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Abstract

A new isomeric state in ^{78}Zn has been identified and studied in the fragmentation of a 60.5 AMeV ^{86}Kr beam on a ^{nat}Ni target. The measured energies of the transitions and the half-life, $T_{1/2}$=319(9) ns, of the isomeric decay suggest a spin and parity assignment I^π=8^+. The deduced B(E2,$8^+ \rightarrow 6^+$) value equals 1.21(5) W.u. is well reproduced in large scale shell model calculations using realistic interactions in the proton-neutron $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, $1g_{9/2}$ model space. Standard E2 polarisation charges of 0.5e for both protons and neutrons were used. This result consists the first experimental evidence of the persistance of the N=50 shell gap in the vicinity of $^{78}_{28}$Ni$_{50}$.

Nuclei in the vicinity of the recently observed doubly magic nucleus $^{78}_{28}Ni_{50}$ [1,2] are amongst the best candidates to study the evolution of nuclear structure far from the valley of stability. The large neutrons to protons ratio in this region might allow the observation of unusual shell effects. In particular, the question of whether the N=50 shell gap persists so far away from stability might be studied in the two-hole (particle) structure neighbours of ^{78}Ni, namely ^{76}Ni, ^{80}Zn or/and ^{78}Zn. As proven in our recent studies [3] we can progress towards ^{78}Ni using isomer spectroscopy following a projectile fragmentation reaction. This method provides information on the energy levels and lifetimes of excited states. The values of transition strengths obtained for the high spin isomers with simple and pure configurations (as observed near shell closures) are essential to extract the nucleon effective charge. In a large scale shell model calculation the effective charge is a measure of the polarisation effects on the core induced by the valence particle undergoing an electromagnetic transition. In the ^{100}Sn region the effective charges for proton, neutron and proton-neutron configurations have been studied. The results were discussed controversially but imply that a large isovector charge is required, i.e. a large difference in proton and neutron polarisation charge [5–7]. For neutron rich systems, with relatively small valence particle binding, due to the reduced overlap of valence neutrons and proton core, a decreasing role of polarisation effects and thus a smaller effective neutron charge is expected. On the other hand a diminishing shell gap could enable core excitations and even deformation as in the well known ^{32}Mg example [8]. The single particle structure at the Fermi surface for proton holes in N=50 nuclei below ^{100}Sn is identical to that of neutrons in Z=28 Ni isotopes below ^{78}Ni, i.e. these are valence mirror states. The respective neutron and proton particle states differing by one major shell exhibit again very similar features. Therefore $^{78}_{30}Zn_{48}$ is related to $^{78}_{28}Ni_{50}$ and $^{76}_{28}Ni_{48}$, as is $^{100}_{48}Cd_{52}$ to $^{100}_{50}Sn_{50}$ and $^{98}_{48}Cd_{50}$, if we exploit isospin symmetry of mirror nuclei in the latter case. The important difference though, is that in contrast to the highly symmetrical ^{100}Sn system, where protons and neutrons occupy the same orbitals, ^{78}Ni has a large neutron excess. This makes the 8$^+$ isomer in ^{78}Zn a very good model state for the 8$^+$ level in ^{76}Ni, which is a two neutron-hole excitation in ^{78}Ni. The mere existence of an isomer in ^{78}Zn implies "a fortiori" its existence in ^{76}Ni and would be a direct proof for the persistence of the N=50 shell closure in ^{78}Ni. By comparison with a shell-model calculation one can, in principle, extract the neutron polarisation charge of ^{78}Ni. A similar method was previously used to extract the effective E2 operator for protons and neutrons in the vicinity of the N=Z doubly magic nucleus ^{100}Sn [5,9,10].

The present work was performed in order to search and study new isomeric states in neutron rich nuclei in the potassium to germanium region produced by the fragmentation reaction of a ^{86}Kr beam. It is a continuation of the previous survey experiment where new spectroscopic information has been obtained for 13 isomeric states [3]. In that work, evidence for the existence of an isomeric state in ^{78}Zn was shown, but due to a very low statistics, both the half-life

and the energy of the isomeric transition could not be accurately deduced.

