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NEUTRON-RICH ISOTOPES OF THE LIGHTEST ELEMENTS

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The search for and the study of new neutron-rich isotopes of the lightest elements have two main goals. One is to establish the limit of particle stability and to find out whether pure neutron nuclei exist at all. The other purpose is to get information about the properties of nuclei in the vicinity of the limits of stability, as it is expected that they differ from the known trends. Despite the fact that in the region of the lightest elements experiments have allowed to approach the limit of nuclear stability, one cannot definitely say that it has been reached as only a few unstable nuclei have been discovered up till now. Explanation to this can be found in that experiments for the production and study of quasistationary or unstable nuclear systems are much more difficult to perform than those aimed at the direct discovery of particle stable nuclei.

A special place in this problem belongs to the heavy isotopes of the lightest elements hydrogen, helium and lithium, and also to the multineutron systems. In this region, in addition to γ-ray and β emission, the nuclei may decay with high probability by the emission of neutrons, α particles and even heavier clusters. Among all these decay modes it is only the particle emission that can take place "instantaneously" according to the nuclear time scale. As a result, when factors inhibiting particle emission do not exist, the nuclear stability is determined, as a rule, by nucleon emission. However, even particle unstable nuclei may live long enough. Different explanations of this can be given including selection rules for isospin, the smallness of phase space of the system's final state, various types of inhibition rules for the transition of nucleons from one nuclear shell to another, the centrifugal barrier, etc. In ref. /1/ the different particle unstable nuclear states are classified in three categories depending on their lifetimes: 1) radioactive nuclei - nuclei that live for time $t > 10^{-12}$ s; 2) quasistationary nuclear states - nuclear states, energetically unstable to particle decay and living long enough according to the nuclear time scale (10^{-12} s $> t > 10^{-22}$ s); 3) unstable nuclei with lifetimes $t \sim 10^{-22}$ s.

Quasistationary states usually manifest themselves as resonances in the cross sections of different processes. The width Γ of these resonances is connected to the lifetimes of the corresponding nuclear states via the relationship $t = \frac{h}{\Gamma} \approx \frac{6.6\ 10^{-16}}{\Gamma\,(\mathrm{eV})}$ (sec). Thus, a necessary condition for the existence of a quasistationary state is that its lifetime $t \gg 10^{-22}$ s. This is equivalent to having $\Gamma \ll 6.6$ MeV.

Fig. 1 presents the neutron vs proton diagram for the lightest elements ($Z \leq 4$). It is in this nuclear region that the greatest neutron excess has been reached up till now ($N/Z = 3$). It can be seen that a few nuclei have been synthesized in their quasistationary states. This means that in the region of the lightest elements nuclei are experimentally produced already beyond the limits of nuclear stability. Actually the only way to study nuclei with a neutron to proton ratio $N/Z > 2.5$ and lying close to the limits of stability at present seems to be via investigations in the region of the lightest elements. The structure of these nuclei may prove to be extremely unexpected. Besides, at some specific circumstances it may happen that there are no limitations to nuclear stability and even a new stability region may be found for extremely large values of the N/Z ratio. A kind of illustration to this is the system of two neutrons (dineutron) which is known to be unbound. However, the dineutron is unbound by only about 70 keV. A small change in the N-N interaction potential could make the dineutron stable. The addition of more neutrons might act as if greater

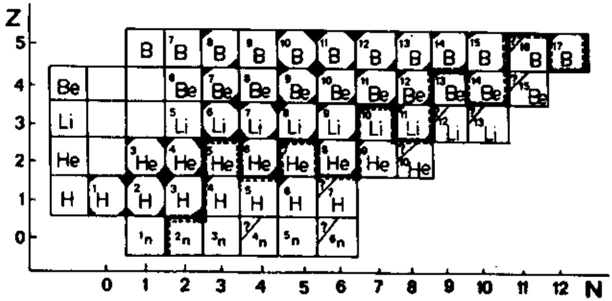


Fig. 1. The Z vs N diagram for the light elements with **$Z \leq 5$. The thick and dashed lines to the neutron drip-line: ◘ - stable nuclei, ◩ - radioactive nuclei, ▨ - neutron un**stable nuclei. For nuclei with question marks the existence either of stable or unstable ground states has not yet been proved

attraction is present, as is, for example, the case of two neutrons and an α particle: neither the system n-n nor the system n-α are stable, but two neutrons and an α particle form together the particle stable nucleus ^{6}He. From the microscopic calculations of A.Baz /2/ it follows that by a small increase in the potentials, which practically do not change the phases of nucleon-nucleon scattering, it is possible to stabilize the neutron nuclei in case the number of neutrons is not less than a few tens.

