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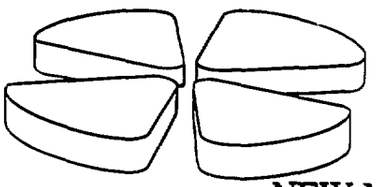

NEW MASS MEASUREMENTS OF NEUTRON-RICH NUCLEI NEAR N=20*

N.A. Orr[1], W. Mittig, L.K. Fifield[2], M. Lewitowicz, E.Plagnol, Y. Schutz, Zhan Wen Long[3]
GANIL, BP-5027, F-14021, Caen Cedex, France

L. Bianchi, A. Gillibert
CEN Saclay, DPhN/BE, F-91191, Gif-sur-Yvette, France

A.V. Belozyorov, S.M. Lukyanov, Yu.E. Penionhkevich
Laboratory of Nuclear Reactions, JINR, PO Box 79, Dubna, USSR

A.C.C. Villari
Departamento de Fisica Nuclear, Instituto de Fisica da USP, Caixa Postal-20516, 01498 Sao Paulo SP, Brasil

A. Cunsolo, A. Foti
INFN, Sezione di Catania e Dipartimento di Fisica, Corso Italia 57, I-95129 Catania, Italy

G. Audi
CSNSM-Laboratoire Rene Bernas, Bat 108, F-91405, Orsay Cedex, France

C. Stephan, L. Tasson-Got
IPN, BP-1, F-91406, Orsay Cedex, France

GANIL P 91 02

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G. Audi
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C. Stephan, L. Tasson-Got
IPN, BP-1, F-91406, Orsay Cedex, France

1 Present address: NSCL, Michigan State University, East Lansing, Michigan, MI 48824-1321, USA

2 Permanent address: Department of Nuclear Physics, A.N.U., GPO Box 4, Canberra 2601, Australia

3 Present address: IMP, Lanzhou, People's Republic of China

* Experiment performed at GANIL

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ABSTRACT

The masses of 39 neutron-rich nuclei in the mass range 17 to 37 have been measured using a direct time-of-flight technique following the fragmentation of a ^{48}Ca beam at 55 MeV/nucleon. The masses of ^{29,30}Ne, ^{34,35}Mg and ^{36,37}Al are reported for the first time. The very neutron-rich nuclei, $^{31\text{-}33}$Na, are found to be 2-4 MeV less bound than previously believed. Comparison is made with recently available large scale shell model calculations encompassing the deformed A~32 nuclei. Conclusions are drawn regarding the extent of the region of deformation, which is found to include ^{30}Ne.

The Z=11 and 12, N≈20 nuclei have long been known to constitute a region of stable deformation corresponding to a collapse in the conventional N=20 shell closure [1], [2]. This behaviour was originally deduced from the much stronger than expected binding energies of the sodium nuclei, ^{31}Na and ^{32}Na, as measured via direct on-line mass spectrometry [3]. The overbinding corresponded to an increase in the two-neutron separation energies at the crossing of the neutron sd-shell closure, where a decrease would be expected. Subsequently similar anomalies were observed in the masses of ^{31}Mg and ^{32}Mg [4]. Additionally a much lower than expected excitation energy was determined for the first 2^+ state in ^{32}Mg [5], [6]. Since these original observations there has been a paucity of experimental information forthcoming concerning these and neighbouring nuclei - although transfer reaction studies of some less exotic nuclei have been performed (^{33}Al [7] and ^{34,35}Si [8], [9]) which have aided in determining the extent of the effect to nuclei of higher Z. This has been due to the inherent difficulty in producing such nuclei very far from stability with reasonable yields. The advent, however, in recent years of the techniques of projectile and target fragmentation coupled with a new generation of spectrometers, notably SPEG [10] at GANIL and TOFI [11] at Los Alamos, have facilitated the continued investigation of these nuclei. The availability of the very neutron-rich beam ^{48}Ca at GANIL has further enhanced the prospects for studying the very neutron-rich light nuclei [12] - [15].

In this paper we report on the results of one such study which undertook direct time-of-flight mass determinations of light neutron-rich nuclei produced in the fragmentation of a ^{48}Ca beam. The objectives of this investigation were twofold - the remeasurement with improved precision of the masses of the neutron-rich isotopes of Ne to Al and the extension of the measurements to nuclei further from stability. The techniques employed in this experiment were similar to those used in earlier studies [16], [17], [18] and the details are only briefly described here.

