Search for superheavy hydrogen-6

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A search has been made for the superheavy isotope of hydrogen, ^{6}H, whose existence has been claimed in two heavy ion experiments. The pion double charge exchange reaction ^{6}Li(π^-, π^+)X at $T(\pi^-)=220$ MeV was used in a high-resolution search for ^{6}H. No evidence for ^{6}H was found anywhere in the missing mass range -10 to $+30$ MeV. In the missing mass region 0–5 MeV 95% confidence upper limits of 0–5 nb/sr for the production cross section were set.

The study of exotic nuclei, i.e., nuclei with the neutron/proton, N/Z, values which differ greatly from those for the neighboring nuclei in the valley of stability, is of special interest in nuclear physics. Extremes of isospin, like extremely high spins or extremely high energy and/or matter density, are of interest because they put our understanding of nuclear forces and nuclear structure to very stringent and demanding tests. Exotic light nuclei, particularly isotopes of hydrogen ($Z=1$) and helium ($Z=2$), are of special interest for at least two other reasons. Firstly, calculations of the structure and stability of few-nucleon systems can now be done almost from first principles. In such nuclei, better than anywhere else, one can test subtle aspects of the nuclear interaction, e.g., the need for three-body and many-body forces. Finally, with large enough N/Z ratios the superheavy isotopes of hydrogen and helium come closest to the matter of which neutron stars are made, and their study may indeed shed valuable light on this interesting astrophysical subject.

Polyneutron nuclei (^{2}n, ^{3}n, ^{4}n) and isotopes of hydrogen heavier than the triton (^{3}H) have been the subject of numerous investigations in the past [1,2]. It is known that the dineutron, ^{2}n is unbound by only ~ 70 keV and that ^{4}H is unbound with respect to ^{3}H+n decay by ~ 3.4 MeV [3]. Neither heavier polyneutrons nor heavier isotopes of hydrogen were found in the numerous searches reported in the literature prior to 1984 [4]. This included our unsuccessful search [5] for ^{5}H in the missing mass spectrum for the reaction $^7\mathrm{Li}+\pi^-\rightarrow \mathrm{p}+\mathrm{X}$. The failure to find ^{5}H, with an even number of neutrons, $N=4$ led to the general belief that the existence of ^{6}H, with an odd number of neutrons, $N=5$, was even more unlikely. This status quo was recently upset by the claims made in two heavy ion experiments. Aleksandrov et al. [6] at the Khurchatov Institute in Moscow reported the "Observation of an unstable superheavy hydrogen isotope ^{6}H in the reaction $^7\mathrm{Li}+{}^7\mathrm{Li}\rightarrow {}^8\mathrm{Be}+{}^6\mathrm{H}$." The reaction was studied at $E(^7\mathrm{Li})=82$ MeV, $\theta(\mathrm{lab})=10°$. Aleksandrov et al. identified a bump above the continuum yield in their missing mass spectrum as ^{6}H which was unbound by 2.7 ± 0.4 MeV with respect to the ^{3}H+3n ($3\mathrm{n}\equiv \mathrm{n}+\mathrm{n}+\mathrm{n}$) threshold and had a width $\Gamma=1.8\pm0.5$ MeV. The production cross section was reported to be ~ 60 nb/sr. Subsequently, Belozyorov et al. [7] at Dubna reported confirmation of this discovery by means of the reaction $^9\mathrm{Be}+{}^{11}\mathrm{B}\rightarrow {}^{14}\mathrm{O}+\mathrm{X}$ at $E(^{11}\mathrm{B})=88$ MeV, $\theta=8°$. They identified a bump above the continuum yield in their missing mass spectrum as ^{6}H which was unstable by 2.6 ± 0.5 MeV and had a width $\Gamma=1.3\pm0.5$ MeV. The production cross section was reported to be 16 nb/sr. If true, these observations pose serious questions about some of the very basic aspects of our understanding of nuclear structure. Detailed shell-model calculations [8] predict a 1^- or 2^- ^{6}H(g.s.) which is unbound by 8–13 MeV with respect to ^{3}H+3n decay. They also predict that the ^{5}H(g.s.), though also unbound, has 4–5 MeV more binding energy than ^{6}H(g.s.). In other words, these predictions are in strong contradiction to the reported observations. Aleksandrov et al. [6], however, argue that the existence of the odd–odd ^{6}H is not incompatible with the non-existence of the odd–even ^{5}H. They invoke an angular momentum barrier argument due to Gol'danskii [9]. They propose that ^{5}H would most likely decay by the emission of an $L=0$ neutron pair and would see no angular momentum barrier. It would therefore decay rapidly. On the other hand, the one neutron decay of ^{6}H would be much slower because of the $L=1$ angular momentum barrier. If ^{6}H and ^{5}H are both unbound by small energies, this can lead to an observably narrow ^{6}H in spite of a too-broad-to-be-seen ^{5}H.