The experimental investigations at the neutron drip-line in the region of the lightest elements was started by the pioneer work of Yu.A.Batusov, V.V.Sidorov et al. /3/ who discovered the quasistationary nucleus ^{6}Be unstable with respect to the decay into ^{4}He + 2p. On the other hand, in the paper of Yu.B.Zel'dovich /4/ it was pointed out that the light neutron-rich nuclei might be much more stable and the existence of the particle stable ^{8}He was predicted.

This prediction strongly stimulated not only the search for and hence the discovery of this nucleus but also the extention of investigations in this direction. Eight neutron-rich nuclei of the quasistationary type were observed: ^{2}n, ^{4}H, ^{6}H, ^{5}He, ^{7}He, ^{9}He, ^{10}Li and ^{13}Be. In addition, the three systems ^{3}n, ^{5}H and ^{7}H were found to be neither stable nor quasistationary.

For the synthesis of neutron-rich light nuclei usually neutron beams from high flux reactors or high energy proton beams have been used. Much greater possibilities appeared with the production of intensive pion beams at the meson factories. Along with this the acceleration of heavy-ions of a broad range of masses and energies up to about 1 GeV/nucleon has opened new ways to the study of exotic nuclei far from the valey of stability.

In the studies of new isotopes much attention is paid to the measurement of their mass excess as it presents the first quantitative information about their structure.

Binary reactions have been successfully used so far as a direct method to measure the mass excess of nuclei. On the basis of the obtained values conclusions are made as to whether these nuclei are stable or not. Binary reactions yield two products in the exit channel. The application of binary reactions for mass excess measurements is particularly useful when the product under study is weakly bound or even unbound. Measuring the energy spectrum of one of the products, which has to be particle stable, conclusions can be drawn about the properties of the other one - information is obtained about the mass excess of the studied nucleus in its ground state and also the existence of any excited states can be established (see fig. 2). This method has

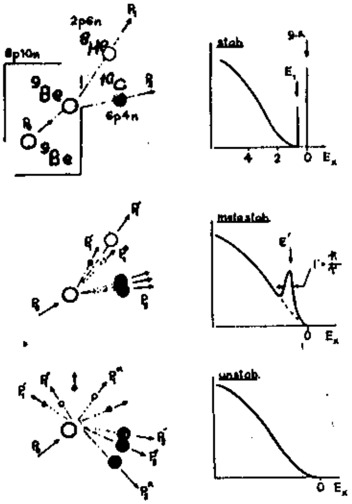


Fig. 2. A schematic presentation of energy spectra corresponding to three cases of nuclei: particle stable, quasistationary (metastable) and unstable nuclei

often been used to determine the mass excess of weakly bound nuclei in pion double charge exchange reactions [5], and recently also in heavy-ion-induced reactions [6]. Among the latter are reactions in which fast exchange of few nucleons between the target and projectile nuclei takes place.

Reactions leading to the formation of exotic nuclei are characterized as a rule by a strongly negative reaction Q-value (-30-60 MeV), hence what one deals with are very low reaction cross sections. Besides, the angular distributions of such reactions are strongly forward peaked while it is well known that at forward angles the cross section for elastic scattering is significant too. These circumstances put some severe restrictions in choosing the experimental technique. The best tools to be used in such experiments are the magnetic analyzers, which give precise energy measurements and are also able to separate the studied products from quite a significant fraction of other reaction products. Magnetic spectrometers are being used in many laboratories where exotic light nuclei are studied, e.g. the LISE facility at GANIL (France), the QME/2 spectrometer at Daresburry (England), the EPICS spectrometer at Los Alamos (USA), the spectrometer MSP-144 at Dubna,etc As a rule the energy resolution of magnetic spectrometers is about 200 keV, they subtend a solid angle of a few milisteradians, and have a sensitivity to about 1 nb/sr. The Dubna MSP-144 magnetic spectrometer was used to systematically study the heavy isotopes of hydrogen and helium, and also some multineutron systems produced in heavy-ion-induced reactions (see fig. 3).

