объединенный
институт
ядерных
исследований
дубна

E6-94-252

V.A.Morozov

ODD PROTON AND NEUTRON SHELLS IN LIGHT NUCLEI

Submitted to «Письма в ЖЭТФ»

1994

A concept of nuclear shell structure has been developing similarly to the a concept of atomic shells. A significant difference in formation of atomic and nuclear shells is that in atoms shells are populated with particles of the same type, namely electrons, while in nuclei particles of two types, neutrons and protons, populate shells, and between them there exists not only Coulomb interaction but also nuclear forces. As a result, magic numbers of atoms and nuclei are different though shell formation mechanisms are similar. Up to recently the observed analogy in formation of atomic and nuclear shells could not be considered complete because analysis of atomic ionization potentials revealed not only even numbers 2, 10, 18, 36, 54, etc., which characterize shell closure, but also small maxima at $Z = 7$, 15 and 33. These configurations correspond to half population of p-shells and involve the maximum number of antisymmetric bonds between p-electrons. Thus, Coulomb repulsion is the smallest, which results in a stronger atomic ionization potential [1].

Some features of nuclear shell structure were defined more precisely in [2-5]. In [2] a mass formula was calculated on the assumption of continuous mosaic nuclear energy surface and it was shown that one must take into account not only magic but also submagic numbers, which must involve odd 33, 87, 89 and 101 in neutron shells. Possible existence of an odd magic spherical shell with $N = 15$ was inferred in [4]. They analysed separation energy S_{2n} for a wide range of light nuclei. Grounds for identification of odd shells in nuclei can be both an increase in nucleon binding energy and a sudden drop in it after crossing the shell, which was observed in this very case. Later it was shown in [5] that the values of hindrance factors for magnetic dipole l-forbidden transitions allow a similar conclusion about the magic character of the number $Z = 15$ (Fig. 1). The hindrance factors in Fig. 1

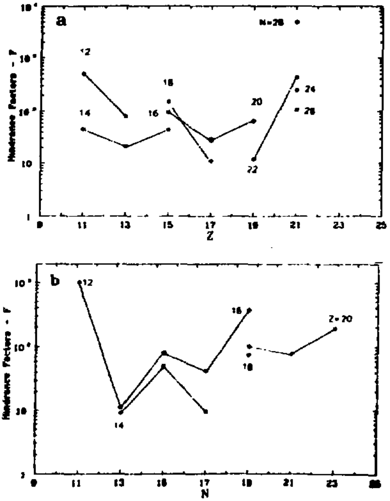

Fig. 1. Hindrance factors of l-forbidden M1 transitions in light nuclei. Numbers in the plots are even nucleons in even-odd and odd-even nuclei.

are calculated from the data of [6, 7] by Moshkovsky's method. The statistical factor was also taken into account in the calculation.

The question naturally arises as to whether there are any other arguments supporting the existence of odd magical numbers in nuclei. A phenomenon of coherent shell closure enhancement in even-even nuclei due to interrelation of proton and neutron shells is known. An very clear example of it is proton subshell closure in ^{146}Gd with Z = 64 and N = 82. This phenomenon is also observed in light even-even nuclei with Z = N (A = 12-32) [8]. That is why it is natural to try to find odd shells in odd-odd nuclei with Z = N. There is a total of 13 odd-odd nuclei with experimentally determined S_n, S_p, S_{2n}, S_{2p} [9]. They are ^{2}H, ^{6}Li, ^{10}B, ^{14}N, ^{18}F, ^{22}Na, ^{26}Al, ^{30}P, ^{34}Cl, ^{38}K, ^{42}Sc, ^{46}V and ^{50}Mn. The sequence of occupying the orbitals by protons and neutrons is the same in all these nuclei. It allows one to expect coherent enhancement of odd shell closure in the nucleus due to substantial overlapping of wave functions of protons and neutrons of the same type. Figure 2 shows separation energies S_n, S_p, S_{2n}, S_{2p} as a function of Z, N.

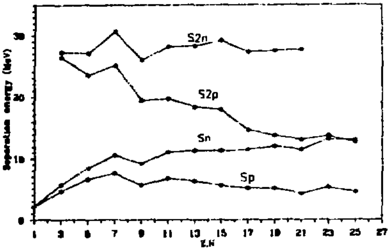

Fig. 2. Nucleon and nucleon-pair separation energies in odd-odd light nuclei at Z = N.

Note that besides the maximum of the function S_{2n} at N = 15 there is a sharp change in S_{2p} at Z = 15, which confirms existence of an odd proton shell. The sudden drop in S_{2n} and S_{2p} for the nucleus with N, Z = 15 is as large as ΔS_{2p} = 3.22 MeV and ΔS_{2n} = 1.94 MeV, which is commensurate with the nucleon pair separation energy for even shell closure in light nuclei. For example, in ^{40}Ca ΔS_{2p} is 8.30 MeV and ΔS_{2n} is 9.09 MeV. Ever more illustrative are N, Z = 7 shells. With them, ΔS_{2p} is 5.70 MeV and ΔS_{2n} is 4.67 MeV, which is comparable with nucleon pair separation energies observed in doubly magic even-even nuclei. A common feature of nuclei with Z,N = 7 and 15 shells is the ground state spin $I^{\pi} = 1^{+}$, whose value depends on the type of $(l_n+l_p)-(s_n+s_p)$ bond. A similar type bond exists in the ^{38}K nucleus with Z,N = 19. With this number of nucleons, separation energies S_n and S_p feature a small maximum. Of special interest are Z,N = 23 shells. The ^{46}V ground state spin $I^{\pi} = 0^{+}$ is determined by the configuration $(\pi 2s)^{-1} = 1/2^{+}$ and $(\nu 2s)^{-1} = 1/2^{+}$. Since proton and neutron $1f_{7/2}$ shells are only half-populated in this case, one can expect this nucleus to be deformed. Supporting evidence for it might be the existence of a deformation region for Ne, Na, Mg, Al, P nuclei with N > 20. Noteworthy is also a small maximum in binding energies at Z,N=11, which, as in the previous case, might be due to nuclear deformation caused by the $1d_{5/2}$ subshell being half-populated.

