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PROPERTIES OF VERY NEUTRON-RICH NUCLEI NEAR THE SHELL CLOSURES $N = 20$ AND $N = 28$

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Свойства супернейтроноизбыточных ядер вблизи замкнутых оболочек $N = 20$ и $N = 28$

Приведены результаты совместных экспериментов Дубна–ГАНИЛ (Франция) и Дубна–РИКЕН (Япония) по синтезу новых ядер вблизи нейтронных оболочек $N = 20$ и $N = 28$ и изучению их свойств.

Методами гамма-спектроскопии исследованы низколежащие состояния в ядрах ^{30,32}Mg, $^{26-28}$Ne, ^{22}O, ^{18}C, а также определены соотношения $E(4^+) / E(2^+)$. Измерены прямым методом массы 20 нуклидов, лежащих между нейтронными оболочками $N = 20$ и $N = 28$. Определены свойства распада ^{30}Ne, ^{26,27,29}F и ряда других ядер. Полученная информация свидетельствует о наличии деформации у ядер вблизи нейтронной оболочки $N = 20$. Представлены результаты поиска дважды магического ядра ^{28}O. Определена лишь нижняя граница его существования, что с большой вероятностью свидетельствует о нестабильности ^{28}O.

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Penionzhkevich Yu.E. E7-99-269
Properties of Very Neutron-Rich Nuclei near the Shell Closures $N = 20$ and $N = 28$

Results are presented of joint experiments carried out by the Dubna–GANIL (France) and the Dubna–RIKEN (Japan) collaborations on the synthesis of new isotopes close to the neutron shells $N = 20$ and $N = 28$ and studying their properties. Gamma-spectroscopic methods were used to study the low-lying states in ^{30,32}Mg, $^{26-28}$Ne, ^{22}O and ^{18}C. The ratios $E(4^+) / E(2^+)$ were determined. A direct method was used to measure the masses of 20 nuclides, located between the shells $N = 20$ and $N = 28$. The decay properties were determined for ^{30}Ne, and ^{26,27,29}F. The obtained information gives evidence on the existence of deformation close to the neutron shell $N = 20$. Results are also presented on experiments aimed at the search for the doubly magic nucleus ^{28}O. Only the upper limit of its production cross section was deduced, which can be taken as evidence of its particle instability.

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

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1 Introduction

One of the fundamental issues in nuclear structure concerns the influence of the magic numbers on the formation of nuclear shells. Until recently it was accepted that nuclei with magic proton and neutron numbers are spherical and their properties are determined by their shell structure. This was strongly manifested in the region of light very neutron-rich nuclei (the isotopes of helium, lithium and beryllium). However, the latest experiments on the synthesis and study of the properties of neutron-rich nuclei at the neutron dripline have shown that the influence of shells on their structure is not a straightforward consequence of their magicity - nuclei with magic proton and neutron numbers can be deformed, and in between the neutron shells with N=20 and N=28 there is evidence of the so-called "island of inversion", which manifests itself in the coexistence of a spherical and deformed configurations in the nucleus [1]. This effect explains the unusual characteristics of the light neutron-rich nuclei, such as irregularity in the masses, neutron binding energies, lifetimes and energy levels.

In the present work, results are presented of the latest experiments performed by the Dubna-GANIL and Dubna-RIKEN collaborations on the gamma-spectroscopy, mass measurements, and also on binding energies and nuclear stability of neutron-rich nuclei close to the neutron shells N=20 and N=28.

2 In-beam gamma-spectroscopy of very neutron-rich nuclei

One of the most challenging goals of nuclear structure is to determine how the structure of atomic nuclei changes far away from the stability line. Recent results on the structure of light neutron-rich nuclei have suggested that some major shell-gaps are weakened when large isospin values are encountered. The typical cases of ^{32}Mg (N=20) and ^{44}S (N=28), where a large collectivity has been found [1,2,3], have brought some evidence for such shell-gap weakening at large neutron excess.