The principle of the technique requires only the determination of the magnetic rigidity and velocity of an ion. That is, for a particle of mass m and charge q traversing an achromatic system, the magnetic rigidity Bρ is related to the velocity as,

$$B\rho = mv/q \qquad (1)$$

Thus, a precise measurement of the rigidity and velocity will allow the mass of the ion to be deduced. The determination of the magnetic rigidity was provided in the present arrangement by use of the SPEG spectrometer [10]. A precise measurement of the velocity of each ion was achieved by measuring the flight-time over an 82m path length.

In the present study a beam of 55 MeV/nucleon ^{48}Ca ions delivered by the GANIL cyclotrons was used to bombard a 330 mg/cm^2 thick Tantalum target. Beam intensities on target were typically 100 nA. The projectile like fragments emitted from the target were analysed by an alpha shaped spectrometer. A time-of-flight start signal was provided by a microchannel plate detector located at the exit of the α-spectrometer. The fragments were then transported along an achromatically tuned beam line to the focal plane of the spectrometer SPEG. The time-of-flight stop signal was derived from a two dimensionally position sensitive microchannel plate detector positioned immediately before the focal plane. The intrinsic resolution of the start and stop detectors was 150 ps, while the overall resolution of the measured time-of-flight was 250 ps for ^{48}Ca ions.

The identification of the ions arriving at the focal plane of SPEG was derived from the measured flight-time (T) together with energy loss and total energy signals from a detector telescope. The telescope consisted of three cooled silicon detectors of thicknesses 50, 300 and 6000 μm. The energy loss signal (ΔE) was obtained by summing the signals from the first two elements of the telescope, while the total energy signal (E) was obtained by summing the signals from all three detectors. Standard particle identification (A,Z) was thus possible via the application of the following relations in the off-line analysis,

$$A/q \alpha T \qquad (2)$$

$$Z \alpha \Delta E^{1/2}/T \qquad (3)$$

$$A \alpha E T^2 \qquad (4)$$

All the fragments observed at the present beam energy were fully stripped (q=Z).

As noted above both the time-of-flight stop detector and the second element of the telescope were position sensitive in two dimensions, thus allowing the angle-of-entry of particles arriving at the focal plane to be determined. Consequently small corrections necessary to compensate for second order aberrations in the system could be made in the off-line analysis.

Measurement of the rigidity of each ion was performed using a position sensitive parallel plate avalanche counter located in the conventional target chamber of SPEG, where the dispersion of the system was 13 cm per percent in momentum. A mass resolution of $3x10^{-4}$ was observed with the experimental arrangement described. This is consistent with the resolutions of 10^{-4} in the measurement of the rigidity and $2.5x10^{-4}$ for the time-of-flight.

Two field settings of the spectrometer and transport system were employed. The first, Bρ=2.46 Tm with the production target oriented at 45° to the beam direction, provided broad elemental and isotopic distributions - 120 nuclei up to ^{46}Cl were identified. The second setting of 2.7 Tm, with the target oriented normal to the beam axis, gave rise to more restricted distributions (90 nuclei up to ^{44}S) with higher yields for nuclei in the region of the neutron-rich sodium and magnesium isotopes. Many nuclei with well known masses were also observed at each field setting and those with adequate yields were employed in the final calibration of the data. The masses of these nuclei were taken from an updated version of the 1986-87 midstream mass evaluations [32]. A paucity of heavy mass calibrants, A=38-46, prevented reliable extraction of masses beyond A=37.

Table 1 lists the results obtained for 39 nuclei along with the results of earlier investigations for comparison. The uncertainties quoted, which range from 70 keV (^{20}N) to 1600 keV (^{35}Mg), comprise three components: the statistical uncertainty, an uncertainty arising from the calibration and an uncertainty which represents the limiting precision of the experimental arrangement. The latter was determined, as outlined in [18], by obtaining a reasonable fit of the data to the high yield nuclei of known mass. In this experiment it was determined to be 40 keV. In the case of the uncertainty ascribed to the calibration, it should be noted that the further a nucleus lies from nuclei with known masses, the larger this quantity will be. For example, for the sodium nuclei this uncertainty evolves from 70 keV for ^{28}Na to 420 keV for ^{33}Na. Similarly an increase occurs in the statistical uncertainty as the yields decrease along isotopic chains - 90 keV for ^{29}Na, the most prolifically produced sodium isotope (5500 counts), to 1400 keV for ^{33}Na (21 counts) at the 2.7 Tm setting.