Abrupt changes in separation energies S_n, S_p, S_{2n}, S_{2p} for these shells are as large as 1-2 MeV. Another point in favour of existence of odd shells at Z,N = 11 and 19 is an increase in hindrance factors F(M1) of l-forbidden M1 transitions at these values (Fig. 1). The nuclei in question belong to the group of light nuclei whose nuclear properties are mainly determined by two-particle interactions in sd shells. Earlier observed anomalies in S_{2n} at N = 15 and N = 19, 20 [10-12] were generally explained by calculations within the unified shell model [13-15], which considers properties of light nuclei in the entire sd space of shell-model wave functions ($0d_{5/2}$-$1s_{1/2}$-$0d_{3/2}$). It was shown that abrupt change in the separation energy S_{2n} is determined by competition of various two-particle interactions. The attractive two-particle interaction ($0d_{5/2}$-$0d_{5/2}$), ($0d_{5/2}$-$1s_{1/2})_{J=2}$ and ($1s_{1/2}$-$1s_{1/2}$), which dominates at N = 15, gives way to repulsive two-particle interaction ($0d_{5/2}$-$1s_{1/2})_{J=3}$ at N = 16. The anomaly around N = 19, 20 for neutron-rich Na and Mg isotopes can be due to inversion of the lowest fp and sd orbits [16].

It is of interest to carry out calculations for odd-odd light nuclei at Z = N within the unified shell sd model in order to find the type of two-particle interaction during formation of the observed odd shells.

Thus, odd shells are observed in odd-odd light nuclei at Z,N = 7, 11, 15, 19, 23 because of possible coherent shell closure enhancement. The Z,N = 11 and 23 shells are most probably deformed. The Z,N = 7 and 15 shells are similar to the atomic shells with the same magic numbers and must be spherical.

Reference

1. A.Bohr,B.R.Mottelson,in *Nuclear Structure*, Vol.I (W.A.Benjamin,Inc., New York,Amsterdam, 1969).
2. N.N.Kolesnikov,Izv.AN SSSR,(ser.fiz.), 49, 2144 (1985).
3. J.H.Hamilton, Nucl.Phys.**A520**,377c(1990).

4. G.Audi, in *"Workshop on Nuclear Structure of Light Nuclei Far From Stability"* (Obernai, France, Nov. 1989).
5. V.A.Morozov, Jad.Fiz. 8,31(1993).
6. P.M.Endt, Nucl.Phys.**A310**, 1-752(1978).
7. P.M.Endt, Nucl.Phys.**A521**, 1-830(1990).
8. V.A.Morozov, Sov.Jour.Part. and Nuclei,**22(4)**,765(1991).
9. A.H.Wapstra, G.Audi Nucl.Phys.**A432**,55(1985).
10. E.Roeckl,P.F.Ditter,C.Detraz et all, Phys.Rev.**C10**,1181(1974).
11. D.J.Vieira,J.M.Wouters,K.Vaziri,R.H.Kraus, Phys.Rev.Lett.**57**,3253(1986).
12. J.M.Wouters,R.H.Kraus,D.J.Vieira et all. Z.Phys.**A331**,229(1988).
13. B.H.Wildenthal,W.Chung, Phys.Rev.**C22**,2260(1980).
14. B.H.Wildenthal,M.S.Curtin,B.A.Brown, Phys.Rev.**C28**,1343(1983).
15. B.H.Wildenthal, Progr.Particle Nucl.Physics,**V11**,Pergamon Press,5,1984.
16. A.Watt,R.P.Singhal,M.H.Storm,R.R.Whitehead, J.Phys.G,Nucl.Phys.**7**,L145(1981).

Received by Publishing Department
on July 4, 1994.

Морозов В.А. E6-94-252

Нечетные протонные и нейтронные оболочки в легких ядрах

На основе анализа значений энергии отделения нуклонов и пар нуклонов S_n, S_p, S_{2n} и S_{2p} в нечетно-нечетных легких ядрах было обнаружено, что вследствие возможного когерентного усиления замыкания оболочек наблюдаются нечетные оболочки при $Z, N = 7, 11, 15, 19, 23$. При этом оболочкиZ, $N = 11$ и 23 скорее всего относятся к классу деформированных. Оболочки Z, $N = 7$ и 15 аналогичны оболочкам с такими же магическими числами в атомах и должны быть сферическими.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1994

Morozov V.A. E6-94-252

Odd Proton and Neutron Shells in Light Nuclei

It is shown by analysis of nucleon and nucleon pair separation energies S_n, S_p, S_{2n}, S_{2p} in odd-odd light nuclei that odd shells are observed at $Z, N =$ $= 7, 11, 15, 19, 23$ as a result of coherently enhanced shell closure. The Z, $N = 11$ and 23 shells are most probably deformed. The Z, $N = 7$ and 15 shells are similar to shells with the same magic numbers in atoms and thus must be spherical.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1994

Редактор Э.В.Ивашкевич. Макет Р.Д.Фоминой

Подписано в печать 19.07.94
Формат 60×90/16. Офсетная печать. Уч.-изд.листов 0.58
Тираж 325. Заказ 47436. Цена 104 р.

Издательский отдел Объединенного института ядерных исследований
Дубна Московской области