The experiment has been performed at GANIL using the LISE spectrometer [11]. The neutron rich $^{86}Kr^{34+}$ beam with an energy of 60.5 AMeV and mean intensity of $1.6\mu Ae$ ($3x10^{11}$pps) impinged on a rotating $100\mu m$ thick ^{nat}Ni target. A $500\mu m$ thick Be backing placed behind the target allowed a reduction of the width of the charge states distribution of produced fragments. A $50\mu m$ thick Be wedge was used in the first dispersive plane of the spectrometer to remove light fragments and to further suppress non-fully-stripped ions. In order to reduce the time of flight of fragments to less than 200 ns (compared with $1.2\mu s$ in our previous experiment[3]) the experimental set-up was placed in the first achromatic focal point of LISE. The heavy ions were detected by a three-element Si-detector telescope. The silicon detectors were $300\mu m$, $300\mu m$ and $500\mu m$ thick, respectively. The last detector was x and y position sensitive and it was mounted at an angle of 45° with respect to the beam axis.

The last Si-detector was surrounded by 4 high-purity germanium detectors: one four-crystal clover of 120% relative efficiency (add-back including), two coaxial-type of 90% and 80% efficiency respectively and one low energy photon spectrometer (LEPS). In order to increase the geometrical efficiency of the setup, two detectors with the highest efficiency, were placed at about 1.5cm from the implantation Si-detector. The distance between the other two Ge-detectors and the beam axis was about 5cm. The sensitivity range for γ-ray energies was between 30 keV and 4 MeV. The total photopeak efficiency was measured to be 6.2(1)% for 1.3 MeV γ-rays. All detectors were mounted perpendicularly to the beam axis. Three large volume BaF_2 crystals were placed at about 0° with respect to the beam axis. The lifetimes of isomeric states were measured by storing the time difference between the heavy ion implantation signal and delayed γ-rays. Two separate time ranges of up to 500 ns and 40 μs respectively were recorded for each Ge crystal using standard time-to-digital converter (TDC) and time-to-amplitude converter (TAC) modules respectively.

The identification of fragments in mass, atomic number and atomic charge was achieved by means of energy-loss, total-kinetic-energy and time-of-flight measurements. The independent confirmation of the fragment identification comes from the observation of characteristic γ-rays corresponding to the previously identified isomeric decays of $^{67,68}Ni$[12,13]. All isomeric states reported in ref. [3] were observed also in the present experiment, in most cases, with much higher statistics. For example, due to the reduced time of flight, increased primary beam intensity and improved γ-detection efficiency, for ^{70m}Ni the number of counts in the corresponding γ-ray lines was about 400 times higher than in the previous work.

In the present letter only results concerning the isomeric state in ^{78}Zn are

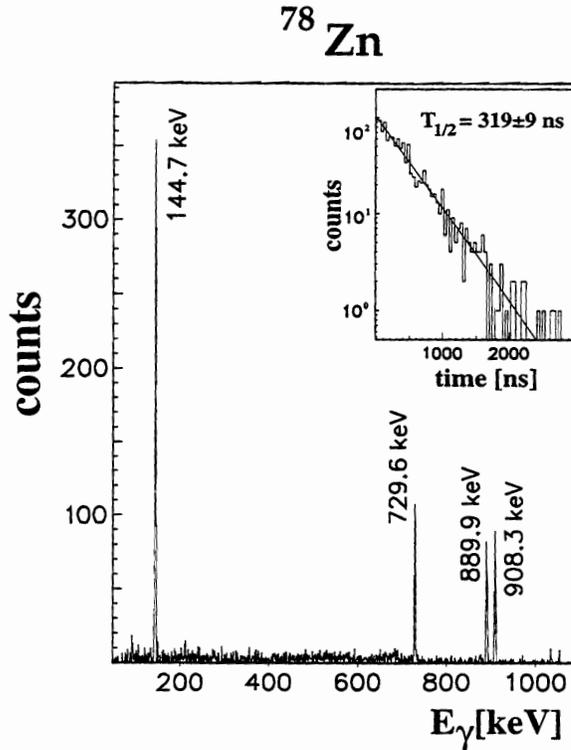Fig. 1. The γ-ray energy spectrum of the isomeric state in ^{78}Zn. The decay curve summed over the four observed transitions is shown in the inset.

presented. A summary of the measured gamma rays and half-lives for other new isomeric states observed in this experiment may be found in ref. [4].

