Search for pion-neutron bound states in 14.6*A* GeV Si + nucleus collisions

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We have conducted a search for bound states of a negative pion and a number of neutrons (pineuts) using the E814 spectrometer. A beam of ^{28}Si at a momentum of 14.6*A* GeV/*c* was used to bombard targets of Al, Cu, Sn, and Pb. We describe our experimental technique, present measured upper limits for pineut production, and discuss the significance of our results.

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I. INTRODUCTION

There have been several speculations about the existence of pineuts. These are bound systems of pions and a number of neutrons [1–6]. For example, as a consequence of the attractive π-N interaction a π^-2n bound state would have a mass of around 2019 MeV and could only decay via weak interactions, since there is no negatively charged nucleon. The lifetime of such an object would be of the order of that of a charged π, namely, $\approx 2.6\times 10^{-8}$ s. The charge reflected forms of such states (for example π^+2p) would be unbound because of Coulomb forces, and members of this family would be susceptible to decay into nucleons. The detection and study of such relatively simple pion-nucleon states would allow us to further our understanding of the nuclear force. Experimental searches for pineuts produced in various reactions involving light ions have yielded negative results [7–10]. Heavy ion collisions, we believe, provide a unique environment for the production of pineuts. In contrast to light ion collisions, pions are produced rather copiously during the collision process, and these can then combine with the neutrons present in the projectile and target nuclei to form pineuts. Recently, a search was conducted at the Lawrence Berkeley Laboratory using ^{40}Ar and ^{139}La projectiles at kinetic energies of 1.8*A* GeV and 1.3*A* GeV, respectively, incident on targets of ^{238}U. Five pineut candidates were found, and subsequently dismissed due to inconsistencies in the events containing the candidates [11]. Also, after our experiment was performed, a search was conducted for π^-2n and π^-3n bound states at RIKEN using ^{18}O + Be interactions at a kinetic energy of 100*A* MeV [12]. No candidates were found. A new calculation using a coalescence model [13] predicts that pineuts, should they exist, would be produced at detectable levels in high energy heavy ion interactions.

We have conducted a search for pineuts in relativistic collisions between 14.6*A* GeV ^{28}Si projectiles and targets of Pb, Sn, Cu, and Al. We used the E814 apparatus at the Brookhaven National Laboratory Alternating Gradient Synchrotron facility. While the advantages associated with heavy ions are common to the search described here and those conducted previously [11,12], the major difference is the projectile energy. The E814 experiment, like the RIKEN measurement, has the ability to detect pineuts at beam rapidity whereas the Bevelac search concentrated on pineuts produced at mid and target rapidities.

II. THE MEASUREMENT

Experiment 814 was designed to study the characteristics of relativistic heavy ion collisions at beam energies of 10–15*A* GeV. The apparatus is described in detail elsewhere [14] and consists of nearly 4π calorimetric coverage around the target, and a magnetic spectrometer that identifies charged particles originating from the target and entering the spectrometer aperture which is centered on the beam axis, and extends 37.6 mrad in the magnetic bend plane and 24.1 mrad perpendicular to it. Data were taken during two periods, in 1989 and 1990, using slightly different detector arrangements. The spectrometer shown in plane view in Fig. 1

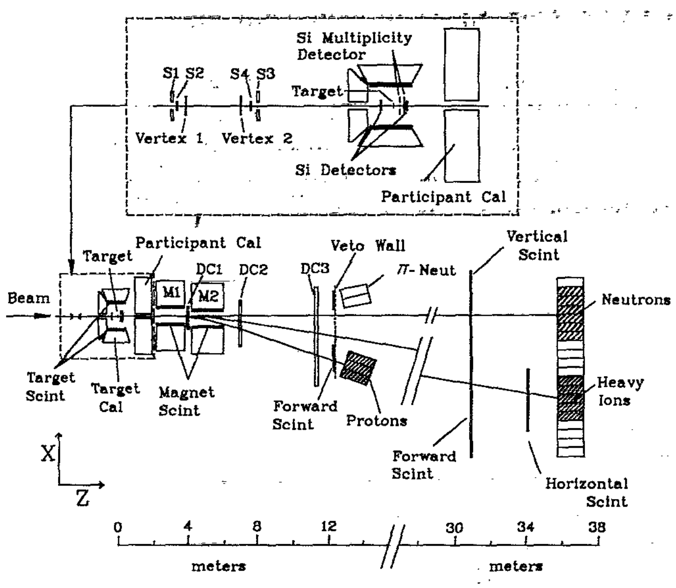

FIG. 1. Schematic plane view of the E814 spectrometer. The apparatus is described in detail in Ref. [14].

