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Multineutron clusters

Perspectives to create nuclei 100% neutron-rich

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Abstract. A new approach to the production and detection of multineutrons, based on breakup reactions of beams of very neutron-rich nuclei, is presented. The first application of this technique to the breakup of ^{14}Be into ^{10}Be and 4n revealed 6 events consistent with the formation of a bound tetraneutron. The description of these data by means of an unbound-tetraneutron resonance is also discussed. The experiments that have been undertaken at GANIL in order to confirm this observation with ^{12,14}Be and ^{8}He beams are presented. Details and illustrations related to this contribution can be found in the conference page at `https://www.phy.ornl.gov/enam04/WebTalks/Mo-1.html`.

PACS. 21.45.+v Few-body systems – 25.10.+s Nuclear reactions involving few-nucleon systems – 21.10.Gv Mass and neutron distributions

1 Introduction

Stable systems formed by few nucleons, such as ^{3}H and ^{3,4}He, have long played a fundamental role in testing nuclear models and the underlying N-N interaction. Their ground states, however, do not appear to be particularly sensitive to the form of the interaction. New perspectives should be provided by light nuclei exhibiting very asymmetric N/Z ratios. For example, among the $N = 4$ isotones one finds the two-neutron halo structure around the α-particle in ^{6}He, or the ground state of ^{5}H observed as a relatively narrow, low-lying resonance. Concerning the lightest isotone, ^{4}n, nothing is known.

The existence of neutral nuclei has been a long-standing question in nuclear physics. Over the last forty years very different techniques have been employed in various laboratories for the search of multineutrons, mainly ^{3,4}n, without success [1]. All the techniques consisted of two stages, the formation and the detection of the multineutron, and the negative results were always interpreted as due to the extremely low cross-section of the reaction used to form the multineutron. Theoretically, *ab initio* calculations [2] suggest that neutral nuclei are unbound. However, the uncertainties in many-body forces, the already relatively poor knowledge of the two-body n-n interaction, and in general the lack of predictive power of these calculations, do not exclude the possible existence of a very weakly bound ^{4}n.

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2 New experimental approach

We have recently proposed a new approach to the production and detection of multineutron clusters [1]. The technique is based on the breakup of energetic beams of very neutron-rich nuclei and the subsequent detection of the liberated multineutron cluster in liquid scintillator modules. The detection in the scintillator is accomplished via the measurement of the energy of the recoiling proton ($E_{\rm p}$). This is then compared with the energy derived from the flight time ($E_{\rm n}$), possible multineutron events being associated with values of $E_{\rm p} > E_{\rm n}$.

In light neutron-rich nuclei, components of the wave function in which the neutrons present a cluster-like configuration may be expected to appear [3]. Owing to pairing and the confining effects of any underlying α-clustering on the protons, the most promising candidates may be the dripline isotopes of helium and beryllium, ^{8}He ($S_{4\rm n}$ = 3.1 MeV) and ^{14}Be ($S_{4\rm n}$ = 5.0 MeV). As breakup reactions present realtively high cross-sections (typically $\sim$ 100 mb), even only a small component of the wave function corresponding to a multineutron cluster could result in a measurable yield with a moderate secondary beam intensity. Furthermore, the different backgrounds encountered in previous experiments are obviated in direct breakup.

The method has been applied to data from the breakup of ^{11}Li, ^{14}Be and ^{15}B beams. In the case of ^{14}Be, some 6 events have been observed with characteristics consistent with the production and detection of a multineutron cluster, most probably in the channel ^{10}Be + ^{4}n (fig. 1). Special care was taken to estimate the effects of pileup; that

