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Is N = 40 magic? An analysis of ISOLTRAP mass measurements

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Abstract. Recently high-precision mass measurements were performed on Ni, Cu, and Ga isotopes at the triple-trap mass spectrometer ISOLTRAP at ISOLDE/CERN. The relative uncertainty was of the order of 10^{-8}. Data indicate a competition between the sub-shell closure $N = 40$ and the mid-shell region $N = 39$ between the well-known magic numbers $N = 28$ and $N = 50$.

PACS. 21.10.Dr Binding energies and masses – 21.60.Cs Shell model – 32.10.Bi Atomic masses, mass spectra, abundances, and isotopes

Shell closures are fundamental characteristics on which nuclear structure is based but which we now know to erode as we explore extreme isospin systems. The first so-called "magic" number to disappear was the $N = 20$ shell closure around Na and Mg and now $N = 8$ [1,2] and $N = 28$ [3] appear to succumb as well. Like a good magic act, shell closures, having disappeared, can also reappear as attested by the cases $N = 16$ [1] and $N = 32$ [4,5,6].

Different observables can be used for the analysis of this "magic number migration": first excitation energies in even-even nuclei, nuclear level densities, interaction cross-sections and, in the grandest tradition, nucleon separation energies. The latter are particularly sensitive to pairing correlations in the context of superfluidity [7], especially for the case of semi-magic nuclei.

Using the ISOLTRAP mass spectrometer [8], we have made precision mass measurements around $N = 40$ for Ni, Cu, and Ga isotopes (fig. 1) in order to finely map the mass surface in this region. The accuracy of the ISOLTRAP mass measurements also permits us to map out the fine structure of the neutron pairing energy which we have analyzed for correlations and signatures of closed or open shells.

ISOLTRAP is a high-precision mass spectrometer located at ISOLDE [9], CERN. It consists of three main parts. First a radiofrequency quadrupole (RFQ) ion beam cooler delivers low energy (2.7 keV) ion bunches with a sharp time structure. Then a cylindrical preparation Penning trap is used for accumulation, cooling, and isobaric purification. Finally a high-precision, hyperbolic Penning trap is used for the measurement of the cyclotron frequency of the stored ions with charge to mass ratio q/m. The mass value can be determined by measuring the cyclotron frequency $\nu_{\mathrm{c}} = qB/(2\pi m)$ with respect to a well-known reference mass. Most of the nuclides in this study were measured with a precision of 10^{-8}. Particularly high resolving power was necessary for the separation of isomeric states in ^{68}Cu [10] and ^{70}Cu [11].

The difference between experimental mass values and values predicted by the Bethe-Weizsäcker mass formula can provide a neutral indication for shell closures. The Bethe-Weizsäcker formula is given by:

$$\begin{aligned}\frac{E_{\mathrm{nuc}}}{A} = {} & a_{\mathrm{vol}} \\ & + a_{\mathrm{sf}} A^{-1/3} \\ & + \frac{3e^2}{5r_0} Z^2 A^{-4/3} \\ & + \left(a_{\mathrm{sym}} + a_{\mathrm{ss}} A^{-1/3}\right) I^2 \\ & + a_{\mathrm{p}} A^{-y-1} \left(\frac{(-1)^Z + (-1)^N}{2} \right) \end{aligned} \qquad (1)$$

with $I = (N - Z)/A$. The coefficients used for the calculations are from J.M. Pearson [12]: $a_{\mathrm{vol}} = -15.65$ MeV, $a_{\mathrm{sf}} = 17.63$ MeV, $a_{\mathrm{ss}} = -25.60$ MeV, $a_{\mathrm{sym}} = 27.72$ MeV,

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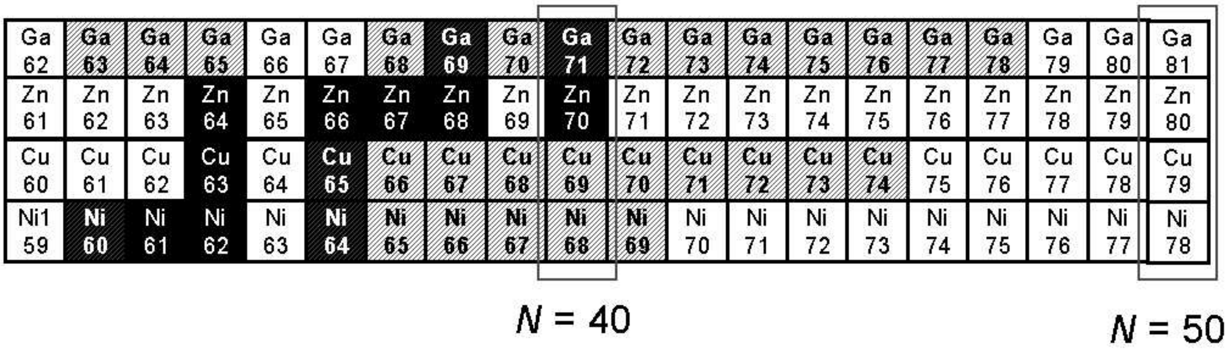

