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Search for Bound States of Neutrons and Negative Pions

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An experimental search has been performed for bound systems of neutrons and negative pions, denoted by $(\pi^-)^Z n^N$. Such negatively charged nuclear fragments might be emitted in energetic proton-nucleus collisions. Upper limits for production cross sections of $Z=1$, $N=2$–6 and $Z=2$, $N=3$ systems have been derived by assuming that the lifetime of the bound pion(s) is of the order of that of the free pion or longer.

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The possible existence of bound clusters of neutrons and negative pions has been studied theoretically since 1968.[1-4] The underlying idea is that the π^--n interaction is dominated by the strongly attractive P_{33} (Δ_{33}-formation) force while nuclear absorption of the pion(s) is impossible in the absence of protons. The lifetime of such states would be determined by the decay of the bound pion(s).

One of us[5] has studied the phenomenological aspects of such hypothetical pion-neutron systems, denoted by $(\pi^-)^Z n^N$ with pion number Z and neutron number N.

Since these systems might be favorably produced in relativistic neutron-rich heavy-ion collisions, an intriguing possibility is that "anomalons" (highly reactive nuclear fragments[6]) could be explained in terms of them.[5,7]

If one assumes that pion-neutron clusters with $Z=1$ exist, their lifetime (τ) is expected to be that of the free pion (26 ns) or longer, depending on the binding energy.[8] For $Z>1$ the lifetime will be correspondingly shorter.

Some information on the possible existence of such clusters can be deduced from existing experimental data. Bozzoli *et al.*,[9] for example, have searched for unknown long-lived negatively charged particles produced by 200-GeV protons on a Be target. Since in that experiment $\pi^- n^2$ and $\pi^- n^3$ particles might not have been distinguished from the observed antideuterons and antitritons, upper limits on the production cross section can be deduced from these data. We obtain

$$\frac{d^2\sigma}{dp\, d\Omega} < 2\times 10^{-35}\, \frac{\mathrm{cm}^2}{(\mathrm{MeV}/c)\ \mathrm{sr}}$$

(90% confidence) for both $\pi^- n^2$ and $\pi^- n^3$ assuming $\tau > 26$ ns. Remarkably, two events are reported with the signature of a particle with charge -1 and mass around 4 GeV. The events were not explained by the authors but could fit into the pion-neutron cluster scenario as candidates for the $\pi^- n^4$ system with a production cross section of

$$\frac{d^2\sigma}{dp\, d\Omega} = 10^{-36}\, \frac{\mathrm{cm}^2}{(\mathrm{MeV}/c)\ \mathrm{sr}}$$

($\tau = 26$ ns).

If pion-neutron bound states do exist, their isospin mirror partners could be long lived as well, provided that Coulomb repulsion does not remove the binding. Kyle and Ingram [10] searched for a bound $\pi^+ p^2$ state in the reaction $\pi^+ + d \rightarrow \pi^- +$ anything at 240 MeV π^+ energy. Their preliminary result[10] is

$$\frac{d^2\sigma}{dp\, d\Omega} < 2\times 10^{-33}\, \frac{\mathrm{cm}^2}{(\mathrm{MeV}/c)\ \mathrm{sr}},$$

independent of the lifetime.

In this Letter we report on a specific search for pion-neutron clusters at the Swiss Institute for Nuclear Research. The 590-MeV, 120-μA proton beam from the ring cyclotron, mainly used for pion production, traversed a 3-mm-thick Be target. The secondary-particle beam channel πM3 (extraction angle 22.5°, solid-angle acceptance 4 msr, momentum acceptance $\Delta p/p = 6\%$ full width at half maximum, and length 15 m) was tuned for negatively charged particles with a momentum centered at 580 MeV/c. For the given proton energy pion production is kinematically forbidden at this momentum. Only an extremely low flux of electrons arising from pion (muon) decays in the first part of the channel should be expected.

In Table I we present the total energy above threshold for production of $(\pi^-)^Z n^N$ with various N and Z, for the kinematical conditions of our experiment. Clearly the larger positive values indicate a more favorable final-state phase-space volume. The negative values specify the binding energy necessary to allow passage through the channel (at 580 MeV/c). If one assumes that the binding energy is less than 46 MeV the present search is thus restricted to the cases $Z = 1$, $N < 6$ and $Z = 2$, $N = 3$.

TABLE I. Total energy above threshold in the present experiment available for $(\pi^-)^Z n^N$ production at zero binding energy.

