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PARTICLE STABILITY OF VERY NEUTRON-RICH VERY LIGHT NUCLEI

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1. INTRODUCTION

Light nuclei play an important role in determining the fundamental constants in the nucleus-nucleus interactions and in testing nuclear models, used in describing the properties of nuclei located far away from the β-stability line. From this point of view of special interest are those close to the neutron drip line. In this region practically all bound nuclei have been synthesized. Investigations are being performed of quasi-stationary states in unbound nuclei beyond the drip line. With the acceleration of radioactive ion beams it has become possible to advance into the region of even more neutron-rich nuclei.

In the present work a short review is given on the status of investigation of superheavy hydrogen isotopes and multineutron systems, which is quite controversial. Also the latest data on the experimental attempt to determine the particle stability of nuclei close to the neutron shells N = 20 and N = 28 are presented. In this region there is evidence of the changing of the magic numbers for very neutron-rich nuclei and its influence on their stability.

2. MULTINEUTRON SYSTEMS AND HYDROGEN ISOTOPES

The maximum neutron-to-proton ratio has been reached only for the lightest elements. In this region, nuclides have been synthesized lying at and even beyond the limit of particle stability. It seems that the only realistic way to study nuclear systems having $N/Z > 2.5$ and lying at the limit of particle stability is to investigate the isotopes of lightest elements and determine their mass in the ground and excited states. The structure of such nuclei may turn out to be quite different from what is observed close to the β-stability line. The most direct way to measure their mass and to study their structure is to use the missing mass method [1]. The missing mass method has been successfully applied in heavy ion reactions in order to measure the mass of super neutron-rich systems such as ^{3,4}n, ^{4,5,6}H, ^{7,8,9,10}He, etc.

Information on the properties of the heavy helium, lithium, beryllium and boron isotopes is given in details in ref. [2]. In this section we present some results obtained by the collaboration FLNR (JINR, Dubna) - the Hahn-Meitner Institute (Berlin) - the RSC "Kurchatov Institute" (Moscow).

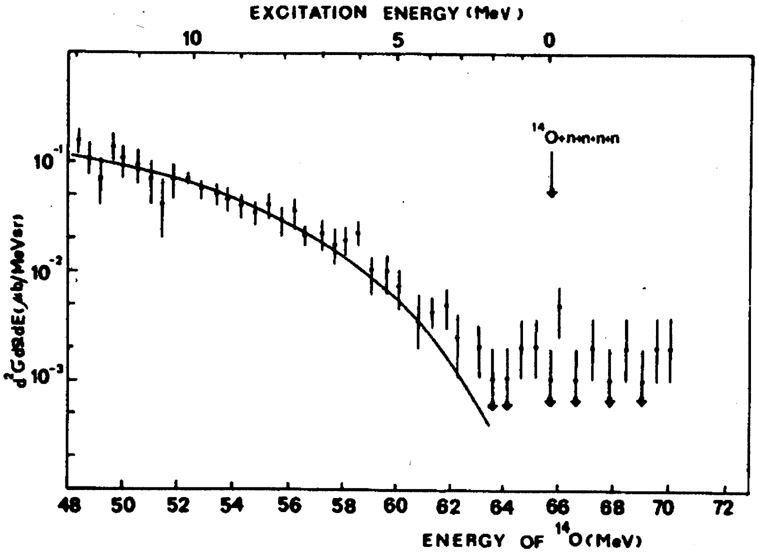

Figure 1. The ^{14}O energy spectrum from the ^{7}Li(^{11}B,^{14}O)^{4}n reaction [6]. The solid line is the five-body phase-space.

3. MULTINEUTRONS

Many experimental studies were aimed at searching for stable or resonant states in systems consisting of a few neutrons.