Though, information on the excitation energies of the first 2^+ states and on the B(E2) values of the $2^+ \rightarrow 0^+$ transitions is not sufficient to fully understand the structure of these nuclei. For instance, the measurement of the $E(4^+)/E(2^+)$ ratio should shed some light on the origin of the large quadrupole collectivity observed.

In order to bring more spectroscopic information on ^{32}Mg and neighbouring nuclei, a novel experimental method has been used. This method is based on the production of very neutron-rich nuclei in relatively higher excited states, through the projectile fragmentation process, and on the detection of their in-beam gamma-decay. Such an experiment has been recently performed at GANIL [4] in order to measure the $E(4^+)/E(2^+)$ ratio in ^{30,32}Mg, $^{26-28}$Ne and ^{22}O. A ^{36}S beam, at 77 MeV/u was used on a 2.77 mg/cm^2 Be target.

It is worth pointing out that most of the produced nuclei are TERRA INCOGNITA for nuclear spectroscopy and thus gamma spectroscopy of these nuclei (such as $^{22-23}$O, $^{27-28}$Ne, $^{32-33}$Mg) is completely unknown. Gamma-spectroscopy for all the produced exotic nuclei is obtained by performing coincidences between the analyzed fragments at the SPEG focal plane and the γ-rays emitted in flight during their decay to the ground state. For that purpose, a highly efficient (25% at 1.33 MeV) gamma array of 74 BaF2 crystals was used around the target covering symmetrically the upper and lower hemispheres (roughly 80% of the solid angle around the target is covered). This array is supposed to provide fragment-γ-γ coincidences.

The γ-spectra obtained by gating on the ^{18}C fragment reveals for the first time γ-spectroscopy information on this neutron-rich nucleus. A γ-line is clearly visible at 1.6 MeV in the BaF2 spectrum, probably the $2^+ \rightarrow 0^+$ transition. Furthermore, the same spectrum shows a shoulder at gamma energy around 2.0 MeV, indicating the decay of an unknown higher excited state.

The γ-line observed for the first time for ^{22}O at 3.1 MeV presents the $2^+ \rightarrow 0^+$ transition, this extends the systematics of the 2^+ transition energies of oxygen isotopes up to N=14. It was shown that oxygen isotopes exhibit the lowest 2^+ energy at half-occupancy of the $d_{5/2}$ state (N=12) just like the Ne and Mg isotopes do. Whether it will continue to follow the same trend up to N=16 or not is a key point to understand why the last oxygen isotope seems to be ^{24}O.

A γ-line at 1.3 MeV was observed for ^{22}Ne. This γ-line is very likely to represent the $2^+ \rightarrow 0^+$ transition in ^{28}Ne, which shows for the first time, that approaching N=20, the 2^+ energies in the Ne isotopes decrease dramatically. The 2^+ energy drops from around 2 MeV in ^{24}Ne and ^{26}Ne to 1.3 MeV in ^{28}Ne (it is worth pointing out that the 2^+ excitation energy of ^{26}Ne has been already measured in a β-decay experiment at GANIL [5]. This behaviour is presumably a sign of shell structure change for neutron-rich Ne isotopes similar to the one observed a long time ago in the Mg isotopes [1].

In Fig.1 BaF2 spectra and Ge spectra of ^{32}Mg are shown. Like for many other produced fragments, the gamma spectra (Ge and BeF2) of ^{32}Mg exhibit more than one line. For all these fragments, γ-angular distributions and γ-γ coincidences between BaF2 detectors has to be analyzed in order to deduce a level scheme. This