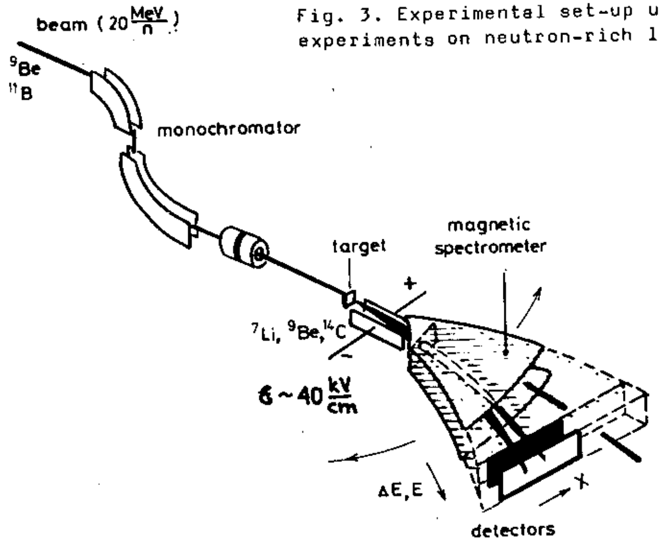


Fig. 3. Experimental set-up used in the Dubna experiments on neutron-rich light nuclei

A great deal of experimental work has been dedicated to the study of helium isotopes. It has been unambiguously shown /6/ that ^{5}He, ^{7}He and ^{9}He are particle unstable. The isotope ^{5}He is found to be unbound by 0.89 MeV, while the isotope ^{7}He is unbound by only 0.45 MeV. The increase of stability for greater A is even stronger for the particle stable isotopes ^{6}He and ^{8}He. A definite explanation of such a behaviour in the stability of helium isotopes has not been found yet. A turning point for the studies of the stability of the heavy helium isotopes was the experiment carried out by K.Seth at Los Alamos to measure the mass excess of the particle unstable ^{9}He produced in the pion DCX reaction /7/. Although negative the neutron binding energy in ^{9}He obtained from this experiment (B_n = -1.14 MeV) exceeds by 1 - 2.5 MeV the predicted value /5/.

In ref. /8/ the results of experiments aimed to measure the mass of ^{9}He in the DCX reaction ^{9}Be(^{14}C,^{14}O)^{9}He are presented. The enhancement in the energy spectrum of ^{14}O over the phase space for the break-up of ^{9}He into ^{8}He + n led to the determination of a mass excess value for ^{9}He equal to $\Delta M(^9\text{He}) = -42.2 \pm 1.1$ MeV. From this mass measurement a value of $B_n(^9\text{He}) = -2.5 \pm 1.1$ MeV was deduced. This is in agreement with the results of ref. /7/. The ^{9}He production cross section was claimed to be about 0.2 μb/sr. If the value of the mass excess of ^{9}He obtained in ref. /7/ is used, on the basis of the Garvey-Kelson mass formula the isotope ^{10}He is predicted to be stable with respect to one neutron decay (B_n = +0.93 MeV), but unstable against two neutron decay

(B_{2n} = -1.66 MeV). These estimates, however, have uncertainties not less than 1 MeV and that is why the stability of ^{10}He with respect to the decay into ^{8}He + 2n cannot be completely ruled out. Thus the stability of ^{10}He is a question of principal interest as far as the limit of particle stability in the region of the lightest elements is concerned. A direct answer to this question can be given by experiment only. The determination of the energy of a quasistationary state in ^{10}He (in the case of its instability) would help to understand the reason for the so-called "helium anomaly".