As far back as the 1950's it became clear that the dineutron did not exist as a bound system [1]. The reported observation of a bound trineutron [3] was not confirmed by more recent measurements using pion double-charge-exchange or heavy-ion transfer reactions [4–6] and the now generally accepted viewpoint is that the trineutron is not bound. Most theoretical calculations of the binding energy of four neutrons predict that a bound state of four neutrons does not exist [1]. At the same time, these calculations do not prove the absence of such a state. Actually, the upper limit of the binding energy of the tetraneutron is equal to 3.1 MeV, since otherwise, the ^{8}He nucleus would undergo not β-decay, but would rather decay by four-neutron emission. Experiments using pions did not lead to the observation of either a bound or unbound tetraneutron [7]. A similar result was obtained in the multinucleon transfer reactions ^{7}Li(^{7}Li,^{10}C)^{4}n [8], ^{7}Li(^{9}Be,^{12}N)^{4}n and ^{9}Be (^{9}Be,^{14}O)^{4}n [6]. An attempt to determine the binding energy of the system of four neutrons was made also in the ^{7}Li(^{11}B,^{14}O)^{4}n reaction [6], where a few events

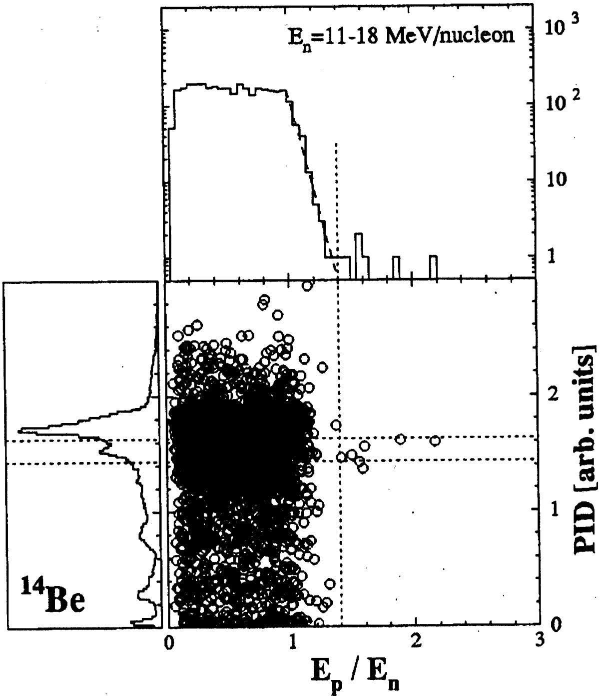

Figure 2. Identification plot for the reaction (^{14}Be,X+n). The dotted lines define the region centered on the ^{10}Be peak [10].

were observed in the energy region corresponding to the ground state of ^{4}n (Fig. 1). However, the statistics in this experiment was very low and definite conclusions concerning the binding energy of ^{4}n could not be made. Presently there are only two experiments suggesting the existence of a stable tetraneutron [9,10]. The first one [9] used an activation method for the identification of the 4n system, formed in the bombardment of an uranium target by α-particles. However, the subsequent analysis pointed to a possible background due to contaminants in the detector/degrader. The second one, recently performed at GANIL [10], is based on the break-up of the radioactive ^{14}Be beam into ^{10}Be + 4n and offers a unique result. In the neutron detectors, which registered neutrons from the break-up of ^{14}Be, six events have been observed, which could be attributed to the bound cluster of 4 neutrons. This result is shown in Fig. 2. However, the small statistics does not ensure a high confidence level of the obtained result - it requires verification.

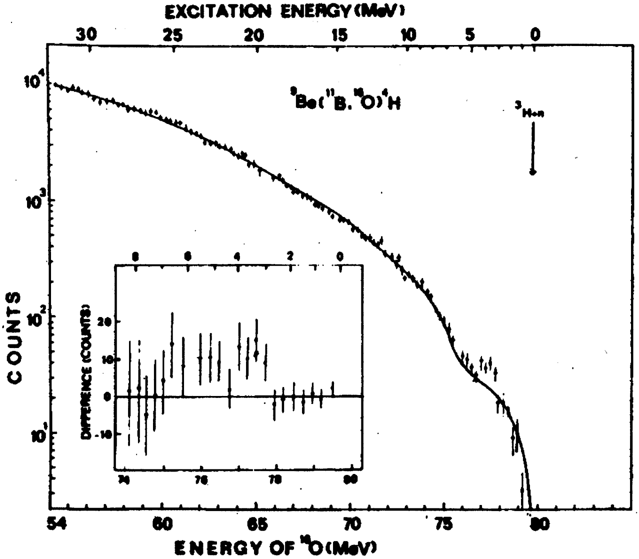

Figure 3. Energy spectrum of ^{16}O nuclei from the $^{9}Be(^{11}B,^{16}O)^{4}H$ reaction [13].