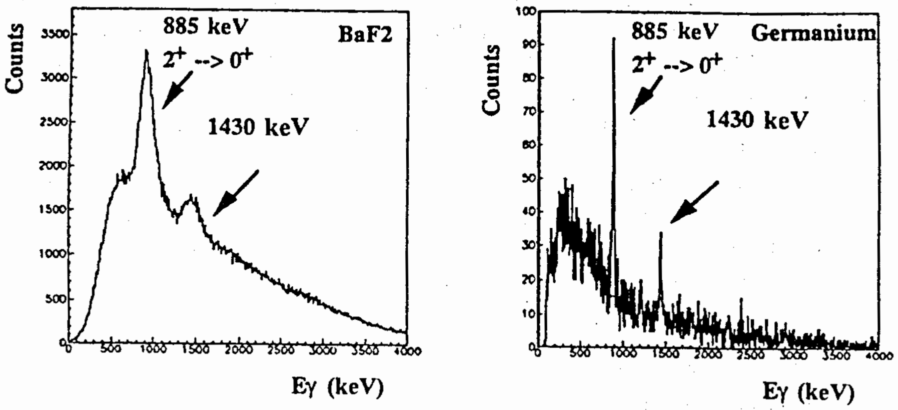

Figure 1. Gamma energy spectra of ^{32}Mg in the BaF2 (left) and in the germanium (right).

type of analysis is quite in progress for ^{32}Mg and reveals that the two lines: the 885 keV (the well known $2^+ \rightarrow 0^+$ transition in ^{32}Mg [1] and the 1.4 MeV newly observed line, are in coincidence. The nature (multipolarity) of the 1.4 MeV γ-ray is not yet extracted from the data. Though, it is likely to be either the 4^+ to 2^+ transition or a transition from a second 2_2^+ to a first 2_1^+ state. In both cases this will shed more light on the physics underlying the so-called shell-effect quenching at the neutron-rich side of the valley of stability.

3 Mass measurement experiments to investigate the shell closures far from stability

Only a few masses of neutron-rich nuclei are known between the N=20 and N=28 shell closures [6]. However, the measurements of these masses are directly related to the binding energies and therefore constitute a most fundamental information one can get on these nuclei. In particular, the evolution of the binding energy of isotopes is illustrated by one of its derivatives, the separation energy of the two last neutrons S_{2n},

$$S_{2n}(A,Z) = [M(A\text{-}2,Z) - M(A,Z) + 2M_n]c^2 .$$

We have performed at GANIL a mass measurement experiment by using a direct time-of-flight technique to investigate the N=20 and N=28 shell closures for nuclei from carbon (Z=6) to calcium (Z=20). The production of these neutron-rich nuclei

has been obtained by the fragmentation of a ^{48}Ca beam at 60 MeV/u on a Ta target located in the SISSI device [7]. A precision of 10^{-6} - 10^{-5}, depending on the statistics, is obtained corresponding to a mass uncertainty from 100 keV (thousands of events) to 1 MeV (several tens of events). During this experiment, 20 masses have been measured in the region of interest with at least a precision better than the one in the table of masses [8].