contains three tracking chambers, labelled DC1, DC2, and DC3. The tracking chambers are located 3.96 m, 6.92 m, and 11.56 m from the target, respectively. DC2 and DC3 contain both drift and cathode pad sections, while DC1 is exclusively a pad detector. The drift sections each contain six wire planes and provide a total of twelve position measurements per track in the magnet bend direction. The single-hit, single-plane position resolution of both drift chambers is 260 μm for minimum ionizing particles. Details of the construction and performance of the tracking chambers in the heavy ion collision environment can be found elsewhere [15,16]. These detectors measure the rigidity of charged particles in the spectrometer with a resolution $\Delta p/p = 1\%$ for protons at beam rapidity. The resolution is dominated by multiple scattering.

The scintillator hodoscopes located behind the drift chambers measure the charges, times of flight, and positions of charged particles. Four BC404 plastic scintillator slats, each of dimension 10 cm $\times$ 0.6 cm $\times$ 1 m and located in front of the calorimeters labelled "pineut" on Fig. 1, are used in the present measurement. They are located $\sim$ 12 m from the target. The scintillation light emitted in each slat is detected at each end by photomultiplier tubes. The ratio of the pulse heights detected by the two tubes is used to determine the vertical positions of the particles, with a resolution of σ_y=3 cm. The particle times of flight are determined with a resolution of 300 ps from an average of the time signals from both phototubes. The pulse height of a minimum ionizing particle traversing these detectors is separated from the noise by more than five standard deviations. Located above and below these scintillators (for the 1990 data taking) were veto walls, also made of scintillating material. They aided in the rejection of downstream interactions. Located behind the scintillator hodoscope is an array of uranium/scintillator calorimeters. It measures the energy of particles striking it with a resolution of $\sigma_E/E = 60\%/\sqrt{E}$, where E is measured in GeV. The calorimeters used in the pineut search consist of two modules, each of dimensions 20 cm $\times$ 120 cm $\times$ 75 cm with phototubes mounted on the rear of the modules. They are located approximately 12 m from the target, and occupy the region from 18.85 cm to 58.55 cm to the left of the beam direction (see Fig. 1) during the 1989 data taking period, and from 26.33 cm to 66.32 cm in the 1990 data taking period. The position resolution of the calorimeter has been measured to be 1.3 cm horizontally and 1.8 cm vertically [17].

In order to reduce the extent of downstream interactions, the large gaps between the detectors in the spectrometer were filled with He bags. Data were measured using targets of natural Al (1.3 g/cm^2), Cu (2.24 g/cm^2), Sn (3.35 g/cm^2), and Pb (4.36 g/cm^2), each with a thickness corresponding to $\sim$ 4% of a ^{28}Si nuclear interaction length. Data were also measured with an empty target frame in order to evaluate the extent of interactions originating from materials other than the target.

The pretrigger implemented for the pineut search required that a minimum energy of $\sim$2 GeV be deposited in the pineut calorimeters. It was augmented by a trigger which required that there be energies in excess of 20 GeV in the same calorimeters. The trigger was satisfied at a rate of about 0.1% of the nuclear interaction rate. It does not place any requirement on the transverse energy (or centrality) of events and therefore does not bias our measurement towards peripheral or central collisions. Owing to the minimum energy requirement at the trigger level, there is some loss of pineut detection efficiency due to energy leakage out of the sides of the calorimeters. We account for this loss in a Monte Carlo calculation of the trigger efficiency. The trigger conditions for 1989 and 1990 were identical.

III. THE ANALYSIS

The pineut candidates we are looking for are tracks with reconstructed momenta in excess of 20 GeV/c, and charge of -1. We estimate fluxes of π^-, K^-, and $\bar{p}$ at these momenta to be less than 10^{-4} per Si+A interaction.[1] It is important to realize at the outset that the trigger is very efficient in selecting events wherein the beam or its fragments interacted with material other than the target. This constitutes the dominant background for the pineut search.