The present results constitute the first measurements of the masses of ^{29,30}Ne, ^{34,35}Mg and ^{36,37}Al, while the majority of the other determinations are the most precise yet made. In comparison with previous measurements good agreement is generally found with the present results with the conspicuous exception of the very neutron-rich sodium isotopes. It should be noted that the masses deduced in the present work for ^{33}Al and ^{37}P are in excellent accord with the transfer reaction studies of [7], [25], [26]. Significant disagreement arises, as noted above, for the very neutron-rich sodium nuclei $^{31\text{-}33}$Na. The present results indicate that ^{31}Na and ^{32}Na are 2 MeV less bound than originally reported [3], while ^{33}Na is 4 MeV less bound. The present mass for ^{31}Na is, however, in good agreement with the only previous direct time-of-flight measurement [16].

These results and the discrepancies with the measurements which provided the original evidence for deformation in the N~20 region [3], are of considerable interest in the light of recent shell model calculations directed at understanding the structure of the neutron-rich nuclei in the vicinity of this so called "island of inversion" [31]. Such calculations have become feasible through the development of shell model codes which can handle large

matrices and of effective interactions which encompass the sd-fp model space [27]-[30], of which the most comprehensive is the "WBMB" interaction [30].

In figure 1, comparison is made between the binding energies measured in the present work with WBMB calculations [31] which employed complete $0\hbar\omega$ bases. Excellent agreement between experiment and the predictions is evident for all the isotopes of silicon and aluminium and for the lighter isotopes of magnesium, sodium and neon up to N=18 or 19. However, for the latter three elements, the measured values begin to depart significantly from the predictions at N=20 and the trend continues to at least N=21 for sodium and N=22 for magnesium. The overbinding of these nuclei is less dramatic than originally proposed, but nevertheless the effect persists and is evidence of some shortcoming of the $0\hbar\omega$ calculations in this region. Notably the present results provide the first evidence that the effect extends below Z=11 and 12 to Z=10.

The failure of the $0\hbar\omega$ calculations has prompted Warburton et al [31] to extend their calculations in order to investigate, within the framework of the shell model, the suggestion (originally proposed through constrained Hartree-Fock calculations [1]) that the overbinding may be attributed to a transition from a spherical shape to a prolate deformation driven by np-nh neutron excitations across the sd-fp shell gap. Using the WBMB interaction and introducing weak-coupling approximations and truncation schemes in the cases where full basis calculations were intractable, they have estimated the binding energies of states with 1, 2 and 3 neutrons promoted from the sd to fp shell orbitals. These they refer to as 1, 2 and $3\hbar\omega$ states. These calculations indicate that for the Z=10-12, N=20-22 nuclei, where the discrepancies between the $0\hbar\omega$ predictions and experiment are found, but *not* elsewhere, the lowest $2\hbar\omega$ state (and to a similar extent for the N=21 isotones the lowest $1\hbar\omega$ state also) is more bound than the lowest $0\hbar\omega$ state. A quantitative comparison between their estimates and the present results are presented in figure 2. The discrepancies, although substatially reduced, are evidently not eliminated entirely. As noted by the authors a further reduction could be anticipated due to repulsion between the $0\hbar\omega$ and $2\hbar\omega$ ground states. Hence, in the light of the measurements reported in this paper, we conclude that the WBMB interaction contains the ingredients necessary to understand the existence of the "island of inversion" in this region of the chart of nuclides. Particularly noteworthy is that these calculations were performed before the results of the present study became available.

Other mass predictions based on empirical and semi-empirical mass relations may be found in [32]. These models in general have very poor predictive abilities in the region of interest - probably due to the sudden change in structure (a smooth behaviour of the nuclear mass surface as a function of A and Z is usually assumed). For example as noted by [31], in the case of the microscopic-macroscopic model of Moeller et al [32] an rms deviation of 1.4 MeV is found between experimentally determined masses and those predicted for nuclei of

Z=13-20, N>20. By comparison the WBMB calculations yield an rms deviation of only 0.3 MeV.