Ga 62	Ga 63	Ga 64	Ga 65	Ga 66	Ga 67	Ga 68	Ga 69	Ga 70	Ga 71	Ga 72	Ga 73	Ga 74	Ga 75	Ga 76	Ga 77	Ga 78	Ga 79	Ga 80	Ga 81
Zn 61	Zn 62	Zn 63	Zn 64	Zn 65	Zn 66	Zn 67	Zn 68	Zn 69	Zn 70	Zn 71	Zn 72	Zn 73	Zn 74	Zn 75	Zn 76	Zn 77	Zn 78	Zn 79	Zn 80
Cu 60	Cu 61	Cu 62	Cu 63	Cu 64	Cu 65	Cu 66	Cu 67	Cu 68	Cu 69	Cu 70	Cu 71	Cu 72	Cu 73	Cu 74	Cu 75	Cu 76	Cu 77	Cu 78	Cu 79
Ni1 59	Ni 60	Ni 61	Ni 62	Ni 63	Ni 64	Ni 65	Ni 66	Ni 67	Ni 68	Ni 69	Ni 70	Ni 71	Ni 72	Ni 73	Ni 74	Ni 75	Ni 76	Ni 77	Ni 78

Fig. 1. Section of the nuclear chart where the nuclides measured at ISOLTRAP are shown in striped boxes. Black squares mark stable nuclides. The two frames indicate the $N = 50$, neutron magic number and the $N = 40$, our region of interest.

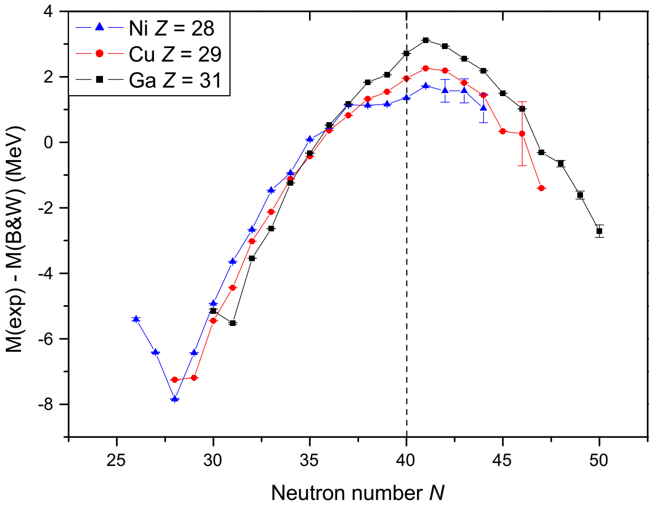

Fig. 2. Difference between the predicted masses by the Bethe-Weizsäcker formula (eq. (1)) and the experimental values as a function of N for $Z = 28$, 29, and 31. Data are from this work and complemented by [13].

and $r_0 = 1.233\,\text{fm}$. We also added a pairing term from J.M. Fletcher [14], with $a_\text{p} = -7\,\text{MeV}$ and $y = 0.4$.

The residuals show especially strong effects ($\sim 15\,\text{MeV}$) for nuclides with $N = 50$ and $N = 82$. Figure 2 shows the mass difference between experimental values and theoretical predictions of eq. (1) for the three isotopic chains of Cu, Ni, and Ga between the known shell closures at $N = 28$ and $N = 50$. The difference is less for $N = 28$ but still above 7 MeV. Between the shell closures the mass differences follow a smooth inverted parabola. However, around $N = 40$ a small indentation is apparent for Ni and Ga, which could be an indication of magicity or simply the indication of a sub-shell closure.

This analysis indicates a barely perceptible imprint of $N = 40$ sub-shell binding on the dominant $N = 39$ mid-shell comportment of binding-energy derivatives. More detailed studies of this question using the shell gap (difference of S_{2n} values) and pairing energy are addressed in a forthcoming publication [15]. Note that detection of such fine structure effects on the mass surface requires mass values with relative uncertainties below $1 \cdot 10^{-7}$, which can be accomplished with Penning trap mass spectrometers such as ISOLTRAP.

References

1. A. Ozawa *et al.*, Phys. Rev. Lett. **84**, 5493 (2000).
2. S. Shimoura *et al.*, Phys. Lett. B **560**, 31 (2003).
3. F. Sarazin *et al.*, Phys. Rev. Lett. **84**, 5062 (2000).
4. J.I. Prisciandaro *et al.*, Phys. Lett. B **510**, 17 (2001).
5. P.F. Mantica *et al.*, Phys. Rev. C **67**, 014311 (2003).
6. P.F. Mantica *et al.*, Phys. Rev. C **68**, 044311 (2003).
7. P. Van Isacker, C. R. Phys. **4**, 529 (2003).
8. F. Herfurth *et al.*, J. Phys. B **36**, 931 (2003).
9. E. Kugler, Hyperfine Interact. **129**, 23 (2000).
10. K. Blaum *et al.*, Europhys. Lett. **67**, 586 (2004).
11. J. Van Roosbroeck *et al.*, Phys. Rev. Lett. **92**, 112501 (2004).
12. J.M. Pearson, Hyperfine Interact. **132**, 59 (2001).
13. G. Audi, A.-H. Wapstra, C. Thibault, Nucl. Phys. A **729**, 337 (2003).
14. J.M. Fletcher, MSc Thesis, University of Surrey (2003).
15. C. Guénaut *et al.*, to be published in Phys. Rev. C (2005).