The measured γ-ray spectrum gated by the events corresponding to ^{78}Zn is shown in fig. 1. This spectrum represents the sum of spectra measured by all Ge-detectors. Four pronounced peaks at the energies of 144.7(5), 729.6(5), 889.9(5) and 908.3(5) keV are clearly observed. When corrected for the detection efficiency and internal conversion α_{tot}(E2;144.7keV)=0.165, all the peaks have the same intensity and half-life and the corresponding γ-rays are found to be in coincidence. From these experimental observables the E2 multipolarity was deduced for the 144.7 keV transition. The assignment of the E2 multipolarity to three other transitions comes from the intensity balance and systematics discussed below. The time decay pattern of the isomeric transition, summed over four γ-rays is shown in the inset of fig.1. An exponential χ^2 fit to the experimental histogram gives a half-life value of 319(9) ns. The γ-ray energies and the half-life measured by means of the much faster BaF$_2$ crystals are also in agreement with those found using the germanium detectors.

The low energy γ-ray at 144.7(5) keV was assumed to correspond to the primary isomeric transition in ^{78}Zn. The assignment of the 729.6(5) keV γ-ray to the $2^+ \rightarrow 0^+$ transition as well as $I^\pi=8^+$ assignment to the isomeric state comes from the systematics of the 8^+ isomers in the neighbouring nuclei as

shown in Fig. 2. Though going from ^{80}Ge towards ^{78}Zn an increase of E(2^+) is expected, a value of about 890 or 908 keV seems to be too high. From the E(2^+) ratios in the above mentioned valence mirrors $^{98}_{48}$Cd$_{50}$ – $^{100}_{48}$Cd$_{52}$ and corresponding pairs ^{50,52}Ti, ^{52,54}Fe, ^{132,134}Te, and ^{208,210}Po [5,14] the latter assignment would imply E(2^+,^{76}Ni)$\simeq$1250 keV$\simeq$ E(2^+,^{70}Ni) [3]. This appears too high, as from ^{70}Ni towards ^{76}Ni an appreciable drop of E(2^+) due to reduced pairing in the ground state is expected, as observed in N=50 [5] and N=126 [14] isotones.
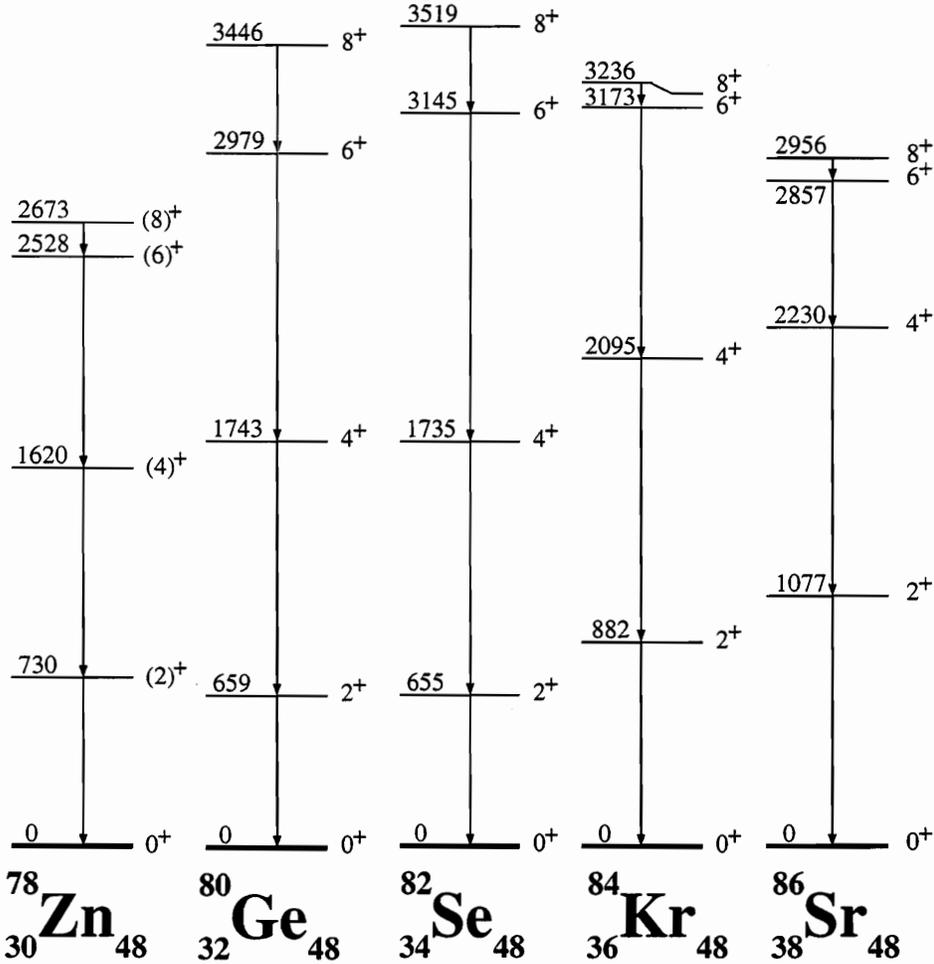