As far as investigations on hydrogen isotopes are concerned no experimental evidence has been found yet for the existense of a particle stable hydrogen isotope with $A \geqslant 4$. At the same time it has been shown experimentally that quasistationary states exist in systems consisting of one proton and 3 or 5 neutrons (^{4}H and ^{6}H) /9/. The energy spectrum of ^{16}O is shown in fig. 4. Here ^{16}O is the complementary partner of ^{6}H in the exit channel of the ^{11}B + ^{9}Be reaction studied in ref. /9/. The absence of any events of energies higher than 79.3 MeV (which corresponds to the formation of the ^{4}H system with zero excitation energy with respect to the ^{3}H + n break-up) indicates the non-existence of any bound states in ^{4}H. The full line in the figure represents the sum of phase space contributions from different multi-body exit channels taking into account all possible decay modes of ^{4}H. The difference between the experimental points and the phase space distribution resulted in a peak which lies at an energy of about 3.5 ± 0.5 MeV above the ^{3}H + n mass and its width is about 1 MeV. The existence of this peak can be explained by the n-T interaction in the final state. As can be seen from fig. 4, the possible existence of a second resonant state in ^{4}H at about 5 MeV cannot be excluded.

Up till now no evidence for a bound or unbound state of ^{5}H has been reported.

A quasistationary state at 2.6 ± 0.5 MeV having a width $\Gamma \approx 1.8$ MeV has been observed for ^{6}H in heavy-ion-induced reactions /9,10/.

Experiments carried out in order to search for a quasistationary state in the ^{7}H system have not given any positive results.

The discovery of the quasistationary state of ^{6}H is of great interest because it is for the first time that a nuclear system with such a big neutron to proton ratio, N/Z = 5, has been observed. Another very important result is that ^{6}H is more bound than the ^{4}H system: experiments give -2.7 MeV and -3.5 MeV for single neutron separation energies of ^{6}H and ^{4}H, respectively. In this sense the ^{4}H and ^{6}H systems behave similarly as the pairs ^{5}He - ^{7}He and ^{6}He - ^{8}He, for which an extra binding trend is observed with the addition of two more neutrons ("the helium anomaly").

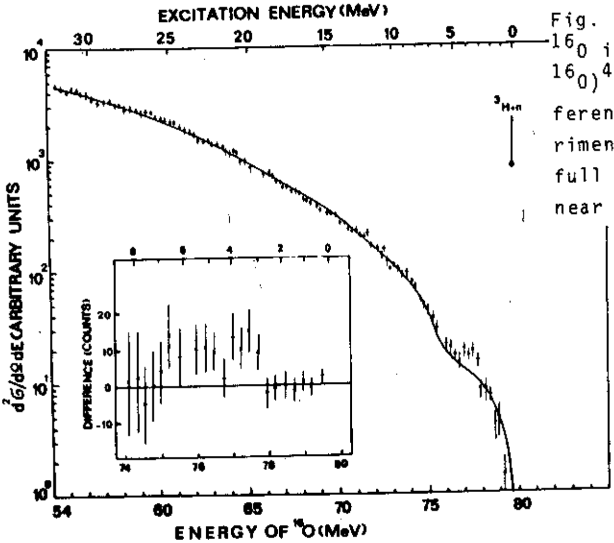


Fig. 4. Energy spectrum of ^{16}O ions from the $^9Be(^{11}B, ^{16}O)^4H$ reaction. The difference between the experimental points and the full line is shown on linear scale in the inset

The results of ref. /9,10/ make it necessary to look in a new way at the problem of the existence of unbound nuclear systems. Up till now it was believed that nuclei with an even number of neutrons are more stable than those with an odd number of neutrons. In the hydrogen isotopes we come to a situation when the isotopes ^4H and ^6H having an odd number of neutrons exist in a quasistationary state. At the same time ^5H and ^7H, while having an even number of neutrons, seem not to exist at all, although it cannot be completely ruled out that they might have binding energies close to zero which exceed those of ^4H and ^6H. A quantitative explanation of this is given in ref. /6/, where the role of the centrifugal barrier is considered. In the case of an even number of neutrons the latter couple and the orbital momentum of the pairs with respect to the rest may be $L = 0$. This can possibly lead, depending on the efficiency of the coupling, to an increase of the transition probability of the centrifugal barrier and, hence, to the increase in the decay width. Thus, even though the decay energy might not be large, particle unstable nuclei with an even number of neutrons may not exist. On the other hand, in the case of nuclei having an unpaired neutron in a state with $L \neq 0$, this neutron must overcome the centrifugal barrier what leads to a finite value of Γ. Obviously this fact may be responsible for the existence of the quasistationary ^4H and ^6H systems. Therefore of principal importance is the search for ^7H.