N \ Z	1	2
2	+307	−46
3	+306	+26
4	+305	−70
5	+166	−183
6	+22	
7	−129	
8	−290	

The detection system positioned just behind the channel exit consisted of two XY wire chambers (W1 and W2) followed by a stack of six plastic scintillators (S1, 1 mm; S2, 5 mm; and E1–E4, each of 15 mm thickness) functioning as a range telescope. The trigger for data readout required signals in W1, W2, S1, and S2. The detection system was calibrated with channel settings for positive particles (e^+, π^+, p, d, t, ^{3}He, and α) at various momenta.

The effective measuring time for the actual search was 90 h, corresponding to an integrated proton beam charge of 37 ± 2 C. The largest contribution to the trigger rate ($\sim 0.3\ \mathrm{s}^{-1}$) was due to low-energetic particles with a homogeneous distribution over the wire chambers.

To restrict the analysis to particles which traversed the beam line with the correct momentum, only those events with wire-chamber tracks aligned parallel to the channel axis within 6 mrad were selected. The events (5% of the triggers) contained mainly minimum-ionizing particles (presumably electrons from pion decays) concentrated in a central spot of 20 cm^2 around the beam axis. Since the spot was similar to the one observed for positive particles we assumed the same focal distribution for $(\pi^-)^Z n^N$ particles. For the final analysis those events were selected which had tracks within the focal spot and which had energy-loss signals in S1 and S2 above minimum ionization. The surviving events were classified according to the last scintillator in the range telescope which produced a signal.

Figure 1 shows two-dimensional ΔE-E distribu-

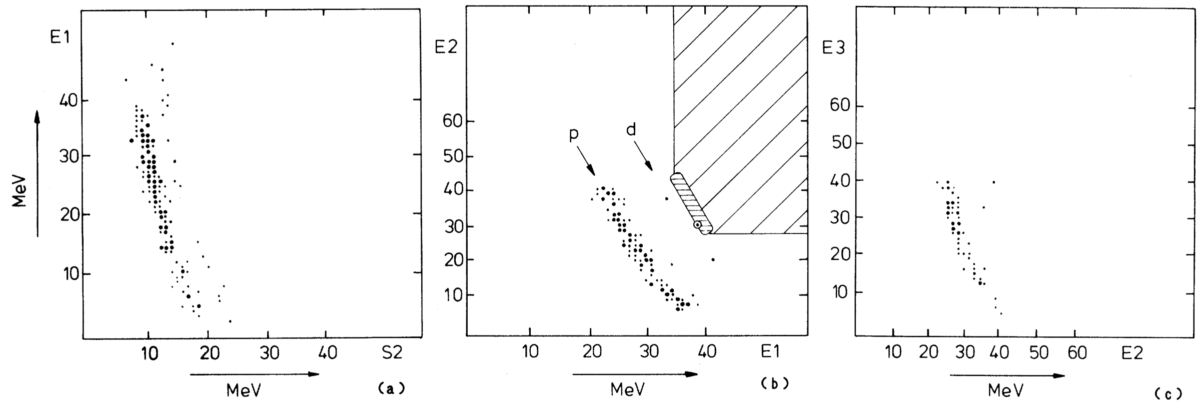

FIG. 1. Two-dimensional energy distributions of the events satisfying various selection criteria. The energy E deposited in the last responding scintillator is plotted vertically vs the energy ΔE deposited in the previous detector: (a) energy in E1 vs ΔE in S2; (b) energy in E2 vs ΔE in E1; (c) energy in E3 vs ΔE in E2. The events concentrated in bands are interpreted as protons and deuterons which traversed the channel (tuned for negative particles) through scattering. The hatched regions indicate where $\pi^- n^2$ events might be expected. One event, almost certainly a deuteron, but on the edge of compatibility with $\pi^- n^2$ has been encircled.

tions of the energies deposited in the last two responding scintillators for particles stopping in E1, E2, and E3. On the basis of a comparison with the calibration run using positively charged particles, all events in the ΔE-E plots can be explained as protons and deuterons that reached the detector through several scatterings inside the channel. The probability of negative ions (H_2^-, D^-, etc.) giving a signature resembling that of a $\pi^- n^2$ has been estimated to be negligible.

A pion-neutron cluster entering the detection setup would either react in flight or be captured at the end of its range into a pseudoatomic orbit. In the latter case it would undergo an electromagnetic cascade until a nuclear interaction takes place with the target nucleus normally followed by absorption of the π^-('s). Subsequent secondary particles would then be emitted (star formation), some of which not only deposit additional energy in the stopping scintillator but can reach neighboring scintillators as well, thereby modifying the signature.