Fig. 2. Systematics of the 8^+ isomeric states in the neutron-rich N=48 isotones. The proposed level scheme of ^{78}Zn is from the present work, those of ^{80}Ge and ^{82}Se from ref. [22] and the others from ref. [14]. The level energies are in keV. The assignment of the 2^+ and 4^+ energies in ^{78}Zn is based on systematics. See text for details.

The only information previously available on excited levels of ^{78}Zn comes from the β-decay of ^{78}Cu [15]. However, the 737 keV γ-ray, assigned tentatively in ref. [15] to the $2^+ \rightarrow 0^+$ transition in ^{78}Zn, has an energy about 7 keV higher than that measured in the present work.

It should be mentioned that as the above assignment of the 729.6(5) keV γ-ray

to the $2^+ \rightarrow 0^+$ transition is based on the systematics, other values for the 2^+ energy in ^{78}Zn, namely 889.9(5) keV or 908.3(5) keV, can not be completely ruled out. Also, the order of the 889.9(5) keV and 908.3(5) keV transitions in ^{78}Zn remains uncertain. However, these uncertainties do not change final conclusions of the present work.

An $I^\pi = 8^+$ assignment to the isomeric state is the most probable for reasons similar to those explained in ref.[5] for the case of the 8^+ isomer in ^{98}Cd. That implies that the 6^+ and 8^+ states are predominantly neutron hole states of configuration $g_{9/2}^{-2}$, while the 0^+ - 4^+ states are mixed with $(fp)_{0-4}^2$ configurations. Thus the 6^+ and 8^+ states are fairly pure neutron hole states. There are of course other possibilities of coupling neutrons together with protons to 6^+ and 8^+ states, but these configurations are not expected to be mixed in strongly as particles and holes do not overlap much in space and therefore their interaction remains small.
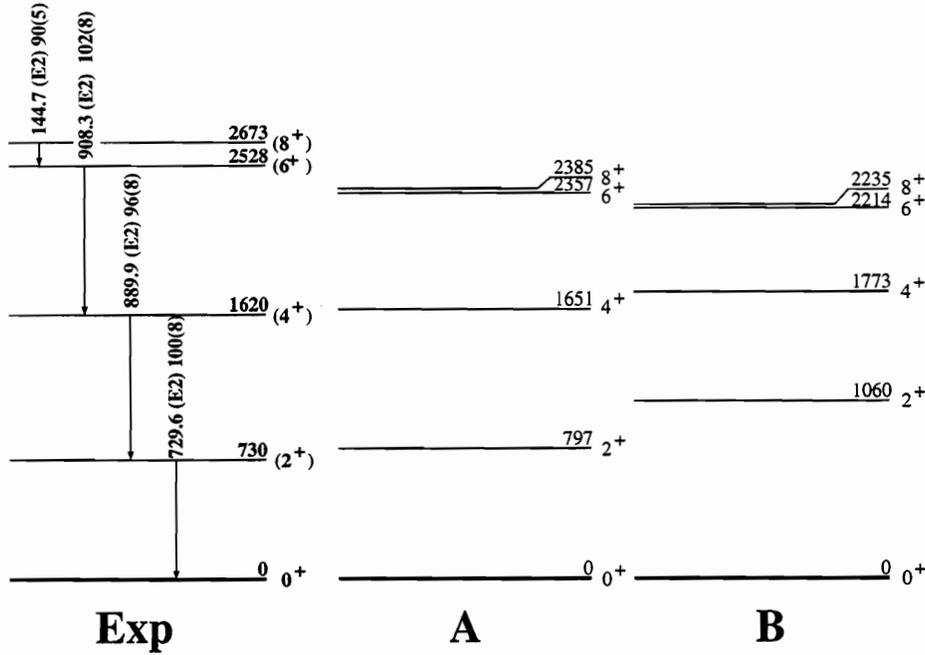