Here it is necessary to note that the perspective of further studying of the multineutron systems (^{4}n, ^{5}n, ^{6}n …) is directly connected with the possibility to use radioactive ion beams. A more definite answer on the stability of the tetraneutron can be obtained in experiments of higher statistics by the investigation of the break-up of radioactive nuclei like ^{8}He, ^{14}Be, $^{15,17}B$ or using the missing mass method with reactions of rather complex transfer such as $^{7}Li(^{9}Li,^{12}C)^{4}n$ and $^{1}H(^{15}B,^{12}C)^{4}n$ with a reaction Q-value amounting to a few MeV. As some theoretical calculations indicate the possible existence of "neutron drops" [11], a challenge for the future may be the search for even heavier multineutrons in reactions such as $^{1}H(^{17}B,^{12}C)^{6}n$, $^{7}Li(^{11}Li,^{12}C)^{6}n$ and $^{14}C(^{8}He,^{16}O)^{6}n$.

4. SUPERHEAVY ISOTOPES OF HYDROGEN

The great number of experimental investigations on hydrogen isotopes with $A > 3$ have revealed quasi-stationary states in the systems ^{4}H, ^{5}H and ^{6}H. The isotope ^{4}H has been studied extensively [1,12]. Fig. 3 shows the spectrum of ^{16}O nuclei from the $^{9}Be(^{11}B,^{16}O)^{4}H$ reaction [13]. The observed excess of events above the phase space (the solid curve is the sum of all possible decay channels: $^{16}O+^{3}H+n$, $^{16}O^{*}+^{3}H+n$, $^{16}O+^{2}H+n+n$, $^{16}O+^{1}H+n+n+n$) is shown in the inset. It is a peak having a width of about 4 MeV. It cannot be excluded that this wide peak consists of two peaks: one

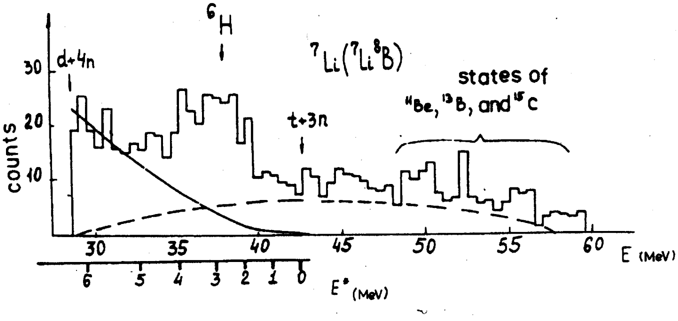

Figure 4. Energy spectrum ^{8}B from the ^{7}Li(^{7}Li,^{8}B)^{6}H reaction [19]

at 3.5±0.5 MeV above the decay threshold of $^4H \rightarrow ^3H+n$ with a width $\Gamma \sim 1$ MeV (the ground state of ^{4}H) and the second at about 5 MeV (an excited state of ^{4}H). The search for ^{5}H was undertaken in many laboratories and this work has been reviewed elsewhere [1,14]. The main conclusion was that there exists no bound ^{5}H. A typical result is the spectrum from the ^{9}Be(^{11}B,^{15}O) reaction [13]. At the same time, the results from experiments with pions have provided some evidence of a very broad resonance at an energy between 3 and 12 MeV. The heavy-ion reaction ^{7}Li(^{6}Li,^{8}B)^{5}H [15] gave evidence for an unstable ^{5}H nucleus at 5.2 ± 0.4 MeV. A study of the ^{1}H(^{6}He, 2p)^{5}H reaction with the radioactive ^{6}He beam reported a decay energy of ^{5}H into ^{3}H+2n equal to 1.1± 0.4 MeV [16]. In the most recent experiment using the same reaction, a ^{5}H resonance at 1.7 ± 0.3 MeV above the ^{3}H+n+n threshold was observed [17]. The width of the observed resonance was 1.9± 0.4 MeV. This result is in good agreement with some theoretical calculations predicting for the ^{5}H energy a value of about 2.5-3 MeV [18]. ^{6}H was synthesized in the ^{7}Li(^{7}Li,^{8}B)^{6}H reaction [19], the corresponding spectrum is shown in Fig. 4. In this work the resonance parameters obtained for ^{6}H were: $E_r = 2.7 \pm 0.4$ MeV and width $\Gamma = 1.8 \pm 0.5$ MeV. The following measurements using the ^{9}Be(^{11}B,^{14}O)^{6}H reaction [13] confirmed the existence of ^{6}H as a resonance (Fig. 5) with practically the same parameters. Thus ^{6}H is the most neutron-rich nuclear system known so far.