The present results are also displayed in figure 3 in terms of two-neutron separation energies (thereby avoiding the odd-even neutron pairing effect). Such a plot, as noted earlier, graphically illustrates the region of stable deformation whereby the monotonic decrease with increasing neutron number is arrested abruptly for the Z=10-12 nuclei at or near N=20. Given that ^{31}Ne is unbound [13] (implying an upper limit of 3.9±1.0 MeV on the two-neutron separation energy) and the apparent resumption in the decline of the separation energies at ^{33}Na and ^{35}Mg, it would be interesting to extend the measurements further along the Z=9-12 isotopic chains. In particular, the masses of ^{29}F and ^{32}Ne, the last known particle stable nuclei of fluorine and neon [13] would be of considerable interest.

In summary, the masses of 39 neutron-rich nuclei in the region of the N=20 shell closure have been measured using a direct time-of-flight method following the fragmentation of an intermediate energy ^{48}Ca beam. Comparison of the results with shell model calculations have demonstrated that the so called "island of inversion" persists into the Z=10 nuclei, becoming apparent at ^{30}Ne (N=20). The effect does not appear to intrude into the Z=13 nuclei. Its extent along the Z=10-12 isotopic chains, while giving indications of terminating at N=22 and 23 for Z=11 and 12 requires further investigation. The magnitude of the effect on the binding energies of the sodium isotopes $^{31-33}$Na has been found to be substantially less (2-4 MeV) than indicated by earlier measurements.

This experiment was performed at the GANIL laboratories and the authors wish to acknowledge the assistance and support of the staff. NAO also wishes to thank Dr W. Mittig and the staff of GANIL for their generous hospitality during his sejour.

REFERENCES

[1] X. Campi et al, Nucl. Phys. **A251** (1975) 193

[2] B.H. Wildenthal et al, Phys. Rev. **C22** (1980) 2260

[3] C. Thibault et al, Phys. Rev. **C12** (1975) 644

[4] C. Detraz et al, Nucl. Phys. **A394** (1983) 378

[5] C. Detraz et al., Phys. Rev. **C19** (1979) 164

[6] D. Guillemaud-Mueller et al, Nucl. Phys. **A426** (1984) 37

[7] P.J. Woods et al, Phys. Lett. **B182** (1986) 297

[8] L.K. Fifield et al, Nucl. Phys. **A453** (1986) 497

[9] R.J. Smith et al, Z. Phys. **A324** (1986) 283

[10] L. Bianchi et al, Nucl. Instr. Meth. **A276** (1989) 509

[11] J.M. Wouters et al, Nucl. Instr. Meth. **B26** (1987) 286

[12] D. Guillemaud-Mueller et al, Z. Phys. **A332** (1989) 189

[13] D. Guillemaud-Mueller et al, Phys. Rev. **C41** (1990) 937

[14] M. Lewitowicz et al, Nucl. Phys. **A496** (1989) 477

[15] M. Lewitowicz et al, Z. Phys. **A335** (1990) 117

[16] A. Gillibert et al, Phys. Lett. **B192** (1987) 39

[17] W. Mittig et al in "Nuclei far from Stability", AIP Conf. Proc. 164 (AIP, New York, 1988) p11

[18] A. Gillibert et al, in preparation

[19] J. Wouters et al, Z. Phys. **A331** (1988) 229

[20] D.J. Vieira et al, Phys. Rev. Lett. **57** (1986) 3253

[21] A. Gillibert et al, Phys. Lett. **B176** (1986) 317

[22] G.T. Hickey et al, Phys. Rev. Lett. **37** (1976) 130

[23] H. Nann et al, Phys. Lett. **B96** (1980) 261

[24] C. Thibault et al in Atomic Masses and Fundamental Constants 6, ed J.R. Nolen and W. Benenson (Plenum Press, 1980) p291

[25] L.K. Fifield et al, Nucl. Phys. **A484** (1988) 117

[26] N.A. Orr, PhD Thesis, Australian National University, 1989
L.K. Fifield, priv. comm.

