Evidence for Dineutrons in Extremely Neutron-Rich Nuclei

Kamal K. Seth and Brett Parker
Northwestern University, Evanston, Illinois 60208
(Received 18 June 1990)

It is shown that the continuum missing-mass spectra for the (π^-,π^+) and (π^-,p) reactions leading to extremely neutron-rich exotic nuclei can be explained in terms of phase-space distributions by invoking the presence of dineutrons as one of the products of the breakup. It is suggested that this indicates the presence of the dineutron as a cluster in these neutron-rich systems during their breakup. It is noted that these observations in weakly *unbound* systems may be analogs of the dineutron halos for which evidence has been found in weakly *bound* nuclei near the neutron drip line.

PACS numbers: 21.60.Gx, 21.10.Gv, 21.40.+d, 25.80.Hp

An interesting new feature of nuclear structure has been suggested recently by the measurements of interaction cross sections of extremely neutron-rich nuclei near the neutron drip line. Tanihata *et al.*[1,2] have used high-energy secondary beams of particle-stable nuclei formed by projectile fragmentation to obtain total interaction cross sections in transmission-type experiments. It was found that the extremely neutron-rich nuclei such as ^{8}He, ^{11}Li, ^{14}Be, and ^{17}B have interaction cross sections which are much larger than those of their neighbors. This was interpreted as indicating abnormally large matter radii for these nuclei. The interaction cross-section measurements were later supplemented by the measurements of narrow momentum distributions for the last pair of neutrons in ^{11}Li and ^{14}Be,[2,3] and by large Coulomb dissociation cross sections.[4] These observations suggest that in these extremely neutron-rich nuclei, with small separation energies of the last two neutrons [$S(2n)=2.14(1)$, 0.25(8), 1.34(11), and 1.49(17) MeV for ^{8}He, ^{11}Li, ^{14}Be, and ^{17}B, respectively], the density distribution of neutrons has a very long tail. This has led Hansen and Jonson[5] to revive an old idea due to Migdal.[6] Migdal suggested that while a dineutron ($S=0$, $T=1$) is known to be unbound (by ~70 keV) by itself, in the field of a nucleus it may act as a bound pair weakly coupled to the nucleus. In other words, the dineutron may exist as a bound system on the nuclear surface, constituting what has been somewhat misleadingly called a neutron "halo." The possibility of the existence of nuclei with halos has aroused great interest and catalyzed a large number of nuclear structure calculations.[7] Since the structure of systems which are slightly *unbound* cannot be very different from those which are weakly *bound*, an obvious extension of the above considerations is to look for signatures of the presence of dineutrons in the decay of unbound systems.

In this Letter we wish to submit evidence for the possible existence of dineutrons in extremely neutron-rich systems which are unbound. The evidence is derived from the analysis of the continuum missing-mass (MM) spectra for the reactions ^{6}Li$(\pi^-,\pi^+)^6$H, ^{9}Be$(\pi^-,p)^8$He, and ^{6}Li$(\pi^-,p)^5$H. These spectra were measured as part of our program to create and study highly neutron-rich light nuclei by means of pion-induced reactions.[8]

The experiments were done at the EPICS facility at LAMPF and have been described in detail elsewhere.[9,10] The ^{6}Li$(\pi^-,\pi^+)^6$H measurements were made[10] at $T(\pi^-)=220$ MeV, $\Theta(\text{lab})=30°$ with an energy resolution FWHM of 0.6 MeV. The ^{9}Be$(\pi^-,p)^8$He and ^{6}Li$(\pi^-,p)^5$He measurements were done[9] at $T(\pi^-)=125$ MeV, $\Theta(\text{lab})=20°$ with an energy resolution FWHM of 1.0 MeV. The measured spectra for the three reactions are shown in Figs. 1, 2, and 3 as functions of the missing mass [MM$\equiv$0 at the ^{3}H$+n+n+n$ threshold for ^{6}H, at the ^{8}He(g.s.) for ^{8}He, and at the ^{3}H$+n+n$ threshold for ^{5}H]. No narrow structures are seen in any of the spectra except for the peak corresponding to ^{8}He(g.s.), indicating that all other systems are unbound.

