Evolution of the $N=20$ shell gap

Zs Dombrádi$^1$, Z Elekes$^{1,3}$, A Saito$^2$, N Aoi$^3$, H Baba$^2$, K Demichi$^2$, Zs Fülöp$^1$, J Gibelin$^4$, T Gomi$^2$, H Hasegawa$^2$, N Imai$^5$, M Ishihara$^3$, H Iwasaki$^5$, S Kanno$^2$, S Kawami$^2$, T Kishida$^3$, T Kubo$^3$, K Kurita$^2$, Y Matsuyama$^2$, S Michimasa$^5$, T Minemura$^3$, T Motobayashi$^3$, M Notani$^3$, H J Ong$^5$, S Ota$^7$, A Ozawa$^6$, H K Sakai$^2$, H Sakurai$^5$, S Shimoura$^5$, E Takeshita$^2$, S Takeuchi$^3$, M Tamaki$^5$, Y Togano$^2$, K Yamada$^2$, Y Yanagisawa$^3$ and K Yoneda$^3$

$^1$ Institute of Nuclear Research of the Hungarian Academy of Sciences, P.O. Box 51, Debrecen, H-4001, Hungary
$^2$ Rikkyo University, 3 Nishi-Ikebukuro, Toshima, Tokyo 171, Japan
$^3$ The Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
$^4$ Institut de Physique Nucléeaire, 15 rue Georges Clemenceau 91406 Orsay, France
$^5$ University of Tokyo, Tokyo 1130033, Japan
$^6$ University of Tsukuba, Tennoudai 1-1-1, Tsukuba-shi, Ibaraki 305-8571, Japan
$^7$ Kyoto University, Kyoto 606-8501, Japan

Abstract. Structure of $N=17, 18$ nuclei has been investigated via proton inelastic scattering and neutron removal reactions up to the neutron dripline in inverse kinematics by use of radioactive ion beams provided by the RIKEN isotope separator, RIPS. Low energy excited states have been found in all the $^{26,27}$F and $^{27}$Ne nuclei, which are out of the neutron $sd$ shell configuration space and are considered as intruder states arising from cross shell excitations. Monte–Carlo shell model calculations with the $sdpf$-$m$ interaction predict low energy negative parity excited states from neutron cross shell excitation at $N=17, 18$, which is in agreement with our experimental results. Observation of intruder states even at $N=17$, especially the $p_{3/2}$ state in $^{27}$Ne at 765 keV is a clear indication of a vanishing $N=20$ shell gap at $Z=8$ as predicted by the $sdpf$-$m$ shell model calculations.

1. Introduction

The study of shell structure has played a crucial role in nuclear physics for a long time. The magic numbers 2, 8, 20, 28, 50, 82, and so on, associated with the shell closures in the atomic nucleus are well known close to the valley of stability. However, it is still a fundamental and presently open question whether the major shell closures and magic numbers change in very neutron–rich nuclei [1, 2]. Experimental data accumulated since the late seventies on a missing $N=20$ shell closure in the Mg–Na region launched the idea of the collapse of the usual shell model ordering of the single particle states in neutron–rich nuclei [3, 4]. According to the early calculations, the effective single particle energy of the $f_{7/2}$ orbit becomes lower than that of the $d_{5/2}$ one in $^{28}$O [4]. However, systematic investigations have revealed that the observed phenomena can also be described by considering a strong correlation energy associated with the proton–neutron $T=0$ interaction leading to a large deformation [3, 5] without assuming a significant change of the single particle energy structure. The deformed 2p–2h states may intrude
below the normal spherical states and form an “island of inversion”. In these calculations, the effective interaction, giving a reasonable description of nuclei close to the stability, leads to an effective $N=20$ shell gap changing from 7 MeV at $Z=20$ to about 5 MeV at $Z=8$ [5, 6]. This shell gap is in agreement with the value calculated with a mean field approximation [7], and large enough to conserve the spherical $N=20$ shell closure. All the experimental data available around the “island of inversion” could be explained without the breakdown of the $N=20$ shell closure [8], suggesting that only a minor weakening of the $N=20$ shell closure takes place.