[27] A. Watt et al, J. Phys. **G7** (1981) L145

[28] M.H. Storm et al, J. Phys **G9** (1983) L165

[29] A. Poves et al, Phys. Lett **B184** (1987) 311

[30] E.K. Warburton et al, BNL Report 40890, 1987

[31] E.K. Warburton et al, Phys. Rev. **C41** (1990) 1147

[32] "1986 - 1987 Atomic Mass Predictions",ed. P.E. Haustein, At. Data Nucl. Data Tables **39** (1988) 185

[33] C. Detraz and D.J. Vieira, Ann. Rev. Nucl. Part. Sci. **39** (1989) 407

TABLES

TABLE 1: Mass excesses of present and earlier work (Δ ($\pm\sigma$) MeV).

Nucleus	Present	[19]	[16]	[20]	[32]	Other
^{17}B	43.90(0.23)	43.62(0.17)	42.82(0.80)			
^{19}C	33.07(0.24)	32.77(0.12)	32.95(0.42)	32.30(0.24)		
^{20}C	37.41(0.46)	37.60(0.22)	37.20(1.13)			
^{20}N	21.79(0.07)	21.78(0.12)	21.62(0.14)	21.64(0.26)		22.20(0.36)[21]
^{21}N	25.30(0.12)	25.09(0.20)	25.21(0.18)	24.76(0.19)		25.58(0.51)[21]
^{22}N	32.31(0.36)	31.99(0.23)	30.73(0.74)			
^{22}O	9.17(0.08)				9.44(0.09)	9.48(0.10)[22]
^{23}O	14.55(0.17)	14.62(0.14)	14.77(0.30)	14.6 (0.3)		14.61(0.66)[21]
^{24}O	19.24(0.41)	18.6 (0.5)	18.70(1.00)			
^{24}F	7.58(0.08)		7.87(0.22)	7.52(0.16)		7.86(0.45)[21]
^{25}F	11.29(0.14)	11.37(0.14)	11.19(0.27)	11.18(0.20)		10.51(0.57)[21]
^{26}F	18.21(0.28)	18.46(0.20)	19.51(0.60)	18.4 (0.9)		17.55(1.27)[21]
^{27}F	24.22(0.72)	25.6 (0.7)				
^{26}Ne	0.42(0.08)				0.44(0.07)	0.44(0.07)[23]
^{27}Ne	7.05(0.16)		6.96(0.28)	5.6 (0.6)[a]		
^{28}Ne	11.14(0.22)		11.43(0.52)	10.7 (0.4)		
^{29}Ne	18.10(0.51)					
^{30}Ne	22.24(0.82)					
^{28}Na	-1.02(0.09)			-1.14(0.18)	-1.14(0.14)	-1.14(0.08)[3]
^{29}Na	2.64(0.13)			2.63(0.21)	2.65(0.15)	2.65(0.10)[3]
^{30}Na	8.50(0.20)		8.57(0.34)	7.1 (0.5)[a]	8.21(0.25)	8.37(0.20)[3]
^{31}Na	12.63(0.31)		12.52(0.93)		11.83(0.58)[b]	10.60(0.80)[3]
^{32}Na	18.37(0.59)				16.55(0.74)[b]	16.4 (1.1)[3]
^{33}Na[c]	25.5 (1.5)				21.47(1.14)[b]	
^{34}Na					26.65(3.57)[b]	
^{30}Mg	-8.94(0.09)			-9.04(0.21)	-9.10(0.21)	
^{31}Mg	-3.22(0.14)		-3.28(0.17)	-3.56(0.20)		-5.0 (0.7) [4]
^{32}Mg	-0.86(0.20)[d]		-0.83(0.25)	-0.75(0.24)	-1.75(1.58)	-1.9 (1.5) [4]
^{33}Mg	4.85(0.30)		5.09(0.84)			
^{34}Mg	8.25(0.44)					
^{35}Mg[c]	17.4(1.6)[e]					
^{32}Al[f]	-11.06(0.10)		-11.06(0.19)	-11.33(0.20)		
^{33}Al	-8.54(0.13)		-8.62(0.15)	-8.84(0.23)		-8.53(0.14)[7]
^{34}Al	-3.04(0.20)		-3.17(0.23)	-3.5 (0.4)		
^{35}Al	-0.28(0.28)		-0.32(0.43)			
^{36}Al	5.76(0.39)					
^{37}Al	9.60(0.54)					
^{36}Si[f]	-12.65(0.18)		-12.57(0.30)	-12.9 (0.6)		
^{37}Si	-6.81(0.28)		-7.03(1.31)			
^{37}P[f]	-19.04(0.19)		-18.55(0.18)	-19.31(0.40)		-19.06(0.12)[25] -18.99(0.04)[26]