In the study of exotic nuclei one is generally interested in peaks or structures in cross sections which correspond to relatively long-lived bound and unbound systems. The continuum background, which is closely related to phase space, and on which such peaks may ride, is generally dismissed as being uninteresting. However, as the classic example of β decay illustrates, even when the continuum corresponds to a pure phase-space distribution important physics relating to the number and masses of the final-state particles is contained in these distributions. Because at present there is no satisfactory dynamical theory of pion double-charge-exchange reactions,[10,11] or of pion absorption reactions[12] leading to the continuum, it is only possible to analyze the continuum data for these reactions in terms of phase-space distributions, with the hope that such analysis can provide new insights into the nature of the decaying systems. In this Letter we analyze our continuum missing-mass distributions in terms of phase-space models with just this expectation. The multiparticle phase-space distributions described in this Letter were obtained by Monte Carlo calculations. An extremely fast and accurate new algorithm developed by Block[13] was used. We note that the *shape* of a phase-space distribution is determined by the *number* (ν) of "particles" or "clusters" in the final state and on the corresponding Q value. For $\nu \geq 4$ the shape is essentially independent of how the invariant mass of the unobserved particles is distributed among them. Thus, for example, the *shapes* of the phase-space MM distributions for the $^6Li(\pi^-,\pi^+)^6H$ reaction corresponding to ^6H breakup into three clusters, $^2H+{}^2n+{}^2n$ or $^3H+{}^2n+n$, are almost identical. (Throughout this Letter we use ^2n to denote dineutron with zero binding energy.) The distributions essentially differ only in the positions of their thresholds. Similar remarks apply to the nearly identical MM spectra for the $^9Be(\pi^-,p)^8He$ reaction corresponding to ^8He breakup into the clusters $^6He+n+n$ or $^4He+{}^2n+{}^2n$.

The important role of the dineutrons in the continuum spectra is most dramatically brought out in the analysis of the measured missing-mass spectrum for the $^6Li(\pi^-,\pi^+)X$ reaction shown in Fig. 1.[10] We will therefore discuss this case first. As shown in Fig. 1, the measured spectrum cannot be fitted with phase-space distributions for the breakup channels which only consist of stable particles, p, n, d, or t. The phase-space distributions containing six separate nucleons, or a deuteron plus four separate neutrons ($^6H\rightarrow{}^2H+n+n+n+n$, short-dashed line in Fig. 1), or a triton plus three separate neutrons ($^6H\rightarrow{}^3H+n+n+n$, dot-dashed line in Fig. 1), all rise extremely rapidly from their thresholds. No arbitrary normalization of these phase-space curves can simultaneously fit the data in the threshold and large-MM regions. They are therefore definitely ruled out. Going beyond this point requires considering clusters known to be unbound. In the first instance, this means the dineutron, known to be unbound by $\sim$70 keV. Since the dineutron is only slightly unbound, and since there appears to be at