As an alternative approach, the Monte Carlo diagonalization method has also been introduced in the shell model for the region of light neutron–rich nuclei adding the two lower $fp$ shell orbits ($1f_{7/2}$ and $2p_{3/2}$) to the $sd$ shell model space (Monte Carlo shell model – MCSM) [9]. The use of the enlarged valence space allows the mixing of the $sd$ and $fp$ configurations and gives a reasonable description of the available experimental data close to the “island of inversion” and even beyond [9, 10, 11]. However, its effective interaction leads to a rapid decrease of the shell gap to 1.2 MeV at $Z=8$ that is to a disappearing $N=20$ shell gap at large neutron excess [12]. As a consequence of the rapidly decreasing shell gap, the MCSM predicts a much wider “island of inversion” than the models with a closed $N=20$ shell. In this model, the crossing of the intruder and normal configurations takes place at $N=18$ resulting in a deformed ground state even at this neutron number and low energy intruder states up to $N=17$, and extends the “island of inversion” to the neutron dripline. This difference suggests a new way to distinguish experimentally between the quadrupole and monopole effects and encouraged the search for the border of the “island of inversion”. Recently, the observation of two excited states at 1249 keV and 1588 keV in $^{29}$Na [13] provided new data that supports the MCSM prediction of having low–lying $fp$ states mixed with the normal ones at $N=18$ [13] and of a small $N=20$ shell gap.

To determine what extent the intruder configurations from the $fp$ shell disturb the structure of the neutron–rich light nuclei, we studied the nuclei $^{27}$F and $^{28}$Ne nucleus via inelastic proton scattering which allows us to determine the mass deformation and the proton and neutron distributions if B(E2) data exist. In addition, we also investigated the excited states of $^{26}$F and $^{27}$Ne simultaneously by neutron knock-out reaction in order to contribute to the clarification of the question whether the $N=20$ shell gap exists at small $Z$ values.

2. Experimental

The experiment was performed at the RIKEN Accelerator Research Facility. An $^{40}$Ar primary beam of 94 MeV/nucleon energy with 60 pnA intensity was transported to a $^{181}$Ta production target of 0.5 cm thickness. The RIKEN projectile fragment separator [14] analyzed the momentum and mass of the reaction products. The experimental setup is shown in Fig. 1. An aluminum wedged degrader of 221 mg/cm$^2$ was put at the momentum dispersive focal plane (F1) for purifying the constituents. The secondary beam included neutron-rich O, F, Ne and Na nuclei with $A/Z \approx 3$. The fragment separator was set to its full 6% momentum acceptance. The total intensity was about 100 particle/s (pps). The identification of the incident beam species was performed on an event by event basis by means of energy loss, time-of-flight (TOF) and magnetic rigidity ($B\rho$) [15]. The separation of the incident particles was complete. Two parallel plate avalanche counters (PPAC) at F3 upstream of the target monitored the position of the incident particles. The beam spot size was 24 mm both in horizontal and vertical directions. The outgoing particles were detected and identified by a PPAC and a silicon telescope of three layers with
thicknesses of 0.5 mm, 0.5 mm and 1 mm located about 80 cm downstream of the target. Each layer was made of a 2x2 matrix of detectors the active area of which was 48x48 mm$^2$. The Z identification was performed by TOF–energy loss method where the TOF was measured between the secondary target and the PPAC. The isotope separation was done by use of the $\Delta E$–E method. The particle spectra are dominated by the beam particles, however if we require coincidence with $\gamma$ rays, the beam could be eliminated, making the $\Delta E$–E method sensitive enough. The de–excitation $\gamma$–rays emitted by the excited nuclei were detected by the DALI2 setup consisting of 146 NaI(Tl) scintillators [17] surrounding the target. The intrinsic energy resolution of the array was 10% (FWHM) for a 662 keV energy $\gamma$ ray.

3. Results

In the $^{26}$F spectrum two peaks were found at 468(17) keV and 665(12) keV [19]. There are indications on the existence of the latter one from another preliminary report on a recent experiment also using projectile fragmentation at GANIL [18]. The $^{27}$F spectrum also showed two peaks at 504(15) keV and 777(19) keV [19]. The presence of two $\gamma$ rays is a clear sign for the existence of two bound excited states which can be obtained by placing the $\gamma$ transitions either parallel or in a cascade in both $^{26,27}$F nuclei.