The data analysis procedure described below was optimized to suppress the backgrounds. The results of the procedure are shown in Table I. Events surviving all of the selection criteria would be identified as pineut candidates. While most of the analysis procedures were the same for the 1989 and 1990 data, some differed. This was because several detectors were added in 1990 to improve the efficiency in iden-

[1]The estimate was obtained by using the invariant cross sections measured by experiment E858 [18] at p_t=0 for the three particle species in Si+Au interactions. The cross section was observed to vary exponentially with the center of mass momentum of the particle. We extrapolate their data to a lab momentum of 20 GeV/c. We assume (conservatively) an m_t slope for the spectra of 130 MeV. We then integrate the spectrum to obtain a value for dN/dy at 20 GeV/c. If we assume dy=0.5, we then obtain an upper limit estimate of the particle yields at momenta in excess of 20 GeV/c. The number of π, K^-, and $\bar{p}$ are 4×10^{-5}, 7×10^{-7}, and 7×10^{-7}, respectively.

TABLE I. A list of the cuts applied offline to the pineut data sets of the years 1989 and 1990. We show the number of events for each target that survive the listed cut.

	Target				
Selection criteria	Pb	Sn	Cu	Al	Target frame
Incident beam on target	301×10^6	338×10^6	135×10^6	311×10^6	484×10^6
(1989)	197×10^6	218×10^6		191×10^6	262×10^6
(1990)	104×10^6	120×10^6	135×10^6	120×10^6	222×10^6
Nuclear interactions	12.0×10^6	13.5×10^6	5.4×10^6	12.4×10^6	
Passed pineut trigger	9278	12 104	4092	10 024	15 079
Single beam events	9238	12 001	4081	10 004	15 001
Only one minimum ionizing particle in scintillators	1921	3012	1832	2893	4709
Good track with proper energy and momentum	21	35	25	34	30
Hits in drift chamber regions accessible from target	8	11	10	19	11

tifying and rejecting background.

The analysis cuts are detailed below.

(1) The pulse height of the beam scintillators is examined to see if it is greater than that for a charge 14 particle. If so, then more than one beam particle is probably present in the apparatus and the event is eliminated from the analysis. Only a small fraction of events are rejected by this cut.

(2) We require that there be only one singly charged particle in the four pineut scintillators in front of the trigger calorimeters. This cut assumes that if a pineut is produced, there will be no other negatively charged particles of similar rigidity. Our estimate of the π^-, K^-, and $\bar{p}$ yields shows that we should be rejecting a negligible number of good events on account of other negatively charged particles being produced in interactions at the target. The class of background events rejected by this selection have two or more charged particles plus neutral particles produced in downstream interactions in regions other than the target. About 75% of the events satisfying the pineut trigger are rejected by this cut.

(3) The next stage of the pineut analysis requires that valid tracks be present in the spectrometer, and that at least one of these tracks intersect the trigger calorimeters. These tracks must also have momenta and energies consistent with those expected for pineuts (see Table II). The momenta of the tracks should be within the range acceptable for a pineut in the fragmentation peak [19]. For these momenta, the (kinetic) energy deposits in the calorimeter should agree with the momenta to within $\pm2\sigma_E$, the uncertainties of the calorimeter energy measurements. The background events rejected by this cut typically have one charged particle striking the calorimeter front face, and other particles striking the calorimeter from the side. Only a few tens of events survive this cut. These were all of the π^-2n variety. None of these events were π^-3n or π^-4n candidates.

TABLE II. Rigidity range for pineut candidates, and the corresponding total (trigger × analysis) efficiency for their measurement for the years 1989 and 1990. The last four columns are combined efficiencies for both years taking into account the beam fluxes integrated each year for each target.

Pineut species	Mass (GeV/c^2)	Momentum (GeV/c)	Efficiency (%) 1989	1990	Pb	Sn	Cu	Al
π^-2n	2.0	31.4 ± 2.7	67	64	66	66	64	66
π^-3n	3.0	46.0 ± 3.4	66	52	61	61	52	61
π^-4n	3.9	60.7 ± 3.8	66	<1	42	42	<1	42

(4) In addition to the track that satisfied the pineut trigger, we required that there be no tracks in the regions of the drift chamber that were kinematically inaccessible to negatively charged particles originating from the target. In the 1990 data taking, the candidates were also required to have a hit on DC1. This last cut is again sensitive to the presence of background in those events selected by the pineut trigger.

This series of cuts eliminated all but a handful of events, as shown in Table I. We examined each of the remaining events to establish whether they could be pristine pineut candidates. None of the candidates were unblemished. Some could be rejected by requiring that there be only a single energy cluster in the calorimeter. At this stage, we explored the extent to which our candidates could come from sources other than the target by using data collected with an empty target frame. The target frames contributed very little to the measured real nuclear interaction rate. It is however clear from Table I that the pineut candidates are mostly background events unrelated to the presence of the target.