Fig. 3. Deduced decay scheme of ^{78m}Zn compared to the predictions of the shell model (A and B). The levels and transition energies are in keV. The relative γ-ray intensities, were normalized to the 729.6 keV transition. The energy of the 2^+ and 4^+ levels is based on systematics. See text for details.

Assuming configurations $\nu g_{9/2}^{-2}$ the experimental value of B(E2;$8^+ \rightarrow 6^+$) = 24.0(11) e^2fm^4 (1.21(5) W.u.) for ^{78}Zn, corresponds to the neutron effective charge of e_ν=1.25(2)e, if harmonic oscillator wave functions with b=($\hbar$/Mω)=1.01 A$^{1/6}$=2.09 fm are used. This is rather large in comparison to e_ν=1.0e needed to reproduce the corresponding B(E2;$8^+ \rightarrow 6^+$) in ^{70}Ni and the B(E2;$17/2^- \rightarrow 13/2^-$) in ^{69}Ni in a shell model calculation in the $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, $1g_{9/2}$ neutron space [16]. Therefore we have extended these calculations

6

	$2p_{3/2}$		$1f_{5/2}$		$2p_{1/2}$		$1g_{9/2}$	
Calculation	A	B	A	B	A	B	A	B
^{79}Cu	1.34	0.30	0	0	3.33	1.77	3.61	3.01
^{77}Ni	4.52	1.54	5.42	4.84	2.23	1.06	0	0

Table 1
Single proton particle and neutron hole energies of the ^{78}Ni core used in the shell model calculations (A) and (B) for ^{79}Cu and ^{77}Ni

into the proton space using the realistic interaction deduced by Sinatkas et al. [17]. Starting from experimental single particle energies in the ^{56}Ni neighbors ^{57}Ni and ^{57}Cu, we have adjusted them to reproduce the neutron and proton single particle states at and beyond the N=40 subshell in ^{68}Ni, namely ^{69}Ni [3] and $^{69-73}$Cu [18]. This is justified by the well known deficiency of realistic interactions with respect to the monopole terms, which can be absorbed in a shift of single particle energies with increasing shell occupancy. This results in the relative single particle energies relative to a ^{78}Ni core given in the table 1. The results of the calculation (A) are shown in fig. 3.