The positions of the peaks were determined to be 1319(22) keV and 1711(30) keV for $^{28}$Ne and 765(20) keV and 904(21) keV for $^{27}$Ne [23]. The energies determined for $^{26}$Ne are in reasonable agreement with the values 1289(9) keV and 1719(11) keV determined earlier in Ref. [20] and 1320(20) keV in Ref. [21]. In Ref. [20] the 1711 keV transition is connected to the 1319 keV one establishing a state at 3030 keV. For $^{27}$Ne, a 772(7) keV line was also observed in a fragmentation reaction [20] while a peak at 870(16) keV was recently detected in the $^{12}$C($^{28}$Ne,$^{27}$Ne) reaction [22]. It is the first time that both peaks were observed in the same experiment giving a clear sign for two bound excited states in $^{27}$Ne. Due to the low neutron separation energy, the two $\gamma$-lines can be placed only in parallel to each other establishing two excited states at 765 keV and 904 keV. In a parallel work, both states were also observed in $^{26}$Ne(d,p) reaction and the 765 keV one was assigned with a high probability to a neutron $p$ configuration [24].

4. Discussion and conclusions

Looking at the energy systematics of the $N=18$ isotones (Fig. 2), one can see that there is a systematic deviation from the prediction of USD shell model: the closer we are to the neutron separation energy, the larger the deviation is. On the other hand, the experimental trend is described by the Monte–Carlo shell model, where mixing of the normal and intruder
configurations results in a decreasing of the energy of the $2^+_1$ states in the even isotones generating the lowering of the excitation energies of the neighbouring odd nuclei, too. Unfortunately, this interpretation is not straightforward. The masses of the $N=18$ nuclei seem to fit in the USD05 scheme, showing no extra binding due to the configuration mixing. In addition, a recent precise measurement of the $B(E2)$ value in $^{28}\text{Ne}$ [22] gives a value of $132(23)$ e$^2$fm$^4$ that is much smaller than that of the MCSM calculation [9] ($269$ e$^2$fm$^4$) and seems to support the assumption of a small deformation. However, it is also possible that the neutron deformation is large in $^{28}\text{Ne}$, and the $0^+_1 \rightarrow 2^+_1$ transition is dominated by neutron excitation – as it was found for $^{16}\text{C}$ [25, 26] – which could not be observed in the above experiment.

From a distorted wave analysis of the $(p,p')$ cross sections, we derived the “matter” deformation length ($\delta_M$) for $^{27}\text{F}$ and $^{28}\text{Ne}$. In the calculations, the standard collective form factors were applied and the global phenomenological parameter set CH89, proposed in [27], was employed for the optical potential. Beyond the statistical error, there might be an additional uncertainty caused by the choice of the optical potential parameter set. As was discussed in our earlier paper [28], this involves 10-20% error on the deformation parameters.

Following the above scenario, and assuming a level scheme of $^{27}\text{F}$ with a spin $5/2^+$ ground state, and an $1/2^+$ excited state at 1281 keV, the “deformation” parameter $\beta_2 = 0.44 \pm 0.1$ is deduced. Because of the poor statistics it is not possible to give a spin assignment to the intermediate excited state at 777 keV. The $\beta_2$ parameter is nearly as large as those observed in the “island of inversion”, and is larger than predicted by the MCSM. More information on the level scheme of $^{27}\text{F}$ is needed to give a definite conclusion.

The “matter” deformation length deduced for $^{28}\text{Ne}$ is $\delta_M=0.95\pm0.18$ fm which corresponds to a moderate mass deformation of $\beta_M=0.25\pm0.05$. It is possible to decompose the mass transition probability into proton and neutron ones. For this purpose, we can apply the Bernstein formula [29], according to which

$$\frac{M_n}{M_p} = b_p b_n \left[ \frac{\delta_M}{\delta_C} \left( 1 + \frac{b_n N}{b_p Z} \right) - 1 \right].$$

Here $b_n/b_p=3$ are the sensitivity parameters for protons and neutrons of our $(p,p')$ probe. Using the measured $B(E2)$ value of $132(23)$ e$^2$fm$^4$ [22] for $^{28}\text{Ne}$, the ratio of neutron and
Experimentally determined low–lying levels of $^{26}\text{F}$ and $^{27}\text{Ne}$ nucleus plotted together with the predictions of shell model calculation using USD interaction [30].