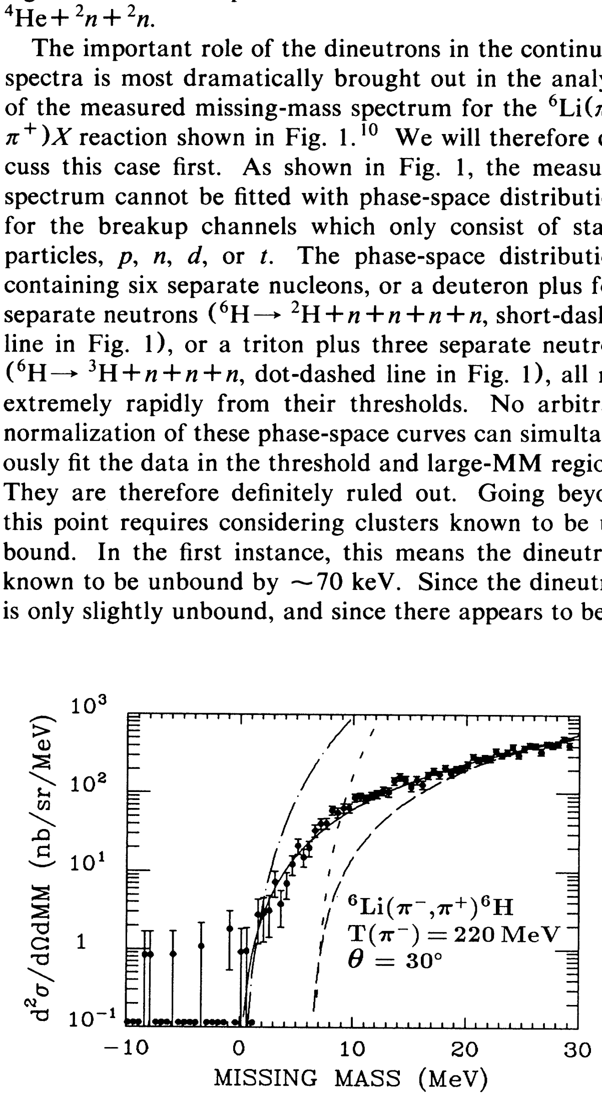

FIG. 1. The missing-mass spectrum for the $^6Li(\pi^-,\pi^+)^6H$ reaction (Ref. 10). The phase-space distributions shown are as follows: dot-dashed line, $^6H\rightarrow{}^3H+n+n+n$; short-dashed line, $^6H\rightarrow{}^2H+n+n+n+n$; long-dashed line, $^6H\rightarrow{}^2H+{}^2n+{}^2n$; and solid line, $^6H\rightarrow{}^3H+n+{}^2n$.

least indirect evidence for its acting as a bound cluster in the nuclear environment of extremely neutron-rich stable nuclei, we include it as a final-state particle (^2n with zero binding energy). This allows us to consider the three-body breakup channels $^6H\rightarrow{}^3H+n+{}^2n$ and $^6H\rightarrow{}^2H+{}^2n+{}^2n$. The phase-space distributions corresponding to these are also shown in Fig. 1; the long-dashed line corresponds to $^6H\rightarrow{}^2H+{}^2n+{}^2n$ and the solid line corresponds to $^6H\rightarrow{}^3H+n+{}^2n$. It is quite clear that the experimental spectrum is very well fitted with the phase-space distribution for the breakup channel $^3H+n+{}^2n$. A $\chi^2/N_{DF}=82/57=1.4$ is found for the best fit. The $^2H+{}^2n+{}^2n$ channel is ruled out because its threshold is displaced by 6.3 MeV [$=E_B(^3H)-E_B(^2H)$].[14]

The fit corresponding to the breakup $^6H\rightarrow{}^3H+n+{}^2n$ is not only excellent, but is also unique. No other single breakup channel or combination of several breakup channels comes even close to fitting the observed MM spectrum. We believe that within the context of a phase-space interpretation of the data this constitutes a very strong signature of the existence of the dineutron cluster in the extremely neutron-rich system, hydrogen-6, which is itself not bound.

Since the idea of the "existence" of dineutrons in unbound neutron-rich systems is rather unconventional, we have searched for similar evidence in our studies of extremely neutron-rich light nuclei by means of (π^-,p) reactions.

Figure 2 shows the missing-mass spectrum for the reaction $^9Be(\pi^-,p)^8He$. In this spectrum the peak corresponding to the bound ^8He(g.s.) is clearly seen with a differential production cross section of 31 ± 6 nb/sr. As illustrated in Fig. 2(a) the observed continuum spectrum differs in a marked and distinctive manner from the phase-space MM prediction corresponding to $^8He\rightarrow{}^6He+n+n$ which would be the normally expected breakup channel. The $^6He+n+n$ curve in Fig. 2(a) has been normalized to the data to illustrate that there is considerable amount of excess yield in both the threshold and the large-missing-mass regions. We find that the observed yield in neither of these regions can be explained without invoking the presence of dineutrons. The characteristic shape in the threshold region mandates a substantial contribution by the breakup channel, $^8He\rightarrow{}^6He+{}^2n$, and the spectrum in the region $MM\geq20$ MeV demands a large contribution from the breakup channel $^8He\rightarrow{}^3H+{}^3H+{}^2n$. As a matter of fact, as shown in Fig. 2(b), the data are very well fitted by a sum of these two contributions alone. A slightly better χ^2 fit can be obtained by the inclusion of a small contribution from the $^8He\rightarrow{}^6He+n+n$ breakup channel, but it does not appear to be necessary. On the other hand, the two dineutron channels are necessary for the fit. To summarize, we conclude that the observed continuum missing-mass spectrum for the $Be(\pi^-,p)^8He$ reaction also contains a strong signature of the presence of