For comparison and to illuminate the influence of different shell model approaches to the monopole problem, fig. 3 also shows the results of a shell model calculation derived from an overall fit of the monopole terms along the Z=28 and N=50 chains [19,20]. The starting point is a realistic interaction from the Oslo group. The interaction was derived for a ^{56}Ni core and the details of the method are discussed in ref. [21]. The single particle energies are taken from ^{57}Ni to be 0.0, 0.77, 1.11 and 3.0 MeV for the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ and $g_{9/2}$ orbitals. The evolution of the mean field through the monopole terms of the interaction is directly connected to the single particle and single hole energies in table 1. The spectra A and B are rather similar and both calculations reproduce the isomerism of the $8^+ \rightarrow 6^+$ transition. Using a polarisation charge of $\delta e = 0.5e$ for both protons and neutrons B(E2) values of 1.47W.u. and 1.06W.u. are calculated for models A and B, respectively, in good agreement with the experimental value 1.21(5)W.u.. Both interactions also reproduce the experimental level schemes and B(E2) values for other known 8^+ N=48 isomers [22] proving the adequacy of the monopole correction applied to the realistic interaction. Thus the effective polarisation charges in the vicinity of ^{78}Ni seem to be close to standard ones.

In conclusion we have observed for the first time an 8^+ isomeric state in ^{78}Zn. This result represents the closest approach to the doubly - magic nucleus ^{78}Ni made so far in γ-spectroscopy studies. From the comparison of the measured transition energies and the B(E2) value with shell model calculations the first spectroscopic information in this region of the chart of nuclei has been gained. The shell model calculation seems to describe correctly the observed isomeric state with the standard neutron and proton polarisation charge of 0.5e. Thus,

in the present work, the first experimental evidence for the persistence of the N=50 shell gap the vicinity of the ^{78}Ni has been obtained.

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References

[1] Ch. Engelmann et al., *Z.Phys.* **A352**, 351 (1995)

[2] M. Bernas et al., *Nucl.Phys.* **A616**, 352c (1997)

[3] R. Grzywacz et al., *Phys.Rev.Lett.* **81**, 766 (1998)

[4] M. Lewitowicz et al. Proceedings of the Int. Conf. Experimental Nucl. Phys. in Europe, June 1999, Sevilla, Spain, eds. B. Rubio, M. Lozano and W. Gelletly, AIP Proceedings 495, p. 43

[5] M. Górska et al., *Phys.Rev.Lett.* **79**, 2415 (1997)

[6] R. Grzywacz, ENAM98, eds. B.M. Sherill, D.J. Morissey, C.N. Davids, AIP Conf. Proc. 455, Woodbury, NY, 430 (1998)

[7] H. Grawe et al., *Acta Phys. Pol.* **B26**, 341 (1995) and *Phys. Scr.* **T56**, 71 (1995)

[8] T. Motobayashi et al., Phys. Lett. **B346** (1995) 9

[9] D. Alber et al., *Z. Phys.* **A335**, 265 (1990)

[10] M. Lipoglavsek et al., *Phys. Rev. Lett.* **76**, 888 (1996)

[11] R. Anne et al., *Nucl. Inst. and Meth.* **A257**, (1987) 215

[12] M. Bernas et al., *J. Phys. (Paris), Lett..* **45**, L- 851 (1984)

[13] R. Broda et al., *Phys. Rev. Lett.* **74** (1995) 868

[14] Table of Isotopes, 8th edition, eds. R.B. Firestone, V.S. Shirley, J. Wiley & Sons, New York, 1996

[15] E. Lund et al., AIP Conference Proc. 164, Proc. of the Conf. Nuclei Far From Stability, Lake Rosseau, Ont. Canada 1987, Editor Ian S. Towner, p.578

[16] H. Grawe et al., Proc. Workshop "The Beta-Decay, From Weak Interaction to Nuclear Structure", Strasbourg, 1999, in print

[17] J. Sinatkas et al., *J. Phys. G: Nucl. Part. Phys.* **18**, 1377 and 1401 (1992)

[18] S. Franchoo et al., *Phys. Rev. Lett.* **81**, 3100 (1998)

[19] F. Nowacki, Ph.D. Thesis CRN 96-7, Université Louis Pasteur, Strasbourg (1996)

[20] E. Caurier, F.Nowacki, A.Poves and J.Retamosa, *Phys. Rev. Lett.* **77**, 1954 (1996)

[21] M. Hjorth-Jensen, T.T.S.Kuo and E.Osnes, *Phys. Rep.* **261**, 125 (1995)

[22] A. Makishima, et al. *Phys. Rev.* **C 59**, R2331 (1999)