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On the possible detection of ^{4}n events in the breakup of ^{14}Be

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Abstract: In a recent paper —F.M. Marqués *et al.*, Phys. Rev. C **65**, 044006 (2002)— a new approach to the production and detection of free neutron clusters was proposed and applied to data acquired for the breakup of ^{14}Be. Six events that exhibited characteristics consistent with a bound tetraneutron (^{4}n) were observed in coincidence with ^{10}Be fragments. Here, two issues that were not considered in the original paper are addressed: namely the signal expected from a low-energy ^{4}n resonance, and the detection of a bound ^{4}n through proccesses other than elastic scattering by a proton. Searches complementary to the original study are also briefly noted.

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The research, both experimental and theoretical, on free neutron clusters gained renewed interest following our report of events exhibiting characteristics consistent with the detection of a bound $4n$ cluster liberated in the breakup of ^{14}Be [1]. The approach employed was based on the breakup of energetic beams of very neutron-rich nuclei and the subsequent detection of the multineutron cluster in liquid scintillator modules. The identification of such events was made through a comparison of the energy deposited in the modules (E_p), as generated by the interaction of the putative neutron cluster with the protons in the scintillator, with the energy derived from the flight time from the breakup target (E_n). Multineutron cluster events would then be associated with $E_p > E_n$.

As described in Ref. [1], the method was applied to data acquired for the breakup of intermediate energy (30–50 MeV/nucleon) beams of ^{11}Li, ^{14}Be and ^{15}B. In the case of the ^{14}Be beam, some 6 events were found exhibiting the characteristics consistent with the production and detection of a multineutron cluster in coincidence with a ^{10}Be fragment. Much effort was made to estimate the effects of pileup; that is the detection for a breakup event of more than one neutron in the same module. Three independent approaches were used to estimate the rate at which such pileup occurred. It was found that pileup could account for at most some 10% of the observed signal. It was thus suggested that at a level of some 2σ a signal consistent with a bound ^{4}n liberated in coincidence with ^{10}Be had been observed.

Not suprisingly these observations have solicited considerable interest. In particular, a number of theoretical studies were undertaken to investigate the conditions under which a bound $4n$ system is permissable (Ref. [2] and references therein). These studies all concluded that given our present unerstanding of the n-n interaction and the physics associated with few-body systems (specifically the influence of three-body forces), it is impossible to generate a bound $4n$ system. Interestingly, however, the calculations of Pieper [2] suggested that it may be possible for the tetraneutron to exist as a relatively low-energy resonance.

Some interest has also focussed on the detection process employed in the experiment. In particular, Bertulani and Sherrill [3] have explored elastic (^{4}n$, p$) scattering, the process proposed in our original analysis to be the dominant one in the production of the observed events [1]. Using what they considered to be reasonable parameters based on the very weak binding of the putative ^{4}n, Bertulani and Sherrill concluded that the cross-section for backward angle scattering would be far too low to result in recoil protons with energies in excess of that of a single neutron (i.e., $E_p > E_n$).

In the present paper the detection process and the possibility of a resonant ^{4}n are addressed. It is argued that the events observed in the breakup of ^{14}Be may be compatible with a low-energy ^{4}n resonance because of the high probability of two or more neutrons being detected in the same detector module. In the case of a bound ^{4}n, processes other than elastic proton scattering will contribute to the detection of events with $E_p > E_n$.

As outlined above, a crucial step in understanding the

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significance of the events observed in the breakup of ^{14}Be with excess energies deposited in the scintillator modules (owing to the finite experimental resolutions $E_p/E_n > 1.4$) was the estimate of the probability of pileup. In our original report, Monte-Carlo simulations constituted one of the approaches employed [1]. The parameters describing the breakup in the simulations were, as described in Ref. [1], adjusted so as to reproduce for each beam and reaction channel the measured energy, angular and multiplicity distributions of the neutrons, and included contributions from both the projectile and target. The pileup probabilities so obtained leading to events with $E_p/E_n > 1.4$ were in line with the observed rates in the case of the ^{11}Li and ^{15}B beam data. In the case of the (^{14}Be, ^{10}Be) channel, a probability for pileup to occur of about 5×10^{-4} was estimated, whereas the 6 events observed corresponded to a probability of 10^{-2}, a factor ∼20 higher.

