ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E-1924

ЛАБОРАТОРИЯ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

R.A.Demirkhanov, V.V.Dorokhov, V.G.Soloviev

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ЯФ, 1965, т2, в1, с10-13.

1964

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ANOMALIES IN THE BINDING ENERGY VALUES OF THE LAST PAIR OF NEUTRONS IN THE RANGE $N = 86 \div 92$

When measuring the masses of the isotopes in the rare-earth region ($138 \leq A \leq 176$) and specifying the energy parameters of nuclei, some interesting anomalies have been observed in the binding energy values of the last pair of neutrons B_{2n} depending on A as well as in the values of B_{2p}, B_n, B_p and other ones.

As was already noted[1,2] the transition from spherical nuclei to deformed ones is accompanied by quite a number of well observable effects: appearance of rotational bands, sharp increase of quadrupole momenta, change in the Coulomb excitation cross section and isotopic shift of spectral lines. These changes point out that in the range $N=88-90$ the deformation of nuclei sharply increases. Such a sharp increase is found nowhere else for even-even nuclei with other number of neutrons.

Mass spectroscopic high-accuracy measurements of nuclei[3,4,5] allowed one to analyse the pairing energies P_n in the range between "magic" numbers $N=82$ and $N=126$. It was shown that P_n has the minimum value near "magic" numbers $N=82$ and 126, in the beginning of the region of deformed nuclei, at $N=90$, it has the maximum value, in the middle of this region it decreases with subsequent growth at the end of the deformation region.

In addition to the above factors defining the beginning and the end of the deformation region in Ref[6] it was shown that the change in the shape of the nucleus is accompanied by a discontinuity in the binding energy values of the last pair of neutrons B_{2n} in the range $N=88 \div 92$.

The nonmonotony in the change of $B_{2n} = f(A)$ is especially well revealed in considering the behaviour of this function in a sufficiently wide mass range, i.e. in analysing the B_{2n} systematics. The systematics $B_{2n} = f(A)$ is convenient enough in the respect that the picture is not complicated by even-odd vibrations of the binding energy; B_{2n} is a linear function of A and the B_{2n} values are often more accurately known than the mass values.

In Refs[7,8] the binding energy of the two last neutrons is systematized as a function of the mass number A in the range $80 \leq A \leq 252$. It is shown that, as a rule, B_{2n} decreases with increasing number of neutrons (at $Z =$ const). The B_{2n} values monotonously (almost linearly) decrease with increasing N in some regions between "magic" numbers. Near the "magic" numbers there occurs a sharp decrease in slope of the $B_{2n} = f(A)$ line. However near the rare-earth deformed nuclei boundaries the increase in the number of neutrons results in the increase of $B_{2n} = f(A)$. It should be noted that the binding energy per nucleon (E/A) does not change its character near the indicated nuclei, namely it monotonously decreases (see[6], Fig. 5 $150 \leq A \leq 160$). Moreover, as is seen by comparing the data of Refs.[9,10] and Ref.[7] the $B_{2n} = f(A)$ values decrease even if the binding energy per nucleon in the nucleus grows. So, in particular, this energy in the range $84 < A \leq 104$ near the strontium masses ($A = 84 \div 88$) increases with A (see Ref.[9], Fig. 1). Meanwhile the binding energy of the last pair of neutrons B_{2n} near the same strontium nuclei decreases (see Refs.[7], Fig. 3).

The discontinuity in the values of $B_{2n} = f(A)$ [7,8] was observed in the case of elements with even Z: gadolinium and samarium. In the case of elements with odd Z (europium and terbium) the picture is somewhat more complicated though at $N = 88 \div 92$ there is also a tendency for $B_{2n} = f(A)$ to be larger.

The B_{2n} values depending on A for the isotopes of gadolinium, samarium and new data on neodymium are given in Fig. 1. Anomalies in the B_{2n} behaviour in the range $N = 88 - 92$ are sufficiently clearly pronounced for the isotopes of Gd to Sm and somewhat less clearly for the isotopes of Nd. It should be noted that the B_{2n} values for the isotopes of Gd and Sm with an odd number of neutrons make these anomalies still more pronounced.

As is known, at $N = 86 \div 92$ there occurs a sharp decrease of the energy of the first excited state 2^+ in even-even nuclei what is well seen from Fig. 2. This is due to the change in the equilibrium shape of the nucleus from spherical form to spheroidal one. Sharp change in the energy of a $2+$ spin and parity state as well as in the B_{2n} values occurs mainly at the transition from $N = 88$ to $N = 90$.