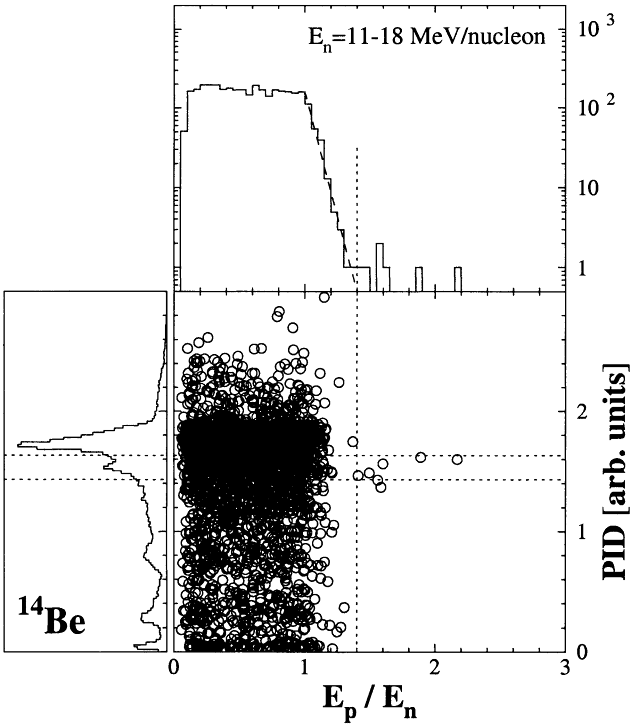

Fig. 1. Scatter plot, and the projections onto both axes, of the particle identification parameter *versus* $E_\mathrm{p}/E_\mathrm{n}$ for the data from the reaction C(^{14}Be, $X+\mathrm{n}$). The PID has been projected for all neutron energies. The dotted lines correspond to $E_\mathrm{p}/E_\mathrm{n} = 1.4$ and to the region centred on the ^{10}Be peak [1].

is the detection for a breakup event of more than one neutron in the same module. Three independent approaches were applied and it was concluded that at most pileup may account for some 10% of the observed signal. The most probable scenario was concluded to be the formation of a bound tetraneutron in coincidence with ^{10}Be [1].

3 Energy of the tetraneutron state

Following the publication of [1], many theoretical papers have investigated the conditions needed for the binding of a four-neutron system [2]. The overall conclusion is that the present knowledge on the n-n interaction and the physics of few-body systems do not predict a bound ^{4}n. Interestingly, however, the calculations of Pieper suggested that it may be possible for the tetraneutron to exist as a relatively low-energy, broad resonance.

In [1], two scenarios were confronted in order to explain the events observed: the scattering of a bound ^{4}n on a proton, and the detection of several neutrons in the same module (pileup). The hypotesis of a bound ^{4}n was found to be consistent with the experimental observations, while the estimates of pileup obtained, mainly through Monte Carlo simulations, were one order of magnitude too low.

If the four neutrons, however, form a resonance at low energy, the decay in flight will lead to four neutrons with very low relative momentum, and one could expect that the probability of some of them to enter the same module may increase. The simulations presented in [1] have therefore been modified in order to include the decay of a ^{4}n resonance [4].

The results of the simulations show the expected increase of the pileup probability towards low resonance energies. For a given resonance energy, the results do not depend much on the width. A significant increase of the pileup probability appears below $E = 2$ MeV, the resonance energy suggested in [2]. A resonance below 2 MeV may, therefore, be consistent with the events observed in [1]. We note that preliminary results of an experiment measuring the α transfer in the reaction ^{8}He(d, ^{6}Li)4n suggest a resonant structure about 2 MeV above threshold [5].

4 Attempts at confirmation

The confirmation of the multineutron candidate events observed with a higher-intensity ^{14}Be beam and an improved charged-particle identification system, and the search for similar events in tyhe breakup of ^{8}He, were proposed to GANIL. Even if the intensity and quality of the ^{8}He beam, delivered by SPIRAL, should be much higher, structural effects may well lead to a stronger ^{4}n component in ^{14}Be g.s. than, say, in ^{8}He. For example, the configuration of the neutrons in a ^{4}n system, $(1s)^2(1p)^2$, is closer to that of the valence neutrons in ^{14}Be than to those in ^{8}He. Therefore, if no events were observed during the ^{8}He run the question whether the tetraneutron exists would remain open.

Unfortunately, several problems concerning the cyclotron lead to null results after two different attempts with ^{14}Be beams, in 2001 and 2002. An analysis of the channel (^{14}Be, ^{8}Be), planned in order to search in parallel for the existence of the hexaneutron, could neither be performed.

On the other hand, some data were acquired with a high-intensity ^{8}He beam from SPIRAL. Preliminary results [6] exhibit the same kind of signal observed in [1], an abnormal number of high-energy proton recoils in the -4n channel with respect to all other channels. Simulations and cross-check analyses are in progress.

The reanalysis of data from a previous experiment on the breakup of ^{12}Be, specially the (^{12}Be, ^{8}Be) channel, was also undertaken [7]. No clear evidence of such events appeared.

5 Conclusion

After four decades of experimental search for multineutrons, or neutral nuclei, the new approach described here has lead to the first observation of events that can, at present, be only explained through the existence of a 4n state. This state could be composed of very weakly bound (neutral) nuclei, as discussed in [1], or a broad low-energy resonance, as discussed in [4]. Following the most complete calculations to date [2], the most likely scenario should be the latter. It would, in addition, explain the preliminary signal observed by [5].

Among the different attempts at confirmation, only the one using an intense ^{8}He beam from SPIRAL was successful. The preliminary results, and the analyses in progress, seem to confirm the existence of the ^{4}n state [6]. A new experiment aiming to study the (^{14}Be*, ^{14}Be + ^{4}n) channel using one-proton knock-out from a more intense ^{15}Be beam will be undertaken at GANIL in 2005.

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