Importantly, these simulations did not include the possibility of any correlations occuring between the neutrons. In the light of the suggestion by Pieper [2] that the ^{4}n system might exist as a low-energy resonance, we have reappraised our original estimates to encompass this possibility.

If the ^{4}n system exists as a low-lying resonance*, the decay in flight will lead to four neutrons with very low relative momentum and, consequently, to an increased probability that two or more will be detected in the same module. The simulations have, therefore, been modified in order to include the decay of a ^{4}n resonance. A complete treatment of the decay of such a resonance would require an examination of all possible decay modes: for example, decay via two dineutrons, via a dineutron and two neutrons, etc. Given our lack of knowledge regarding the ground-state structure of the ^{4}n system, such a comprehensive study seems unwarranted.

In the present context, however, whereby we wish to establish whether the signal observed might result from a resonant ^{4}n, an estimate based on four-body phase-space decay is all that is required, as the absence of any final-state interactions between the neutrons will lead to the lowest rate of pileup of any of the decay scenarios.

Simulations have therefore been carried out for a range of values of the energy and width (E, Γ) of the resonance, which was parameterised by a Breit-Wigner lineshape. As in the original work, both the geometric layout and intrinsic detection efficency of the neutron array were taken into account. The simulations display for a wide range of energies and widths the expected increase of the pileup probability at low resonance energies. For a given resonance energy, the results do not depend very strongly on the width. We therefore display in Fig. 1 the results obtained when the width of the resonance is set equal to the resonance energy. We also note that the probability for pileup is not very sensitive to the form of the resonance used to describe the ^{4}n. As is clearly evident in Fig. 1, a significant increase of the pileup probability occurs for $E < 2$ MeV.

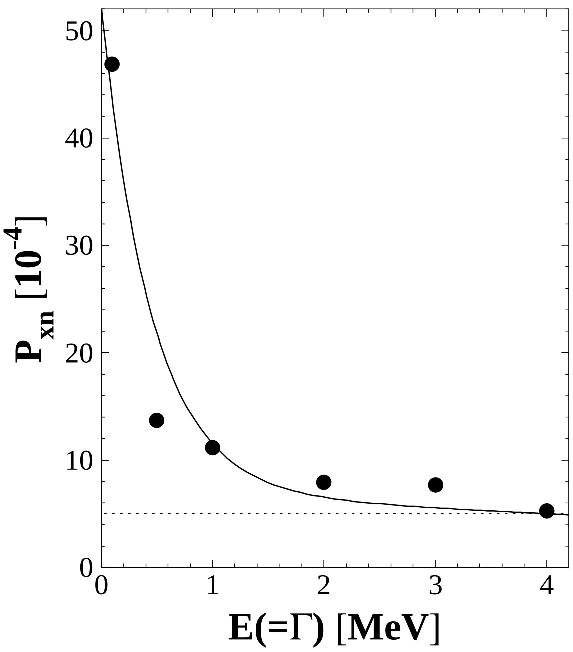

FIG. 1: Pileup probability for different ^{4}n resonance energies obtained from the Monte-Carlo simulations described in the text. Here the width of the resonance has been set equal to the resonance energy (see text). The solid line is shown only as a guide to the eye. The dashed line corresponds to the value obtained from the simulations presented in Ref. [1].

The results presented here should be considered as qualitative. In particular, the effects of a resonance will be reduced by the corresponding spectroscopic factor for the formation of the ^{4}n in the breakup of ^{14}Be. On the other hand, as outline above, the pileup associated with the decay of a resonant ^{4}n would be enhanced by final-state interactions between the neutrons. We conclude, therefore, that the events reported in our original work could be consistent with the existence of the ^{4}n system as a resonance, with an energy of the order of 2 MeV or less above threshold. We note that similar results are obtained even if the resonance is very broad, as suggested in Ref. [2].

The technique proposed in our original paper [1] for the detection of a multineutron cluster liberated in breakup reactions was based on the characteristics of (n,p) scattering, the predominant mechanism for the detection of neutrons in a liquid scintillator. More specifically, the energy recorded in a detector, and attributed to the recoil of a proton (E_p), cannot exceed the energy of the incident neutron as measured by the time-of-flight (E_n). Excluding the complications of pileup, events with $E_p > E_n$ will, in principle, be generated by the scattering of a heavier neutral particle. As described in Ref. [1], charged particles were vetoed out by the zero-degree Si-CsI telescope and lead shields on the entrance windows of the detector modules.