The future studying of hydrogen isotopes is also dependent on the use of radioactive ion beams. For instance the ^{6}H system can be looked for in such exotic reactions as ^{2}H(^{8}He,^{4}He)^{6}H and ^{7}Li(^{11}Li,^{12}B)^{6}H.

As the reaction Q-value is only few MeV, we can expect to produce these nuclei with high yield. Reactions induced by stable nuclei, the rather strongly negative reaction Q-values of which are compensated by the high beam intensity, can also be used, e.g. ^{2}H(^{18}O,^{14}O)^{6}H and ^{7}Li(^{13}C,^{14}O)^{6}H.

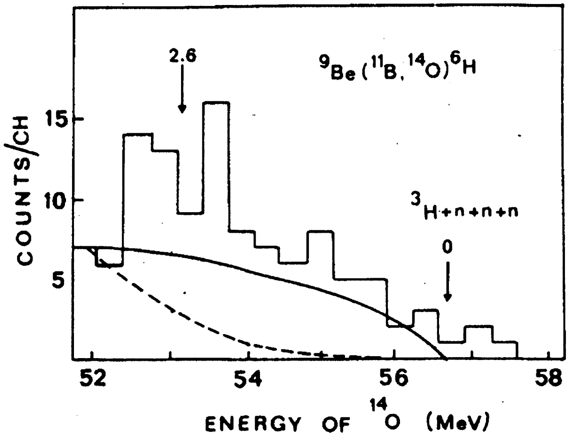

Figure 5. Energy spectrum ^{14}O from the $^9Be(^{11}B,^{14}O)^6H$ reaction [13]

5. THE NEUTRON DRIP LINE IN THE OXYGEN-MAGNESIUM REGION

The latest experiments aimed at mapping the neutron drip line in the oxygen-magnesium region are on the particle instability of neutron-rich oxygen isotopes $^{26,27,28}O$ [20] and the discovery of particle stability of ^{31}Ne and ^{31}F [21].

A particular feature of nuclei in this region is the development of static deformation in spite of the expected effect of spherical stability due to the magicity of the neutron number N=20.

Concerning the N > 20 area it was argued that the deformation might lead to enhanced binding energies in some of the yet undiscovered neutron-rich nuclei, that was confirmed by the particle stability of ^{31}F. Thus one may expect that the drip line for the fluorine - magnesium elements could move far beyond the presently known boundaries. Besides, the observed deformation of ^{44}S [22] suggested a significant breaking of the N = 28 closure for nuclei near ^{44}S. Therefore, the study of nuclei in the region of the neutron closure N = 28 is strongly motivated.

New attempts to determine the neutron drip line for the F-Ne-Mg isotopes in the region of the neutron numbers N=20-28 were undertaken recently in the frame of the RIKEN-Dubna and GANIL-Dubna-IPN Orsay collaborations [23,24].