In a recent paper of Canadian physicists[13] B_{2n} has been investigated as applied to gadolinium, samarium and neodymium in the range $N = 88 \div 92$. The mass differences of these elements were measured by a large mass spectrometer and highly accurate data were obtained. In calculating some values of B_{2n} they used the most recent data on α decays and (n, γ) reactions. The main conclusions drawn in this paper prove the presence of the anomalies in the change of $B_{2n} = f(A)$ shown in Refs.[6,8]. However, Ref.[13] contains data only on even-even nuclei.

Bes and Szymanski[14], basing on a model taking into account pairing correlations, have calculated the equilibrium deformations of some even-even nuclei and obtained results which are in good agreement with experiment. However at $N < 88$ they found a sharp change in the nucleus shape from spherical to deformed one.. From their calculations it follows that at $N = 88$ the difference of the total energies for the deformation $\beta = 0{,}3$ and $\beta = 0$ is about 1 MeV.

At $N = 90$ the quantity

$$B_{2n} = E(N=90) - E(N=88) - 2m_n$$

includes the total energy of the $E(N=90)$ nucleus (containing 90 neutrons) of spheroidal equilibrium form and the $E(N=88)$ energy of the spherical nucleus (containing 88 neutrons). Thus at $N = 90$ the energy of separation of the two last neutrons includes also the energy due to the change in the equilibrium deformation of a nucleus from $\beta = 0{,}3$ to the β values close to zero., i.e. the energy related to the change of the nuclear structure. The effect is responsible for the anomaly in the B_{2n} behaviour depending on the number of neutrons (or A). The discontinuity in B_{2n} at $N = 90 - 92$ was roughly estimated to be 1 MeV, this value in its order of magnitude agrees with experimental data given in Fig. 1.

Further mass and binding energy measurements in the rare-earth region justify the above regularities. The Ne, Pr and Ce mass measurements[11] and the binding energy calculations in the range ($N = 88 \div 92$) show that the anomaly in the B_{2n} values somewhat decreases as Z decreases remaining quite noticeable for Nd and is smooth for Pr and Ce . An analogous picture is observed for Dy , Ho and Er (with increasing Z).

It should be stressed that to calculate the binding energy and respectively, the B_{2n} values in the case of elements with a small number of stable isotopes (elements with odd Z : La , Pr , Eu , Tb) and especially in the case of Pm we must use mainly data on nuclear reactions and α and β decays which are insufficiently reliable sometimes. Hence, there is a possibility of obtaining wrong conclusions when using insufficiently correct data on reactions or decays. However for elements with even Z for this mass region Ce , Nd , Sm , Gd , Dy the use of incorrect data is essentially excluded and the conclusions are, in a sufficient degree, reliable.

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Recieved by Publising Departament
on December 24, 1964.

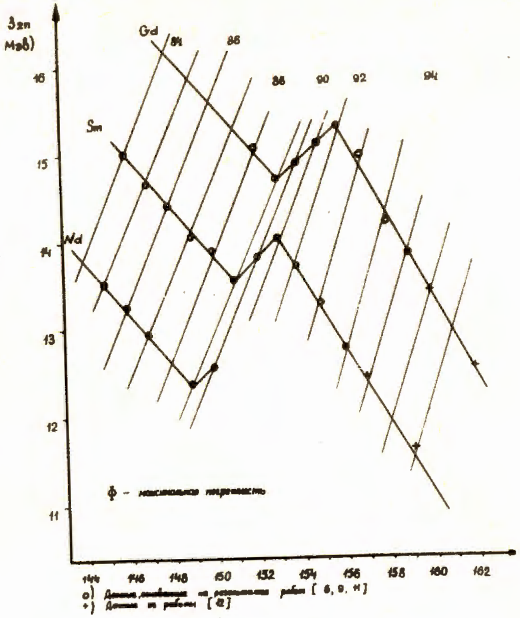

Fig. 1. Energies of the last pair of neutrons.

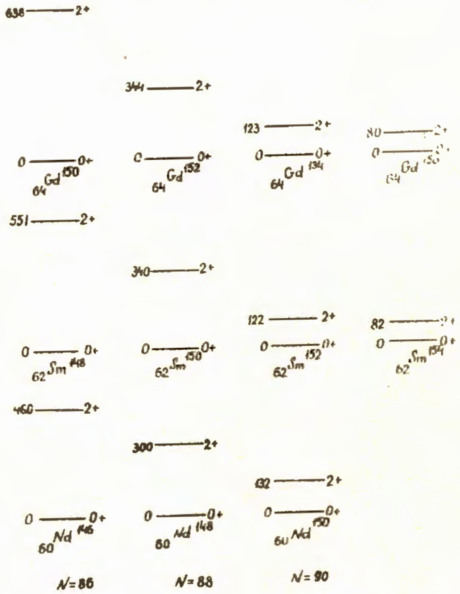

Fig. 2. Energies (in kev) of the first rotational 2+ states in nuclei with the neutron number N =86,88,90 and 92.