Much experimental and theoretical work has been devoted to the search for particle stable or quasistationary systems of two, three, four and more neutrons.

It has been shown that the dineutron system is unbound. This also follows from the hypothesis of the charge invariance of nuclear forces. As it has been shown in the work of A.Baz et al.[1], if the tetraneutron (^4n) is stable, then heavier multineutron systems have a high probability to exist too, and even neutron droplets might be expected to be stable. Moreover, it was also shown that despite an eventual non-existence of the tetraneutron, it is quite probable that heavier multineutron systems would exist because the surface tension would lead to a critical size of a "neutron droplet" much larger than that of the tetraneutron. The latest theoretical predictions on the subject of the stability of ^3n and ^4n are quite controversary: from complete absence of resonant states in these systems to the possible existence of a stable tetraneutron.

In order to synthesize the tetraneutron experimentalists have tried many reaction types. Application has been made of nuclear fission with deuterons, thermal and fast neutrons, of fragmentation reactions, of charge exchange reactions, of light nuclei break-up after pion capture. Use has been made also of reactions induced by ^3He and ^4He, the reactions $T(\pi^-,\gamma)$ and $^4He(\gamma, 2\pi^+)$. Multineutrons have been detected either by a time-of-flight method or by means of induced activity with a consequent radiochemical separation of the decay products of nuclei having captured the multineutrons. Only the authors of ref. /11/, where the activation approach has been used, claim to have observed stable multineutrons. It must be, however, noted that such experiments demand a target of high purity and a very severe account of different furtuitious events. It seems that an unambiguous answer to the question of multineutron stability can be reached in experiments involving the measurement of the energy spectrum of the complementary product. In this case, not only a conclusion about the **system's stability can be** drawn, but also about the system's mass.

In ref. /12/ experiments are described in which with high sensitivity the energy spectra of oxygen isotopes were measured in the binary reaction $^7Li(^{11}B,^{15,14}O)^{3,4}n$. The aim of these experiments had been to study the ^3n and ^4n systems. The oxygen energy spectra are shown in fig. 5. The dashed line in fig. 5a represents the phase space distribution corresponding to a five-body break-up in the exit channel, viz. $^7Li + ^{11}B \longrightarrow ^{14}O + n + n + n + n$. The full line in fig. 5b corresponds to the four-body phase space for the reaction $^7Li + ^{11}B \longrightarrow ^{15}O + n + n + n$. By comparing the calculated phase space and the experimental points it is seen that in the region of zero neutron binding energy in the ^4n system about 6 events can be considered. However, because of low statistics no definite conclusions concerning the nature of these events has been offerred.

The existence of the stable tetraneutron and its properties can be connected with the resonance T = 2 in a system of four nucleons. For this reason many experiments have been carried out to search for a T=2 state in the nuclei ^{4}He, ^{4}Li. The interaction in the p + ^{3}He system has been studied too.

All attempts to find a T = 2 resonance in a system of four nucleons have been unsuccessful so far.

Nevertheless the interest in the stability of multineutron nuclei remains very high. A great lot of theoretical work still predicts the stability of very neutron-rich nuclei (in particular, the magic nucleus ^{8}n) and even the existence of neutron droplets. These questions do not concern nuclear physics alone, but also have an astrophysical aspect. That is why further experimental and theoretical work in this field is still necessary.

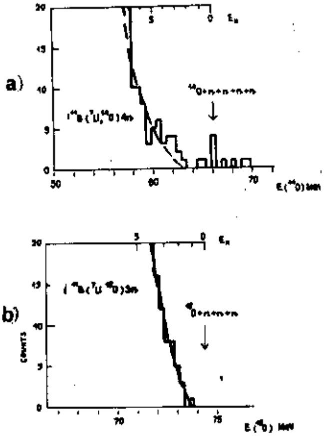


Fig. 5. Energy spectra of ^{15}O and ^{14}O produced in the bombardment of a ^{7}Li target by ^{11}B ions