Footnotes:

a) Biased by isobaric contamination [33].

b) Extracted from the unpublished work of Thibault et al reported in [24].

c) Observed only at $B\rho = 2.70$ Tm.

d) The $Q_\beta = 18.3 \pm 1.4$ MeV derived for $^{32}Na(\beta^-)^{32}Mg$ [4], coupled to the present ^{32}Mg mass excess implies a ^{32}Na mass excess of 17.4 ± 1.4 MeV.

e) $S_n = -1.07 \pm 1.66$ MeV. The particle stability of ^{35}Mg and the present ^{34}Mg mass excess would imply a ^{35}Mg mass excess of less than 16.32 ± 0.44 MeV.

f) Observed only at $B\rho = 2.46$ Tm.

FIGURE CAPTIONS

FIGURE1: Comparison between the present experimental results and binding energies predicted by $0\hbar\omega$ WBMB calculations [31].

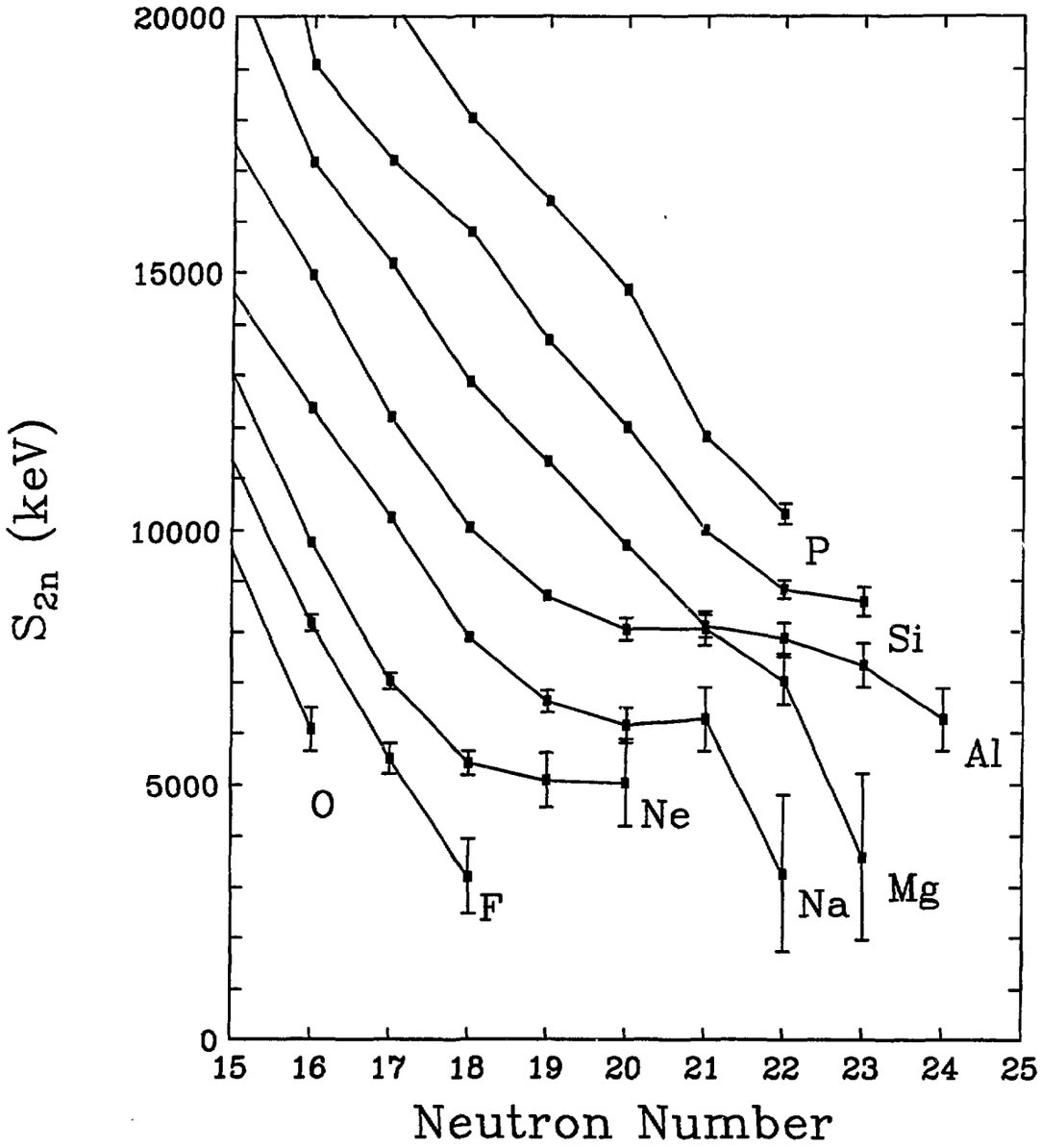
FIGURE 2: Comparison between the present experimental results and $2\hbar\omega$ weak coupling binding energy estimates of [31] for the N=20-22 Ne, Na and Mg nuclei. For the nuclei with N<20 and N=23, for which $E_x(0\hbar\omega) < E_x(2\hbar\omega)$, the comparison is with the $0\hbar\omega$ WBMB calculations.