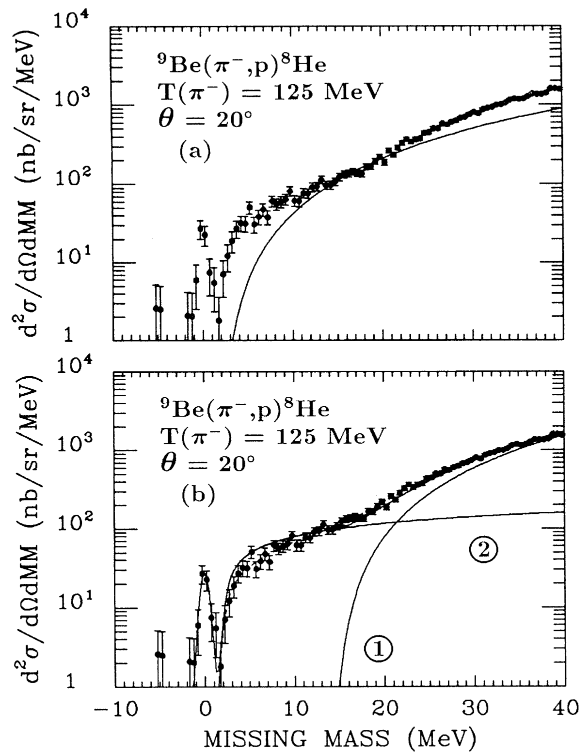

FIG. 2. The missing-mass spectra for the ^{9}Be$(\pi^-,p)^8$He reaction (Ref. 9). The peak at MM=0 corresponds to the ^{8}He(g.s.). The phase-space distributions shown are as follows: (a) solid line, $^8\text{He} \to {}^6\text{He}+n+n$; (b) best-fit curve as sum of curve 1 for $^8\text{He} \to {}^3\text{He}+{}^3\text{He}+{}^2n$ and curve 2 for $^8\text{He} \to {}^6\text{He}+{}^2n$.

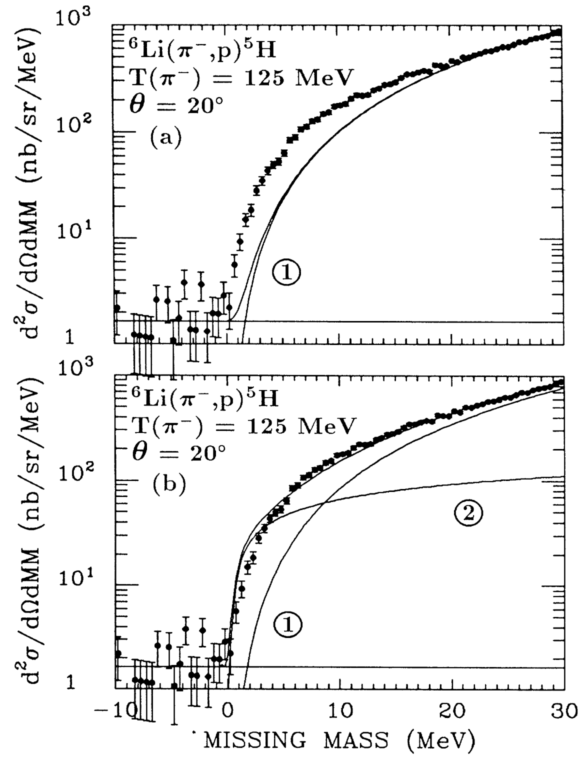

FIG. 3. The missing-mass spectra for the ^{6}Li$(\pi^-,p)^5$H reaction (Ref. 9). The constant line at the bottom corresponds to the background. The phase-space distributions shown are as follows: (a) curve 1, fit for $^5\text{H} \to {}^3\text{H}+n+n$; (b) best-fit curve as sum of curve 1 for $^5\text{H} \to {}^3\text{H}+n+n$ and curve 2 for $^5\text{H} \to {}^3\text{H}+{}^2n$.

dineutrons in unbound ^{8}He.

Our third example comes from the reaction ^{6}Li$(\pi^-,p)^5$H. The measured MM spectrum is shown in Fig. 3. In this case the conventional expectation would be that the dominant breakup channel is $^5\text{H} \to {}^3\text{H}+n+n$. Indeed this channel is found to be necessary but not sufficient. As illustrated in Fig. 3(a) the fit corresponding to this channel alone falls woefully short in explaining the observed yield in the threshold region, in a manner which strongly resembles the discrepancy noted in the ^{8}He case described above. It is found that this discrepancy can only be corrected by adding the contribution of the dineutron-containing breakup channel $^5\text{H} \to {}^3\text{H}+{}^2n$; the best fit corresponding to the sum of the two channels is shown in Fig. 3(b). Thus once again we conclude that a phase-space description of the data mandates the presence of dineutrons in the breakup.