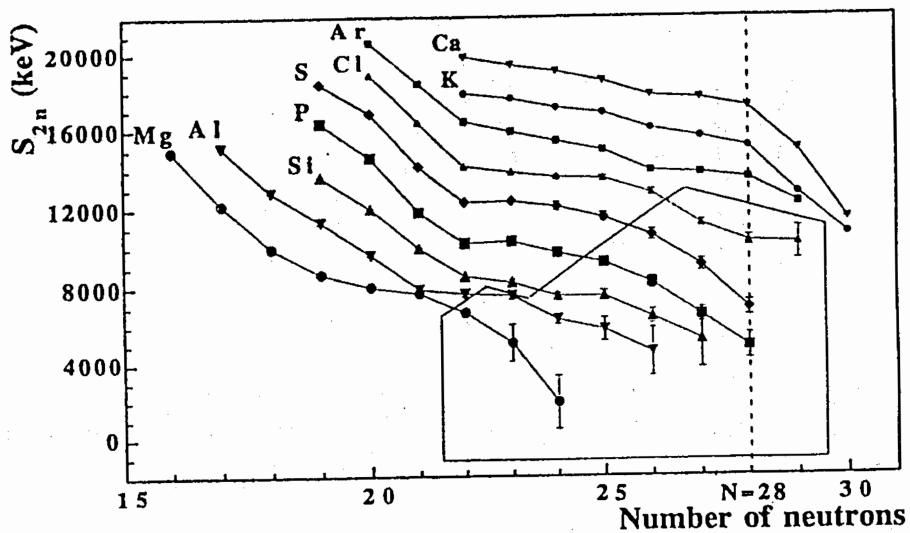

Figure 2. Experimental S_{2n} values between the N=20 and N=28 shell closures. The S_{2n} in the frame are the new points added by the experiment.

The new S_{2n} values deduced from this experiment are shown in Fig. 2. Here, we just comment the S_{2n} for P and S isotopes. If one considers the behaviour of the S_{2n} for Ca isotopes as a reference of the standard shell structure ($f_{7/2}$ closed shell), the P and S isotopes clearly do not follow this trend. From N=20 to N=26, the S_{2n} values include an extra-energy given by deformation, which allows the nuclei to minimize their binding energies with one more degree of freedom. This behaviour is consistent with measurements made at MSU on S isotopes [3]. At N=26, a strong decrease is observed. This may be the result of a possible vanishing of the N=28 shell closure at least for these two elements. The S_{2n} appear to be at least 2 MeV lower than expected by mass extrapolations for N=28 [8].

In the case of the standard shell structure, the microscopic energy should be minimized at the shell closures. An example is given in Fig. 3 by the Ca isotopic chain, where the N=20 and N=28 shell closures are clearly identified. One can see the sudden change at N=26 already pointed out in the previous figure for P and S isotopes. Up to N=26, no anomaly is observed compared to the Ca. The N=28 magic number does not coincide anymore with a minimum of the microscopic energy, which can be related to the vanishing of the shell closure. This trend is well reproduced by the shell calculation [9]. The RMF calculation gives a very good agreement with the data [10], if one excludes the odd-even effect due to the adjustment of the pairing force.

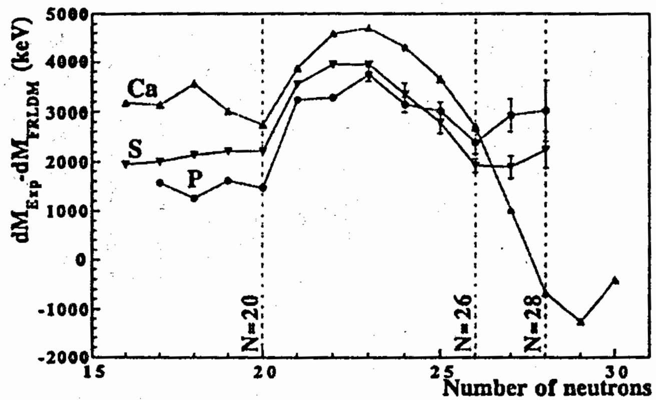

Figure 3. Shell corrections to the mass excess of the macroscopic part of the FRLDM for P, S and Ca isotopes.

A more qualitative interpretation is obtained by the observation of a new isomeric state in ^{43}S during the same experiment. The existence of such an isomer can be explained in a shell model by the inversion of a spherical with a deformed configuration. The standard spherical configuration is no longer the ground state, its spin is a $3/2^-$ instead of a $7/2^-$, in this model. Coexistence and inversion of spherical and deformed configurations would thus be the origin of the observed behaviour.

4 Decay properties of neutron-rich nuclei near the N=20 closed shell

The decay properties for the region of N=20 nuclei can be explained by the transition from spherical to deformed shapes in the so-called "island of inversion".

