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Mass Systematics Involving
Low-Lying Excited States*

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Abstract: A step phenomenon in the nuclidic mass excess surface associated with magic numbers $\underline{N}, \underline{Z} = 8$ and 20 is shown to exist, whereas only breaks occur at higher magic numbers. Excited states are included which reveals possible smooth trends within Shell-Model subshells.

Introduction

For the evaluation of the nuclear binding energy surface it is helpful to consider the excited states together with the ground states^{1, 2)}.

The (positive) total nuclear binding energy for any state is $\underline{B} = \underline{B}_{g.s.} - \underline{E}_x$ where "g. s." refers to the ground state and $\underline{E}_x$ is the excitation energy.

For simplicity the mass excess $\underline{\Delta}$ can be used instead, since the total nuclear binding energy is

$$\underline{B}(\underline{A}, \underline{T}_z) = \frac{1}{2}\underline{A}[\underline{\Delta}(n^1) + \underline{\Delta}(H^1)] + \underline{T}_z[\underline{\Delta}(n^1) - \underline{\Delta}(H^1)] - \underline{\Delta}(\underline{A}, \underline{T}_z).$$

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Both brackets are constant; the first term depends linearly on the mass number A and the second is constant since only sequences of nuclides with constant I_z -component of the isobaric spin, T_z , are considered. Therefore a straight line in the mass excess $\Delta(A)$ for $T_z = \text{const.}$ means a linear relation in the total binding energy $B(A)$.

The steep increase of Δ in the light mass region can be compensated for by plotting the sum of the mass excess with a straight line, $\Delta + pA$, where again linear relations are conserved.

Results

Fig. 1 presents such a graph for self-conjugate even nuclides with $p = 1.5 \text{ MeV}$ for convenient display.

The 2^+ and 4^+ levels of Ne^{20} , Mg^{24} , and Si^{28} lie on almost straight trends, but the ground states do not. Weak indication has been given by Morita and Takeshita³⁾ for a level in Ne^{20} at 0.65 MeV — it happens to be just in the right position to fit a trend — which has not been found in other reactions. However, it is not yet ruled out by using the same reaction $\text{F}^{19}(\text{d}, \text{n})\text{Ne}^{20}$. Therefore there is either a peculiar shift of the Ne^{20} ground state or an additional 0^+ level which would lead the trend to $0^{16} 6.05 \text{ MeV}, 0^+$. In any case, a step occurs at $N, Z = 8$. Similarly, there is a step at $N, Z = 20$ with Ti^{44} corresponding to Ne^{20} . The mass excess of Ni^{56} is our prediction from systematics of nuclides with $N = 28$.

The 0^+ trend through excited states of Si^{28} and Mg^{24} apparently represents configurations with a filled $2s_{\frac{1}{2}}$ subshell (for protons and neutrons) while the $1d_{\frac{5}{2}}$ subshell is being occupied. If the tentatively

indicated level Si^{28} 6.31 MeV, 2^+ exists, the energy required for exciting these 2^+ states from the 0^+ states below them would be independent of the additional $2s_{\frac{1}{2}}$ alpha-particle. In S^{32} , the ground state is shifted down by 0.41 MeV if there is no additional 0^+ level. Earlier reports of a level at 0.5 and 0.43 MeV respectively have been mainly ruled out except for a slight asymmetry in the $\text{P}^{31}(\text{d}, \text{n})\text{S}^{32}$ ground state group. From the position S^{32} 0.41 MeV a straight trend leads over Ar^{36} to Ca^{40} , representing the occupation of the $1p_{\frac{3}{2}}$ subshell.

Fig. 2 gives these nuclei with a neutron attached. Here the filling of the $1p_{\frac{3}{2}}$ subshell (while a $2s_{\frac{1}{2}}$ neutron remains single) is an established straight trend.

A trend through the lowest Si^{29} and Mg^{25} $\frac{1}{2}^+$ states leads in O^{17} to a level 6.0 MeV above the first $\frac{1}{2}^+$ level, apparently reproducing the step noted earlier in O^{16} . The $\frac{5}{2}^+$ states lead to 3.3 MeV above ground state in O^{17} where no level is known. In the corresponding Ca^{41} there is a level at the right position for which $\frac{7}{2}^-$ is possible.

Fig. 3 shows the nuclides with two neutrons more than the self-conjugate ones. The Ca^{42} ground state is shifted down by 0.64 MeV from a smooth trend which is suggested by the sequence of the ground states of Fe^{54} , Cr^{50} , and Ti^{46} as well as by the 2^+ and 4^+ trends indicated. An interesting open question is whether the known 6^+ level in Ca^{42} belongs to the band on the known 1.84 MeV, 0^+ level or destroys the pattern suggested. The 2^+ and 4^+ levels of Fe^{54} apparently do not belong to these trends because of the neutron shell closure $\underline{N} = 28$.

Since the $1d_{5/2}$ subshell is shorter than the $1f_{7/2}$ shell, we cannot see anything there, except that the downward shift of the Ca^{42} ground state has its analogon in O^{18} . The level schemes are still too incomplete for locating the states with two neutrons occupying the $2s_{1/2}$ subshell.

Conclusions

- 1.) There is a perfect analogy between magic numbers 8 and 20.
- 2.) Smooth trends are likely to exist within subshells which may be destroyed, however, by configuration mixing or other unknown effects immediately after magic numbers 8 and 20.

The almost linear trends mean that about the same energy is liberated when the constituents of an alpha-particle are added repeatedly to a nucleus. The Coulomb repulsion apparently is compensated by the nuclear interactions with particles already in the same subshell.

- 3.) A step exists at these magic numbers in the mass excess (and total nuclear binding energy) surface.
- 4.) If additional levels should turn out to exist and complete these trends, the ground states of O^{17} and Ca^{41} , O^{18} and Ca^{42} , as well as Ne^{20} and Ti^{44} may have to be considered as cluster configurations of O^{16} and Ca^{40} in their ground states plus one neutron, two neutrons, and an alpha-particle respectively. The additional states may then contain O^{16} and Ca^{40} respectively in their first excited state. This may be the reason that they are hard to populate - if they exist at all.

References

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Figure Captions

Fig. 1. Nuclidic mass excess Δ for ground states (circles) and excited states (dashes), with a linear function $1.5 A$ added, versus the mass number A . Parentheses indicate doubtful experimental data, brackets indicate expectations if this systematics holds without exceptions. Uncertainties are given separately for ground state mass excesses and excitation energies (≤ 30 keV if not shown). Heavy lines show possible trends (dashed if doubtful).

Fig. 2. Odd-neutron nuclei with $T_{\frac{1}{2}} = \frac{1}{2}$. For conventions, see Fig. 1.

Fig. 3. Even nuclei with $T_{\frac{1}{2}} = 1$. For conventions, see Fig. 1.

Fig. 2

Fig. 3

END