The horizontally hatched region in Fig. 1(b) indicates where $\pi^- n^2$ events are expected to show up for zero binding energy and for a 3% momentum spread of the beam. As a result of star formation, events may also be expected at higher E1 and E2 values, as indicated by the diagonal hatching. At most one event (circled) on the edge of consistency with $\pi^- n^2$ [Fig. 1(b)], most probably a scattered deuteron, has been observed. However, if the downstream counter E3 were triggered by a secondary particle from a "star," the corresponding event would appear in Fig. 1(c) with the E2 signal above 28 MeV. All events satisfying the latter condition can be ruled out as $\pi^- n^2$ because of the energy loss in the counter E1.

Because of their lower range at identical momentum, heavier pion-neutron systems could have shown up in Fig. 1(a). Applying similar selection criteria as for the $\pi^- n^2$ case discussed above, we observed no candidates. Upper limits on $(\pi^-)^Z n^N$ production can then be derived depending on the mass, charge, and assumed lifetime. This is shown in Fig. 2 for the case $Z = 1$. Clearly the sensitivity of the experiment rapidly decreases for (a) lifetimes shorter than that of the free pion (e.g., for increasing pion number) and (b) increasing mass (neutron number). In both cases the length of the channel

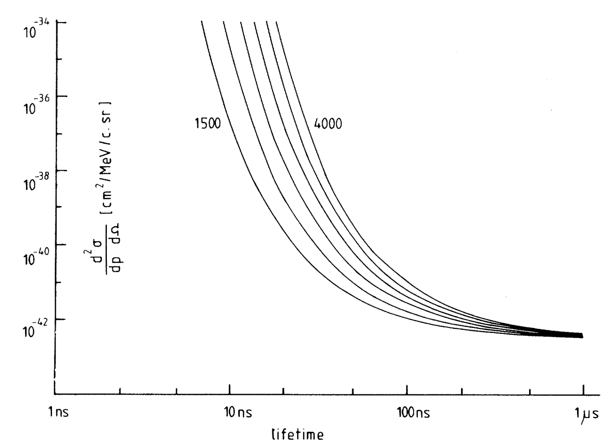

FIG. 2. Upper limits (90% confidence) of production cross sections for $\pi^- n^N$ as a function of lifetime for masses between 1500 and 4000 MeV/c^2 in 500-MeV/c^2 steps.

TABLE II. Upper limits on the differential cross section for $(\pi^-)^Z n^N$ production with the assumption of the lifetime larger than 26 ns.

Z	N	$\frac{d^2\sigma}{dp\,d\Omega}$ [cm^2/(MeV/c)·sr]
1	2	6.1×10^{-40}
1	3	1.4×10^{-38}
1	4	3.2×10^{-37}
1	5	6.8×10^{-36}
1	6	1.5×10^{-34}
2	3	2.2×10^{-38}

becomes increasingly unfavorable in comparison with the expected decay length. A summary of deduced upper limits of the differential production cross sections for all cases of Z and N investigated and $\tau > 26$ ns is given in Table II. The values for $Z=1$, $N=2$ and 3 are, respectively, five and three orders of magnitude lower than upper limits derived from Bozzoli *et al.*[9]

In the absence of a theoretical model for $(\pi^-)^Z n^N$ production we obtain a "naive" order of magnitude estimate for the cross section as follows. We conjecture that any $\pi^- n^2$ is produced by coalescence of a π^- and a correlated neutron pair (n^2) in a similar way that a triton (t) can be thought of as being formed by an incoming proton (p) and n^2. One might then expect for the cross section σ at comparable momenta

$$\sigma(\pi^-)/\sigma(\pi^- n^2) \cong \sigma(p)/\sigma(t).$$

In the calibration run with positive particles of 580 MeV/c we obtained

$$\sigma(p):\sigma(d):\sigma(t): \cong 1:0.04:0.0023.$$

From these numbers we deduced that the probability for a $\pi^- n^2$ to pick up additional neutrons in the target nucleus (leading to heavier clusters) can be estimated as roughly 4% per neutron. Pion production cross sections have been measured under similar conditions as in our experiment.[11] The cross section for the production of such π^-('s) which can form bound pion-neutron systems is typically 2 μb/(MeV/c)·sr, With use of this value the estimated cross sections for $\pi^- n^2$, $\pi^- n^3$, and $\pi^- n^4$'s are $\sim 5\times10^{-33}$, $\sim 2\times10^{-34}$, and $\sim 8\times10^{-36}$ cm^2/(MeV/c)·sr, respectively, under the assumption that these systems are bound by a few megaelectronvolts. Our experimental upper limits from Table II are several orders of magnitude lower than the above estimates.

In conclusion, our data make it highly unlikely that long-lived ($\tau > 26$ ns) $\pi^- n^2$ and $\pi^- n^3$ clusters exist. In view of the large difference in incident proton energy, our result for the $\pi^- n^4$ cross section cannot be considered to contradict our $\pi^- n^4$ conjecture concerning the two events observed by Bozzoli *et al.*

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