In order to determine an upper limit on the pineut yield, it is necessary to determine the percentage of pineuts produced that would be detected by the apparatus, assuming that the pineuts are bound with respect to strong decays. A Monte Carlo program was written using the GEANT package [20] to accomplish this by tracking generated pineut particles through the spectrometer. Pineuts are assembled from their ingredients under the assumtion that their binding energy is 5 MeV. In the rest frame of the two or more neutrons, the pion momentum is ~38 MeV. At beam velocities, for example, the momentum of the π^-2n system is increased on account of the π^- by ~2 GeV/c. The longitudinal momentum spread is increased by ~0.5 GeV/c. The simulated pineuts are selected to have rapidities distributed on a Gaussian with a mean of $y_{\rm beam}=3.44$, and width $\sigma_y=0.09$, consistent with

TABLE III. The measured yields and upper limits (90% confidence level) per 10^7 nuclear interactions for the production of pineuts at beam rapidity in Si+A collisions.

Target	π^-2n Per 10^7 interactions	π^-2n	π^-3n Upper limits per 10^7 interactions	π^-4n
Pb	1.5±4.8	9.4	3.1	4.5
Sn	3.6±4.8	11.5	2.8	3.9
Cu	20.3±10.5	37.5	8.2	
Al	14.5±6.4	26.8	3.0	4.4

a nuclear fragmentation model [19]. The transverse momentum distributions are obtained from the same model. The pineuts in the rapidity window 3.35→3.53 are then tracked through the spectrometer using GEANT, and the percentage of pineut tracks intersecting the pineut scintillators and calorimeters are determined. In addition, if a pineut hits a calorimeter module, the total energy deposited in the calorimeter is calculated from a parametrization of the energy shower profile [17]. If the energy deposit in the pineut calorimeters is below 20 GeV, then the trigger would not have detected the pineut and it is not recorded in the acceptance calculation. Pineuts with lifetimes in excess of 2.6×10^{-8} seconds and travelling at beam rapidity ($\gamma=15.6$) would have a decay length in the laboratory of $\beta\gamma c\tau\geq121.68$ m. This distance greatly exceeds the 6.5 m from the target to the exit of the second magnet. Hence only ≈5% of such pineuts would decay in our apparatus. The low efficiency in the 1990 data for the π^-4n channel is on account of the locations of the calorimeter and scintillators for this data taking period.

In the data analysis, there are additional inefficiencies owing to cuts, and the imperfect performance of the detectors. For the 1989 and 1990 data taking periods these were determined to be 81% and 75%, respectively. The overall efficiency for the detection of pineuts for both the 1989 and 1990 data taking periods are listed in Table II.

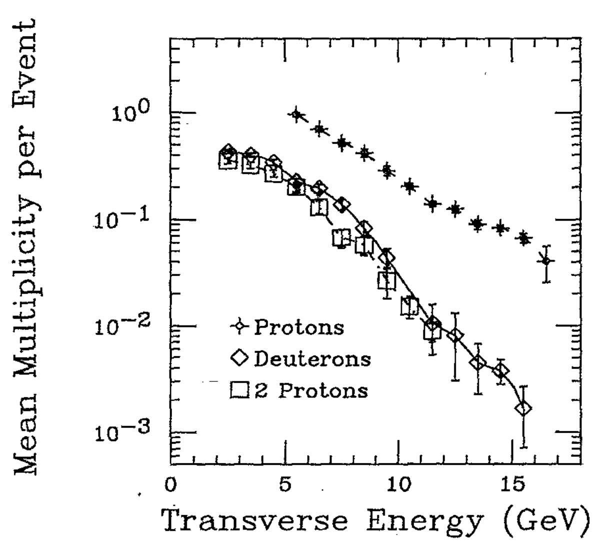

FIG. 2. The multiplicity of two protons and deuterons produced in interactions of Si beams and Pb targets compared with the multiplicity of single protons.

