2016[2]. Based on the new mass values, some issues in the studies of nuclear structures and nuclear astrophysics have been addressed in Refs. [3-7].

Table 1 Mass excesses (ME) measured in CSRe together with those in AME12[1].

| Nuclide | $ME_{\mathrm{CSRe}}$/keV | $ME_{\mathrm{AME12}}$/keV | Nuclide | $ME_{\mathrm{CSRe}}$/keV | $ME_{\mathrm{AME12}}$/keV |
|---|---|---|---|---|---|
| $^{27}$P | −685(42) | −722(26) | $^{45}$V | −31 885(10) | −31 885.3(9) |
| $^{29}$S | −3 094(13) | −3 160(50) | $^{47}$Cr | −34 565(10) | −34 561(7) |
| $^{44g}$V | −23 827(20) | −24 120(180) | $^{49}$Mn | −37 607(14) | −37 620.3(24) |
| $^{44m}$V | −23 541(19) | −23 850(210) | $^{51}$Fe | −40 198(14) | −40 202(9) |
| $^{46}$Cr | −29 471(11) | −29 474(20) | $^{79}$Y | −57 803(80) | −58 360(450) |
| $^{48}$Mn | −29 299(7) | −29 320(170) | $^{81}$Zr | −57 524(92) | −58 400(160) |
| $^{50}$Fe | −34 477(6) | −34 490(60) | $^{82}$Zr | −63 632(10) | −63 940(200) |
| $^{52g}$Co | −34 361(8) | −33 990(200) | $^{83}$Nb | −57 613(162) | −58 410(300) |
| $^{52m}$Co | −33 974(10) | −33 610(220) | $^{84}$Nb | −61 219(12) | −61 020(300) |
| $^{54}$Ni | −39 278(4) | −39 220(50) | $^{80}$Zr | −54 176(250)# | −55 520(1490) |
| $^{56}$Cu | −38 643(15) | −38 240(200) | $^{84}$Mo | −53 958(250)# | −54 500(400) |

# extrapolated in this work

In collaboration with the RIB physics group, an in-ring reaction for $^{58}$Ni(p, p)$^{58}$Ni in inverse kinematics was performed successfully at the 90° laboratory angle with an internal gas-jet target at CSRe. This opens opportunities for low momentum transfer reaction studies on giant resonances, which play an important role in defining the equation of state for nuclear matter.

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# 2 - 5 Isochronous Nuclear Mass Measurements in CSRe

Zhang Yuhu and CSRe mass measurement collaboration

We have performed isochronous mass measurements for the neutron-deficient fp-shell nuclei[1] produced via projectile fragmentation of an energetic $^{58}$Ni beam. Special techniques have been applied to the current measurements and data analyses in order to increase the resolving power of isochronous mass spectrometry in the heavy ion storage ring CSRe in Lanzhou, *e.g.*, inserting a metal slit in the dispersion section of the ring, and using a new technique to correct the effects of the unstable magnetic fields of the RIBLL2-CSRe system. On the basis of the newly measured masses, several nuclear structure studies in the fp shell have been performed. Main results and conclusions from this work are summarized as follows:

(1) The mass excesses of the $T_z$ = tx nuclei $^{52g,52}$Co and $^{56}$Cu have been measured for the first time with an uncertainty of ∼10 keV. This is the highest precision reached in the isochronous mass spectrometry for short-lived neutron-deficient nuclei. Our measurements show that $^{52g,52}$Co and $^{56}$Cu are ∼370 keV and ∼400 keV more bound than the evaluations in AME12[2], respectively. The new mass of $^{56}$Cu allows us to observe the mirror symmetry of low-spin excited levels between $^{56}$Cu and $^{56}$Co within an uncertainty of 50 keV. The energy of the $T = 2$ isobaric analog state in $^{52}$Co is newly assigned precisely, which fits well into the fundamental Isobaric Multiplet Mass Equation.

(2) The mass excesses of five $T_z = -1$ nuclei $^{44}$V, $^{46}$Cr, $^{48}$Mn, $^{50}$Fe, and $^{54}$Ni have been re-measured with a precision of one order of magnitude higher than the values in AME12. Especially, the mass excesses of $^{44}$V and $^{54}$Ni are ∼300 keV and −60 keV, respectively, deviating from the literature ones. The new mass data allow us to establish the general A-dependence features of vector and tensor Coulomb energies up to $A = 58$ for the $T = 1$ isobaric triplets. We have shown that the oscillation pattern of tensor Coulomb energy persists for fp-shell nuclei. This fact may provide a test ground for investigating the effects of isospin symmetry breaking, as well as a guideline for mass extrapolation and measurement of heavy nuclei in and even beyond fp shell.

(3) The masses of four $T_z = -1/2$ nuclei $^{45}$V, $^{47}$Cr, $^{49}$Mn, and $^{51}$Fe, which are obviously outside the isochronous window, were also measured. The deduced mass excess values agree well, within the experimental errors, with the recent JYFLTRAP measurements (for $^{45}$V and $^{49}$Mn) or with our previous IMS measurements (for $^{47}$Cr and $^{51}$Fe) in CSRe. The consistent results for $^{51}$Fe and the new mass of $^{52m}$Co help us to re-assign the $T = 2$ isobaric analog state in $^{52}$Co by referring to the experimental data on β-delayed protons and β-delayed $\gamma$'s of $^{52}$Ni.

(4) The mass excess of the expected low-lying $6^+$ isomer in $^{44}$V has been determined for the first time to be −23541(19) keV, which is, similar to its ground state, ∼300 keV less bound than the evaluations in AME12[2]. The excitation energy $E_x$ =286(28) keV was found to be very close to the $E_x$ value of an analog state ($E_x$ =271 keV) in its mirror nucleus $^{44}$Sc.

(5) We have investigated the $Z$ and $N$ dependences of residual p-n interactions around the doubly magic nucleus $^{56}$Ni using our new mass of $^{56}$Cu. Similar to the case around $^{208}$Pb, the hypothesis still holds that the p-n interaction strength is positively correlated with the spatial overlap of wave functions of the last valence neutron(s) and proton(s). Further analyses show that the empirical p-n interactions deduced from atomic masses change suddenly across the shell closures throughout the chart of nuclides. This is due to sudden changes of the spatial overlap of shell model orbitals of the last valence neutron and proton. Consequently this sets constraints on the applicability of local mass relationships, e.g., Eqs. (8), (9) and (10) of Ref. [3], to predict unknown masses with high accuracy.

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