Proton multipole matrix elements can be calculated to be $M_n/M_p=1.2\pm0.3$. The $M_n/M_p$ ratio for $^{26}\text{Ne}$ is close to unity, which is quite far from the $N/Z=1.8$ ratio, showing that the $2^+_i$ excitation cannot be characterized by the coherent motion of protons and neutrons. With the relation $\delta_n(p)=R\beta_n(p)$, it is possible to deduce the neutron and proton deformation parameters. This results in $\delta_n=0.23\pm0.05$ using the $\beta_p=0.36\pm0.03$ value deduced from the experimental $B(E2)$ [22]. Thus, both the neutron and the proton deformations are much smaller than is characteristic of nuclei in the “island of inversion” and means that also the concept on a strongly enhanced neutron transition probability that compensates the small $B(E2)$ can be rejected. Thus, the transition probabilities do not support the concept of mixing normal and intruder states, although the experimental results may fit into the configuration mixing scheme by making further assumptions on the change of the effective charges. So the energy systematics along the $N=18$ line cannot be considered as a clear evidence for the decreasing $N=20$ shell gap. But a direct observation of a single particle state from the $fp$ shell could pose a stringent test on the $N=20$ shell gap. In the $sd$ shell model, the number of predicted bound excited states is one in $^{27}\text{Ne}$ (i.e., $s_{1/2}$) while MCSM allows three of them (i.e., $s_{1/2}$, $p_{3/2}$ and $f_{7/2}$). The $\gamma$-ray spectrum of $^{27}\text{Ne}$ showed that two excited states at 765 keV and 904 keV are populated with similar intensities. Comparing our level scheme with the one calculated in the $sd$ shell model shown in Fig. 3, it is seen that one of the excited states may correspond to the $1/2^+$ state predicted by both models; the other one should come from an out of the $sd$ shell model space excitation. The case is similar to $^{26}\text{F}$, where one of the two bound excited states ($4^+$) predicted by USD shell model is isomeric. Thus, one of the observed excited states in $^{26}\text{F}$ corresponds to the $2^+$ state, while the other one comes from an out of $sd$ model space configuration. Observation of two low–lying excited states in these nuclei is in agreement with the MCSM prediction and the existence of a low energy $3/2^-$ state with a strong $\ell=1$ component can hardly be interpreted without the assumption of a small $N=20$ shell gap.

The energy of the shell gap cannot be determined from the energy of the intruder configurations observed along the $N=17$ line since the quadrupole and monopole effects contributing to the lowering cannot be separated in a simple way in proton open shell nuclei. But the size of the $N=20$ shell gap is predicted to be nearly constant along the $Z=8$ line. Therefore, the determination of the negative parity states with respect to the $d_{3/2}$ one could be a direct measure of the $N=20$ shell gap. Due to the high energy of the $d_{3/2}$ neutron state, odd oxygen isotopes next to the stability line did not allow the performance of this job. Adding neutrons to $^{16}\text{O}$, the Fermi level is gradually increasing, which results in a decreasing excitation energy for the $d_{3/2}$, $f_{7/2}$ and $p_{3/2}$ states. The last bound oxygen isotope $^{23}\text{O}$ may be the best case to search for the size of the $N=20$ shell gap. We have measured the $^{22}\text{O}(d,p)^{23}\text{O}^* \rightarrow ^{22}\text{O}+n$ reaction in inverse kinematics using the invariant mass method [31]. Our preliminary results show that the
first intruder configuration can be found at about 1 MeV above the neutron \(\frac{3}{2}\) state. Thus, the \(N=20\) shell gap completely disappears at \(Z=8\) in agreement with the MCSM prediction [12].

Acknowledgments

The present work was partly supported by the Grant-in-Aid for Scientific Research (No. 1520417) by the Ministry of Education, Culture, Sports, Science and Technology and by OTKA T42733, T46901 and F60348.