The lack of experimental information on the very neutron-rich isotopes in the C-Al region is mainly due to the very low production cross section. Therefore a very exotic primary beam of ^{36}S (78 MeV/u) ions, which gives an opportunity to study the β-delayed neutron emission from neutron-rich nuclei with the magic neutron number N=20, such as ^{29}F, ^{30}Ne and ^{31}Na was used in the experiment. The experiment was carried out at GANIL [11].

For the first time the β-decay half-lives and neutron emission probability were measured for ^{30}Ne, ^{26,27,29}F. Additionally, the cases of ^{22}N, ^{24}O, $^{24-29}$Ne, ^{25}F, ^{30,32}Na were re-examined (see Table) [1].

Table. Experimental values of the β-decay half-lives and neutron emission probability of neutron-rich nuclei close to N=20.

Isotope	Experimental results			
	This work		Table of Isotopes, 1996	
	$T_{1/2}$ ms	P_n %	$T_{1/2}$ ms	P_n %
^{22}N	31 (5)	37 (14)	24 (7)	35 (5)
^{24}O	67 (10)	12 (8)	61 (26)	58 (12)
^{25}F	70 (10)	14 (5)	59 (4)	15 (10)
^{27}F	9.6 (0.8)	11 (4)		
^{29}F	2.4 (0.8)	100 (80)		
^{27}Ne	22 (6)	0 (3)	32 (2)	2 (0.5)
^{28}Ne	20 (3)	11 (3)	17 (4)	22 (3)
^{29}Ne	15 (3)	27 (9)	200 (10)	
^{30}Ne	7 (2)	9 (17)		
^{30}Na	50 (4)			
^{31}Na	18 (2)		48 (2)	30 (4)

The measured half-lives for ^{28}Ne and ^{30,31}Na agree within the error bars with the previous experiments. The only important discrepancy is observed for ^{29}Ne. The experimental half-lives obtained here are in good agreement (within a factor of two) with the sd shell model calculations of Wildenthal et al. [12], including the values for ^{27,29}F and ^{29,30}Ne. The last suggest that the deformation phenomenon, predicted and observed in the Mg - Na region, disappears below Z=11. Thus the standard shell-model space seems to be sufficient to predict half-lives of fluorine and neon isotopes in the vicinity of N=20.

5 Evidence for particle instability of ^{28}O

The recent discovery of the particle stability of ^{31}Ne [13], in contrast to most mass predictions, has motivated us to re-examine the location of the fluorine dripline. The nucleus ^{31}Ne is located in the deformation region centered at Z~11 and N~20, the so-called "island of inversion" region. A particular feature of this region is the tendency towards prolate deformation in spite of the effect of spherical stability due to the magicity of the neutron number of 20 [14]. Toward a lower Z along N=20, the question of the possible stability of the doubly magic nucleus, ^{28}O, has recently attracted much attention, even though the particle instability of $^{25,26}O$ beyond ^{24}O has been clearly shown by two experiments [15,16]. The expectation for ^{28}O to be stable stems from an enhanced stability anticipated from the double magicity or the deformation. The stability of ^{28}O has been discussed in several theoretical papers, which however yielded conflicting results. In the frame of the Dubna-RIKEN collaboration a search of new isotopes around N=20 (^{28}O, ^{31}F, ^{25}N) has been carried out using the RIKEN accelerator facility and a 94.1 MeV/u ^{40}Ar-beam [17]. In this experiment a new isotope ^{31}F (8 events) was observed for the first time (Fig. 4). The absence of events corresponding to the $^{25,26,27,28}O$ isotopes as well as $^{24,25}N$ and ^{30}F is clearly confirmed.