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[*] The reference in our original paper of a resonance referred only to a metastable state of the ^{4}n with a halflife long enough to reach the detector array (∼100 ns).

The calculations undertaken by Bertulani and Sherrill [3] suggest that the cross-section for elastic scattering of a very weakly-bound system, such as a ^{4}n, on a proton would be very forward peaked. The elastic scattering towards backward angles, responsible for high-energy proton recoils, was estimated to be around five orders of magnitude below that of the forward angle scattering. This lead to an integrated $(^4\mathrm{n}, p)$ cross-section at backward angles of only a few μb [3].

In the context of this result, it should be pointed out that another process involving reactions in the scintillator will occur; namely breakup. Indeed, the loss of yield in the elastic scattering channel may be attributed to breakup. In terms of reactions on the protons in the scintillator, it will occur via inelastic scattering or knockout of one of the neutrons. Breakup will, of course, also occur on the carbon component of the organic scintillator[†] via absorption or diffractive dissociation.

In all cases, the breakup of the ^{4}n liberates 4 free neutrons. In the energy range considered in the original work, some 10–20 MeV, the intrinsic detection efficiency for a neutron is $P_n \sim 40\%$. The probability for two or more neutrons to be detected, that is to scatter on protons in the same detector and deposit energies sufficent for them to be observed, is

$$1 - \bar{P}_n^4 - 4P_n\bar{P}_n^3 \ \sim \ 52\%$$

leading, therefore, to a fraction of events with $E_p/E_n > 1.4$ similar to that of the isotropic elastic scattering scenario sketched in Fig. 3 of Ref. [1].

Based on the cross-section for breakup of similarly weakly bound systems, such as ^{11}Li, one may expect that for a bound ^{4}n to be of the order of 1 b or larger. The probability to detect a tetraneutron via breakup in a DEMON module will, therefore, be of the order of ~0.5 b (i.e., 0.52 × 1 b) or more. Given that for energies in the range 10–20 MeV the cross-section for (n, p) is of the order of 0.5 b [4], the probability for detecting a bound tetraneutron via breakup is comparable to that for detection via $(^4\mathrm{n}, p)$ scattering under the original assumption of isotropic scattering.

In conclusion, it has been shown that the events reported in our original paper [1] are consistent with the detection of the ^{4}n system as a weakly bound cluster or a low-energy resonance. In the case of a bound ^{4}n, breakup in the liquid scintillator modules has been identified as the principal detection process. As outlined above this mechanism is expected to lead to a detection probability of the same order or larger than that estimated in Ref. [1] under the assumption of ^{4}n-p elastic scattering.

In the resonant ^{4}n scenario, it has been shown how the in-flight decay of a low-energy resonance into 4 neutrons with low relative momentum increases the probability of two or more of them to be detected in the same module, leading to events with $E_p/E_n > 1.4$. A resonance with an energy of around 2 MeV or less above threshold was shown to be compatible with the events observed in Ref. [1].

In order to discriminate between a bound and resonant ^{4}n we have undertaken a breakup measurement with an intense ^{8}He beam [5]. As outlined in [1], provided that sufficent statistics are acquired, the centre-or-mass α–^{4}n angular distribution should provide a means to discriminate between the bound and unbound scenarios. A complementary technique, which should in principle also be capable of distinguishing between a bound and a resonant ^{4}n, is that of missing-mass-type experiments. In the light of presently available beams, the α transfer reaction $d(^8\mathrm{He}, ^6\mathrm{Li})4n$ proposed by Beaumel *et al.* holds considerable promise [6]. In a similar fashion, inelastic scattering, such as the $p(^8\mathrm{He}, p'\alpha)4n$ reaction, or at higher energies α-knockout, may be employed. Unfortunately, similar studies are very difficult, if not impossible, in the case of ^{14}Be. If, therefore, the spectroscopic factor for the presence of a ^{4}n system is very small in ^{8}He and significant in ^{14}Be, the technique described here and in Ref. [1] may provide the only means to access the tetraneutron.

[†] As well as on the materials making up the entrance window and lead shields of the detector modules.

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