This problem could be dealt with from a different point of view. It is enough to recall that very neutron-rich light nuclei (such as ^{17}B, ^{29}F, ^{26}O etc.) could after β-decay emit clusters or a few neutrons (see fig. 6). The first experiments induced by heavy ions of energies up to 100 MeV/nucleon have shown that projectile fragmentation reactions are an efficient tool for the production of new very neutron-rich light nuclei (fig. 7). The probability of producing isotopes with masses close to the projectile mass was shown to be dependent on the N/Z ratio of the projectile. In such a case very perspective seemed to be ^{48}Ca beams. The first results on the synthesis of neutron-rich nuclei in ^{48}Ca-induced reactions were obtained at the BEVALAC (USA). As the intensity of the ^{48}Ca beams delivered in GANIL is much higher, about two orders of magnitude larger yields could be expected there.

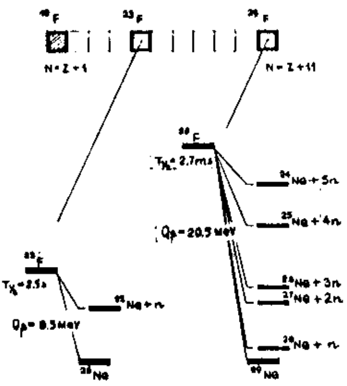


Fig. 6. Decay schemes of ^{23}F and ^{29}F

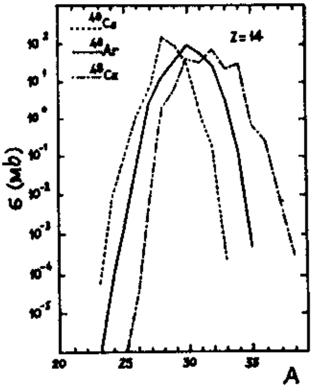


Fig. 7. Isotopic distribution of Z=14 nuclei in ^{40}Ca-, ^{40}Ar- and ^{48}Ca-induced reactions at about 50 MeV/nucleon

In order to synthesize new neutron-rich light nuclei an experiment was performed by a collaboration Dubna - GANIL using accelerated ^{48}Ca ions with an energy of about 50 MeV/nucleon /13/. The results of this experiment are presented with the help of a N-Z diagram shown in fig.8 Twenty five new isotopes have been synthesized, including the heaviest stable isotopes for some elements ^{29}F, ^{24}O, ^{32}Ne. Some other neutron-rich light nuclei have been obtained with rather high probability which

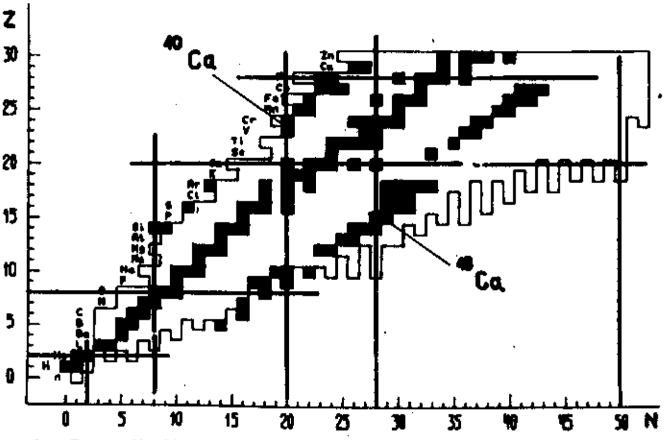


Fig. 8. Z vs N diagram for light nuclei. The black squares represent nuclei discovered in ^{48}Ca- and ^{40}Ca-induced reactions studied at GANIL

allowed to study their characteristics such as mass excess and half-life. The neutron decay of these nuclei was studied with the experimental set-up shown in fig. 9. Earlier neutron multiplicity measurements were carried out for the decay of ^{17}B /14/. The obtained data showed that ^{17}B can decay by the emission of 1,2,3 or 4 neutrons with probabilities $P_{1n} = 62$, $P_{2n} = 0.11$, $P_{3n} = 0.33$, $P_{4n} = 0.004$ (see fig. 10). Thus, an unambiguous answer to the question whether multineutron systems exist or not could be given in correlation measurements, where neutrons are detected after the β-decay of the neutron-rich light nuclei. Such correlation experiments are planned in Dubna and in GANIL with the help of a 4π-neutron detector consisting of 200 ^{3}He-counters. Such a system would allow to register any correlation between the emitted neutrons. Another way of solving this problem is to measure the recoil energy of the residual nucleus after neutron emission. The recoil energy E_x of a neutron decaying nucleus should be proportional to the one neutron separation energy E_s. Therefore the recoil energy after the emission of x-neutrons by the ^{17}B nucleus is equal to