IV. DISCUSSION

The results of this pineut search are summarized in Table III. The pineut yields per nuclear interaction shown in column 2 were obtained using the numbers shown in Table I for the incident beam, and the numbers of pineut candidates for a given target (signal), and for the empty target frame (background). We subtract the background from the signal and divide the result by the number of nuclear interactions sampled, and the overall efficiency for the measurement. Our final results are consistent with our not having observed pineuts. While one could argue for less than 3 standard deviation effects, our previous statement that none of the pineut candidates looked "pristine" leads us to use our data to calculate upper limits for pineut production. Also shown in the table are the 90% confidence level upper limits for pineuts produced per hadronic interaction. For the π^-2n system, we report values which are the means + 1.64 standard deviations. For the π^-3n and π^-4n systems, since no candidates were observed, our limits are based on the assumed detection of 2.3 candidates. The ARC (a relativistic cascade) model [21] has been used recently as input to a dynamical coalescence calculation of pineut abundances [13]. The estimate for π^-2n production in Si+Au collisions within $\pm\sigma_y$ of beam rapidity is $\sim5\times10^{-3}$ per peripheral interaction.

In making comparisons with our data, we will derate predictions for peripheral collisions by a factor 0.7 to account for the fraction of the interaction cross section they represent. Our "predictions" for the π^-3n and π^-4n are evaluated using additional penality factors deduced from the mean multiplicity (per event) of protons, deuterons, and 2 protons. Figure 2 shows the mean multiplicities plotted as a function of transverse energy. These data were measured using the forward spectrometer, and are discussed elsewhere [14,22]. From this figure it is evident that the multiplicity of deuterons is about equal to the multiplicity of two protons (or two neutrons). Let us assume that pineuts are produced only in peripheral collisions. For events with transverse energy E_t less than 5 GeV,[2] the mean multiplicity per event of beam rapidity protons for Si + Pb collisions has been measured by our experiment to be in the range from 1 to 2 [23]. We assume 1.6. The mean multiplicity per event of beam rapidity deuterons is, from Fig. 2, in the range 0.3→0.5. We assume 0.4. Thus the penalty factor for the addition of a neutron to a proton is estimated to be 1.6/0.4 = 4. We assume

[2]We define peripheral events as ones whose transverse energy $E_t<5$ GeV. They correspond to ~70% of the total geometric cross section.

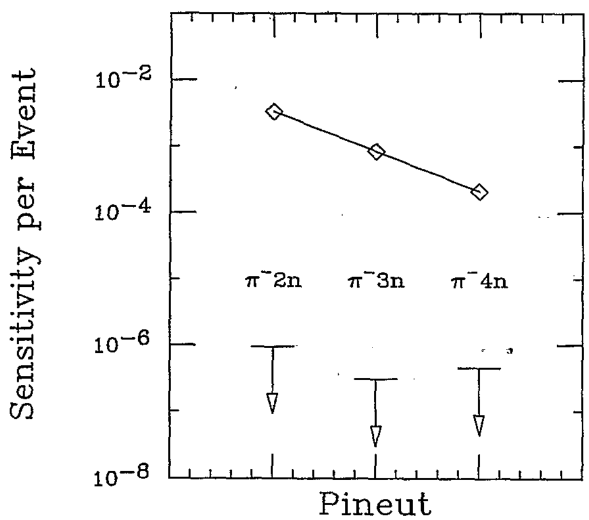

FIG. 3. The measured upper limits (90% confidence limit) for the production of pineuts at beam rapidity in Si+Pb collisions. The limits are shown as horizontal lines. The predictions of the ARC based dynamical coalescence calculations [13] for the π^-2n, and extrapolations to the π^-3n and π^-4n are shown as diamonds.

that 4 and 16 would then be the penalty factors for the addition of one and two neutrons to the π^-2n system. As a point of interest, the penalty factors found in the ARC calculation for the addition of nucleons and pions at midrapidity were 7 and 3, respectively.

The pineut production estimates from ARC are summarized graphically in Fig. 3, and compared with our measurements for Si+Pb collisions. From the figure, it is evident that our measurements represent pineut production upper limits which are several orders of magnitude below their estimated production rates. We conclude therefore that it is rather unlikely that there exist bound states of the pion and two or more neutrons. There could, however, exist resonant states in such systems, as has been discussed recently [24].

V. CONCLUSIONS

We have searched for the production of pineuts in collisions of Si beams with targets of Al, Cu, Sn, and Pb. We consider our results to be consistent with having found no evidence for pineut production at a sensitivity level which is several orders of magnitude lower than pineut abundances predicted by a dynamical coalescence model. Our analysis therefore suggests that such particles are not likely to have pionic lifetimes.

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