These experiments were devoted to the direct observation of ^{31}F, ^{34}Ne, ^{37}Na and ^{40}Mg among the products of a primary ^{48}Ca beam fragmentation. The very neutron-rich beam and target were chosen to optimize the production rate of the drip-line nuclei. The mean beam intensity of the ^{48}Ca beam reached 150 pnA. The ^{34}Ne and ^{37}Na isotopes were unambiguously identified, whereas ^{33}Ne, ^{36}Na and ^{39}Mg were not observed [23,24]. The most interesting nuclide in this region, viz. ^{40}Mg, was also not observed. The upper limit for its production cross section was estimated to be less than 0.01 pb. Various theoretical calculations exist and predict the position of the neutron drip line in this region. The FRLD model [25] gives a very strong binding energy for ^{40}Mg - the one- and two-neutron separation energies (S_n and S_{2n}) are even above 3.4 MeV. It should be noted that the FRLD model gives correct predictions for the stability of ^{31}Ne and ^{31}F. According to the shell model predictions [26], the last bound isotopes are ^{24}O, ^{27}F, ^{34}Ne, ^{37}Na, and ^{38}Mg. According to another shell model calculation [27], the nuclei ^{26}O, ^{34}Ne and ^{40}Mg are the last stable isotopes against two-neutron emission. SM, HF and RHB calculations for even-mass O, Ne and Mg isotopes indicate the disappearance of shell magic numbers, and suggest an onset of deformation and shape coexistence in this region [27,28].

Table 1
One (S_n) and two (S_{2n}) -neutron separation energies for nuclei near the neutron drip line calculated in a STFFS spherical basis. For nuclei in column 6, $S_{2n} < 0$

Z	Nucleus	N	S_n, MeV	S_{2n}, MeV	Nucleus	N	S_n, MeV
8	^{24}O	16	3.59	5.85	^{26}O	18	0.69
9	^{29}F	20	1.64	0.90	^{31}F	22	< 0
10	^{32}Ne	22	1.65	0.33	^{34}Ne	24	0.16
11	^{37}Na	26	0.99	0.07	^{39}Na	28	< 0
12	^{42}Mg	30	1.13	0.38	^{44}Mg	32	0.91

The properties of neutron drip-line isotopes from the O-Mg region were calculated using a self-consistent theory of finite Fermi systems (STFFS)[29].

The results of these calculations for S_n and S_{2n} in a spherical basis are shown in Table 1. We can see that for even-even nuclei the position of the boundary in the considered region is determined by the instability with respect to two-neutron emission. For ^{26}O it was found that a quasi-stationary state in the ^{24}O+2n system may exist as ^{26}O*. Similarly for other extremely drip-line nuclei of A(even-even) type, A*=A+2n quasi-stationary systems may exist, for example ^{36}Ne* and ^{40}Mg*. The lifetime of such systems is expected to be $\tau \geq 10^{-18}$ s.

It should be noted that only the results for ^{24}O and ^{37}Na correspond to the experimental data. This is not surprising because the ^{24}O isotope is a spherical one. In the case of ^{37}Na, due to the deformation effects, up to $\beta_2 < 0.4$ the neutron-drip-line number is N = 26, which corresponds to the spherical basis calculations.

According to the calculations [29], the neutron drip line extends beyond N = 20 and reaches N = 24 for neon and even N = 26 for sodium isotopes most probably as a consequence of the mixing of the d3/2 and f7/2 states.

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Нуклонная стабильность сильнонейтроноизбыточных легких ядер

Дан краткий обзор результатов исследования тяжелых изотопов водорода ^{4,5,6}H и мультинейтронных систем, состоящих из трех и четырех нейтронов. Данные достаточно противоречивые. Предлагаются эксперименты для их дальнейшего изучения. Представлены также результаты самых последних экспериментов по определению нуклонной стабильности ядер, находящихся в области нейтронных оболочек с N=20 и N=28. В этой области, известной как «область инверсии», существуют доказательства изменения магических чисел и их влияния на стабильность сильнонейтроноизбыточных ядер.

Работа выполнена в Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ.

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Penionzhkevich Yu. E., Kalpakchieva R., Lukyanov S. M. E7-2003-47

Particle Stability of Very Neutron-Rich Very Light Nuclei

A short review is given of the status of investigation of the heavy hydrogen isotopes ^{4,5,6}H and the multineutron systems consisting of three and four neutrons. The available data are rather controversial. Experiments are suggested for their further study. Also the latest results from the experimental attempt to determine the particle stability of nuclei close to the neutron shells N=20 and N=28 are presented. In this region, known as «island of inversion», there is evidence of the changing of the magic numbers for very neutron-rich nuclei and its influence on their stability.

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

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