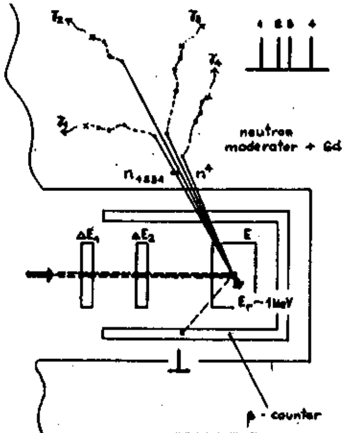
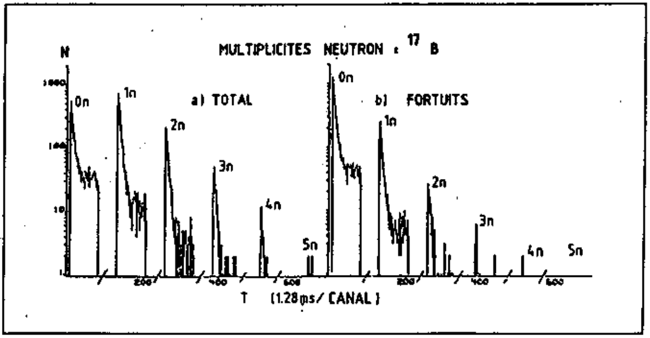


Fig. 9. A schematic presentation of an experimental set-up for the study of delayed neutron emission and measurement of neutron multiplicity in the decay of exotic nuclei

Fig. 10. Measured β-activities of ^{17}B /14/



$E_x \approx \frac{x}{17-x} E_s$. In the case of isotropic neutron emission from a loosely bound system the recoil energy is less than 0.1 MeV. At a production rate of ^{17}B about 0.4 nuclei per second and at a 4-neutron emission probability $P_{4n} = 4\times10^{-3}$, it is possible to detect about 300 events per 48 hours corresponding to 4n-emission and much more 2n- and 3n-events at the same time. It is expected that such experiments may let us know do multineutron systems exist or not. Obviously it is most important to produce at first the β-decaying nuclei with sufficiently large cross section.

References

1. A.I.Baz, V.I.Goldansky, V.Z.Goldberg, Ya.B.Zeldovich, In:Light and Medium Heavy Nuclei Close to the Border of Nuclear Stability (in Russian), Nauka, Moscow (1972).
2. A.I.Baz, V.F.Demin, M.V.Zhukov, Yad. Fiz. 9, p. 1184 (1969).
3. Yu.A.Batusov et al. Yad. Fiz., 28, p. 459 (1978).
4. Ya.B.Zeldovich, ZhETF 38, 1123 (1960).
5. H.Nann. Atomic masses and fundamental constants 6, p. 51, Plenum Press, New York and London (1979).
6. A.A.Ogloblin, Yu.E.Penionzhkevich. Treatise on Heavy-Ion Science, v.8, p. 261, Plenum Press, New York and London (1989).
7. K.Seth. Proc. 4th Int. Conf. on Nucl. Far From Stability, p. 655 (1981).
8. A.V.Belozyorov et al. Preprint JINR (Dubna) P7-86-322 (1986).
9. A.V.Belozyorov et al. Nucl. Phys. A460, p. 352 (1986).
10. D.B.Aleksandrov et al. Yad. Fiz. 39, p. 513 (1984).
11. V.A.Ageev et al. Preprint KINR-85-4 (Kiev) (1985).
12. A.V.Belozyorov et al. Nucl. Phys. A477, p. 131 (1988).
13. D.Guillemaud-Mueller, Yu.E.Penionzhkevich et al. Preprint GANIL 88-14 (1988).
14. J.P.Dufour et al. Contributed papers, Third Intern. Conf. on Nucleus Nucleus Collisions, p. 26, Saint-Malo, France (1988).

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