References

[1] Warner D 2004 Nature 430 517
[2] Friddmann J, Wiedenhover I, Gade A, Baby LT, Bazin D, Brown BA, Campbell CM, Cook JM, Cottle PD, Diffenderfer E et al 2005 Nature 435 922
[3] Wildenthal BH and Chung W 1980 Phys. Rev. C 22 2260
[4] Storm MH, Watt A and Whitehead RR 1983 J. Phys. C 9 L165
[5] Warburton EK, Becker JA and Brown BA 1990 Phys. Rev. C 41 1147
[6] Retamosa J, Caurier E, Nowacki F and Poves A 1997 Phys. Rev. C 55 1266
[7] Peru S, Girod M, Berger JF 2000 Eur. Phys. J. A 9 35
[8] Caurier E, Nowacki F and Poves A 2001 Nucl. Phys. A 693 374
[9] Utsuno Y, Otsuka T, Mizusaki T and Honma M 1999 Phys. Rev. C 60 054315
[10] Utsuno Y, Otsuka T, Glasmacher T, Mizusaki T and Honma M 2004 Phys. Rev. C 70 044307
[11] Utsuno Y, Otsuka T, Mizusaki T and Honma M 2001 Phys. Rev. C 64 011301
[12] Otsuka T, Utsuno Y, Fujimoto R, Brown BA, Honma M, Mizusaki T 2002 Eur. Phys. J. A 13 69
[13] Tripathi V, Tabor SL, Mantica PF, Hoffman CR, Wiedeking M, Davies AD, Liddick SN, Mueller WF, Otsuka T, Stolz T et al 2005 Phys. Rev. Lett. 94 162501
[14] Kubo T, Ishihara M, Inabe N, Kumagai H, Tanihata I, Yoshida K, Nakamura T, Okuno H, Shimoura S, Asahi K et al 1992 Nucl. Instrum. Meth. B 70 309
[15] Sakurai H, Lukyanov SM, Notani M, Aoi N, Beaumel D, Fukuda N, Hirai M, Ideguchi E, Imai N, Ishihara M et al 1999 Phys. Lett. B 448 180
[16] Ryuto H, Kunibu M, Minemura T, Motobayashi T, Sagara K, Shimoura S, Tamaki M, Yanagisawa Y and Yano Y 2005 Nucl. Instrum. Meth. A 555 1
[17] Takeuchi S, Motobayashi T, Murakami H, Demichi K and Hasegawa H 2003 RIKEN Acc. Prog. Rep. 36 148
[18] Stanoiu M, Azaiez F, Dombradi Zs, Sorlin O, Brown BA, Belleguic M, Sohler D, Saint-Laurent MG, Lopez-Jimenez MJ, Penionzhkevich YE et al 2004 Phys. Rev. C 69 034312
[19] Elekes Z, Dombradi Zs, Saito A, Aoi N, Baba H, Demichi K, Fulop Zs, Gibein J, Gomi T, Hasegawa H et al 2004 Phys. Lett. B 599 17
[20] Belleguic M, Azaiez F, Dombradi Zs, Sohler D, Lopez-Jimenez MJ, Otsuka T, Saint-Laurent MG, Sorlin O, Stanoiu M, Utsuno Y et al 2005 Phys. Rev. C 72 054316
[21] Pritychenko BV, Glasmacher T, Cottle PD, Fauerbach M, Ibbsotom RW, Kemper KW, Maddalena V, Navin A, Romminger R, Sakharuk A et al 1999 Phys. Lett. B 461 322
[22] Iwasaki H, Motobayashi T, Sakurai H, Yoneda K, Gomi T, Aoi N, Fukuda N, Fulop Zs, Futakami U, Gacsi Z et al 2005 Phys. Lett. B 620 118
[23] Dombradi Zs, Elekes Z, Saito A, Aoi N, Baba H, Demichi K, Fulop Zs, Gibein J, Gomi T, Hasegawa H et al 2006 Phys. Rev. Lett. 96 182501
[24] Obertelli A, Gillibert A, Alamanos N, Alvarez M, Auger F, Dayras R, Drouart A, de France G, Jurado B, Keeley N et al 2006 Phys. Lett. B 633 33
[25] Elekes Z, Dombradi Zs, Krasznahorkay A, Baba H, Csatskos M, Csige L, Fukuda N, Fulop Zs, Gacsi Z, Gulyas J et al 2004 Phys. Lett. B 586 34
[26] Ong HJ, Imai N, Aoi N, Sakurai H, Dombradi Zs, Saito A, Elekes Z, Baba H, Demichi K, Fulop Zs et al 2006 Phys. Rev. C 73 024610
[27] Varner RL, Thompson WJ, McBee TL, Ludwig EJ and Clegg TB 1991 Phys. Rev. 201 57
[28] Dombradi Zs, Elekes Z, Kanungo R, Baba H, Fulop Zs, Gibein J, Horvath A, Ideguchi E, Ichikawa Y, Iwasa N et al 2005 Phys. Lett. B 621 81
[29] Bernstein AM, Brown VR and Madsen VA 1979 Phys. Rev. Lett. 42 425
[30] http://www.nscl.msu.edu/ brown/resources/SDE.HTM
[31] Elekes Z, Dombradi Zs, Bishop S, Fulop Zs, Gibein J, Gomi T, Hashimoto Y, Imai N, Iwasa N, Iwasaki H et al 2006 RIKEN Acc. Prog. Rep. 39 (in press)