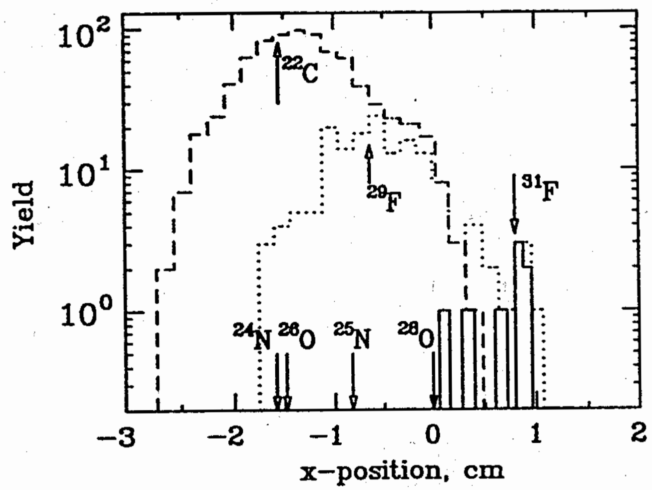

Figure 4. Experimental distributions of the horizontal positions for isotopes transmitted to the first focal plane (F2) of the RIPS spectrometer. The centroids experimentally detected for the ^{22}C (dashed histogram) and ^{29}F (dotted histogram) isotopes were in agreement with the calculated values (upward arrows) obtained by an energy loss calculation. The position distribution of the ^{31}F isotope (solid line histogram) was also in accord with the calculation. The expected events for $^{24,25}N$ and $^{26,28}O$ could be centered at the middle of F2, and their expected center positions are shown by the downward arrows.

The non-observation of an isotope does not necessarily prove its unbound character. To achieve more definite evidence we have plotted the observed yields versus Z for the nuclei with N=2Z+4, as shown in Fig. 5. The calculated yields are in good agreement with the observed yields over the whole range, connecting smoothly the results of ^{22}C and ^{31}F. The yields of ^{25}N and ^{28}O, which lie between ^{22}C and ^{31}F, can therefore be estimated with fair reliability by the interpolation method.

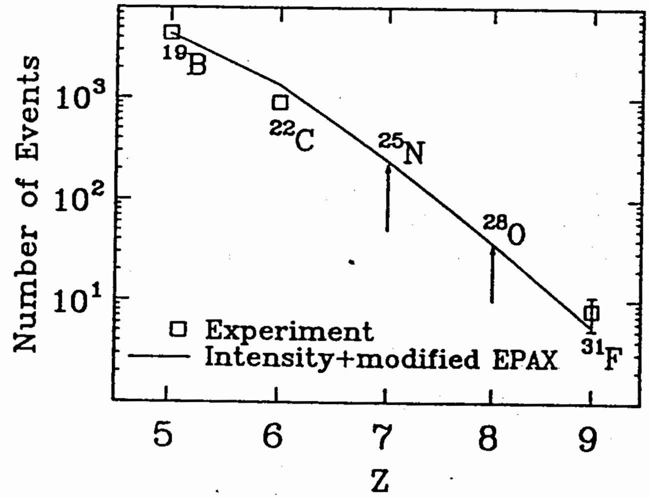

Figure 5. Isotopic production for nuclei with neutron numbers N=2Z+4. The solid curve presents the expected yields according to the INTENSITY code using the modified EPAX parameterization. The expected yields for ^{28}O and ^{25}N are indicated by arrows.

The fact that the experimental results of no events distinctly deviate from the estimated yields provides strong evidence for the particle instability of $^{24,25}N$, $^{27,28}O$ and ^{30}F. The sudden change in stability from oxygen to fluorine indicates an extra push of stability for the very neutron-rich fluorine isotopes.

The experiments on the properties of nuclei in the vicinity of the N=20 and N=28 shells should be continued so as to study the deformation of nuclei in this region. This can be achieved by means of γ-spectroscopy and by using the direct method of Level Mixing Resonances (LMR), as well as by mass and structure measurements of unbound nuclei using the missing mass method. For instance, in the case of ^{25}O one could use the reaction $^{26}F(d,^{3}He)^{25}O$ and in the case of ^{26}O - the reaction $^{24}O(t,p)^{26}O$.

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