To summarize, in the absence of any dynamical theories of pion double-charge-exchange and pion absorption reactions populating the continuum, we have presented a phase-space analysis of these reactions. Within the context of this model, notable success is obtained in fitting the continuum spectra by including dineutrons in the breakup channels. This strongly suggests that in these extremely neutron-rich, particle-unstable "nuclei" the continuum wave function has a strong overlap with a dineutron cluster. The dineutron appears to exist, at least at the moment of breakup, and the phase-space distributions contain its characteristic signature. We wish to emphasize that this signature is to be distinguished from the effects of conventional s-wave final-state interactions. We have actually tested the effective-range prescription for including final-state interaction between two outgoing neutrons in our Monte Carlo phase-space calculations and have determined that it completely fails to explain the effects for which we have invoked the existence of the dineutron in these nuclei.

If our explanation of the continuum spectra measured in the above reactions is correct, the hypothesis of dineutrons in neutron-rich nuclei can be examined for many more exotic nuclei than are available as beams from projectile fragmentation. Particularly interesting tests of our ideas will be provided by the measurements of the continuum spectra for the reactions ^{9}Be$(\pi^-,\pi^+)^9$He and ^{11}B$(\pi^-,\pi^+)^{11}$Li. Such measurements are planned for the near future.[15] We predict that the breakup spectra for these reactions will not be fitted by the phase-space distribution for ^{8}He$+n$ and ^{9}Li$+n+n$ breakup, respectively, and that large admixtures of the phase-space distributions containing dineutrons (^{9}He$\to$ ^{6}He $+n+{}^2n$ and ^{11}Li$\to$ ^{9}Li$+{}^2n$) will be required. Bertsch and Foxwell[7] have indeed suggested that a cluster-model description of ^{11}Li as ^{9}Li$+{}^2n$ may be necessary to explain the large measured Coulomb dissociation cross section for ^{11}Li on ^{208}Pb.

This work was supported in part by the U.S. Department of Energy.

[1]I. Tanihata *et al.*, Phys. Lett. **160B**, 380 (1985); also I. Tanihata *et al.*, Phys. Rev. Lett. **55**, 2676 (1985).

[2]I. Tanihata, Nucl. Phys. **A488**, 113c–126c (1988).

[3]T. Kobayashi *et al.*, Phys. Rev. Lett. **60**, 2599 (1988).

[4]T. Kobayashi *et al.*, Phys. Lett. B **232**, 51 (1989).

[5]P. G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987).

[6]A. B. Migdal, Yad. Fiz. **16**, 427 (1973) [Sov. J. Nucl. Phys. **16**, 238 (1973)].

[7]H. Sato and Y. Okuhara, Phys. Lett. **162B**, 217 (1985); G. W. Bertsch, B. A. Brown, and H. Sagawa, Phys. Rev. C **39**, 1154 (1989); G. Bertsch and J. Foxwell, Phys. Rev. C **41**, 1300 (1990); T. Hoshino, H. Sagawa, and A. Arima, Nucl. Phys. **A506**, 271 (1990).

[8]K. K. Seth *et al.*, Phys. Rev. Lett. **41**, 1589 (1978); H. Nann *et al.*, Phys. Lett. **96B**, 261 (1980); K. K. Seth *et al.*, Phys. Rev. Lett. **58**, 1930 (1987).

[9]Kamal K. Seth *et al.*, in *Proceedings of the Fourth International Conference on Nuclei Far From Stability, Helsingor, 1981,* edited by P. G. Hansen and O. B. Nielsen (CERN Report No. 81-09, 655, 1981).

[10]B. Parker, Kamal K. Seth, and R. Soundranayagam, Phys. Lett. (to be published).

[11]See, for example, S. A. Wood *et al.*, Phys. Rev. Lett. **54**, 635 (1985); E. R. Kinney *et al.*, Phys. Rev. Lett. **57**, 3152 (1986); P. A. M. Gram *et al.*, Phys. Rev. Lett. **62**, 1837 (1989).

[12]See, for example, D. Ashery and J. P. Schiffer, Annu. Rev. Nucl. Part. Sci. **36**, 207 (1986).

[13]M. M. Block (to be published).

[14]The nucleus ^{4}H is unbound by nearly 3 MeV and is not considered here. If it were considered possible, the three-body breakup reaction ^{6}H$\to$ ^{4}H$+n+n$ would lead to a phase-space distribution whose shape would be identical to that of the two three-body distributions illustrated in Fig. 1, but it would also be completely ruled out by its $\sim$3-MeV displaced threshold.

[15]K. K. Seth *et al.*, LAMPF Proposal No. 1066U, 1987; T. Kobayashi *et al.*, LAMPF Proposal No. 1191, 1990.