FIGURE 3: Plot of two-neutron separation energy versus neutron number. For nuclei not appearing in table 1 the data of [32] have been used.

NOTE ADDED IN PROOF:

Mass measurements of neutron-rich isotopes between Neon and Argon have very recently been performed using the TOFI spectrometer [34]. While not extending to ^{30}Ne, ^{33}Na and ^{35}Mg, these data support the conclusions of the present work. The authors are grateful to D. Vieira for bringing this work to their attention.

[34] X.G. Zhou et al., Bull. Am. Phys. Soc. **35** (1990) 1648 and D.J. Vieira, priv. comm.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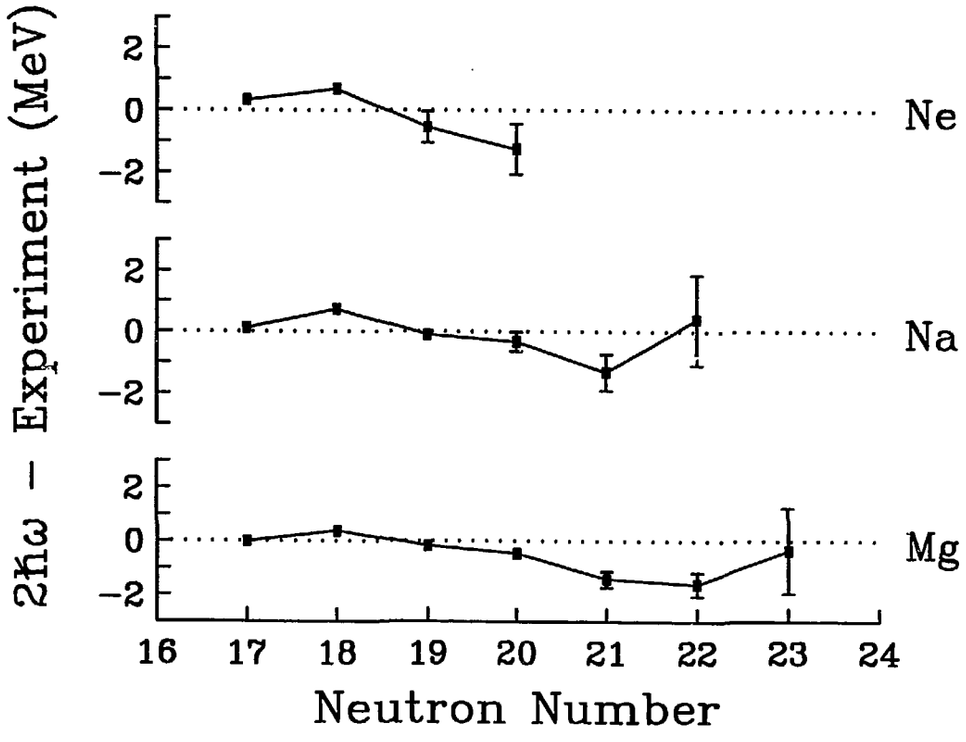
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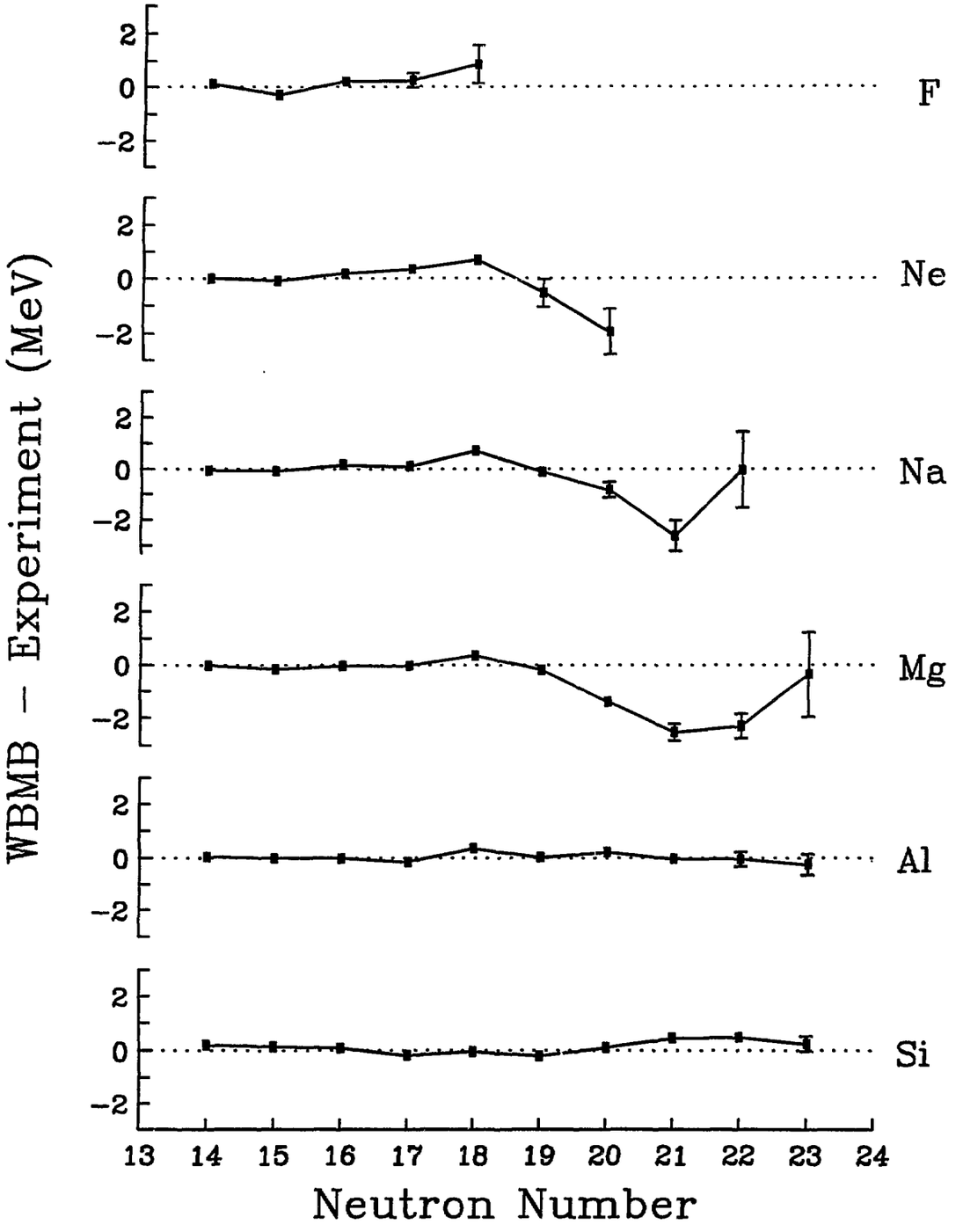
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