Because of the important questions raised by the claims for the discovery of ^{6}H, we have studied the pion double charge exchange reaction ^{6}Li(π^-, π^+)X in order to search for ^{6}H. We note that the pion double charge exchange (DCX) reaction has proved to be dramatically successful in populating neutron-rich exotic nuclei, many observed for the first time [5]. The latest example of the success of this reaction is provided by our discovery [10] of the most neutron rich nucleus ever identified, ^{9}He ($N/Z=3.5$), by means of the reaction ^{9}Be(π^-, π^+)X. In this letter we report on the results of our attempt to find ^{6}H.

The pion DCX reaction, ^{6}Li(π^-, π^+)X was studied at the EPICS spectrometer facility at LAMPF. The spectrometer and the detector systems are shown schematically in fig. 1. They have been described before [11]. A 220.0 MeV π^- beam of intensity $\sim 5\times 10^7\ \pi^-$/s was incident on a high-purity lithium-6 hydride (^{6}LiH) target in the form of a plate of dimensions 19.9 cm$\times$10.0 cm$\times$0.99 cm. The target contained (by weight) 85.29% of enriched lithium metal (94.82% ^{6}Li, 5.18% ^{7}Li), 14.04% hydrogen, 0.19% oxygen and 0.48% trace elements. The areal density of ^{6}Li was 566 ± 5 mg/cm^2. Reaction products were detected and analyzed at 30°. By measuring π^- elastic scattering from the same target it was determined that the energy resolution was FWHM$=$0.65 MeV.

Three stages of particle identification, optimized by measuring DCX as well as elastic scattering of both π^+ and π^- of appropriate momenta, were used in the present experiment. Time-of-flight was measured over the ~ 9 m flight path between the scintillator S1 at the entry to the spectrometer and scintillators S2 and S3 just beyond the focal plane. Heavy particles (mostly protons) were eliminated by imposing a cut on the mean pulse height in the two scintillators S2 and S3. Electrons were eliminated by means of a cut on the Čerenkov pulse height spectrum. Finally, decay-muons and "leakage electrons" (due to the inefficiency of the Čerenkov counter) were eliminated by a conservative cut on the time-of-flight itself. The resulting missing mass spectrum, shown in fig. 2, is seen to be almost entirely free of extraneous particles, as judged from the paucity of counts below zero missing-mass.

The absolute normalization (uncertainty $\pm 5\%$) for DCX cross sections was obtained by measuring π^- proton elastic scattering under the same experimental conditions by using a CH_2 target of 74 mg/cm^2 thickness. A detailed measurement of the acceptance of the spectrometer–detector system was made with $\pm 1\%$ statistical precision in the entire $\delta\equiv\Delta p/p=-10\%$ to $+10\%$ region by moving the ^{12}C elastic scattering peak across the focal plane in small steps. The acceptance data were fitted with a smooth curve and the curve was used to correct the DCX data for the acceptance variations. In the results presented in

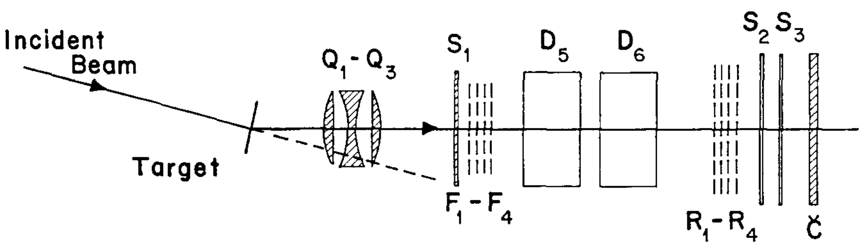

Fig. 1. A schematic illustration of the spectrometer–detector system used in the present experiment. Q_{1-3} is a quadrupole–triplet D_5 and D_6 are dipoles. S_1, S_2 and S_3 are scintillation counters. F_{1-4} and R_{1-4} are drift chambers. Č is a gas threshold Čerenkov counter.

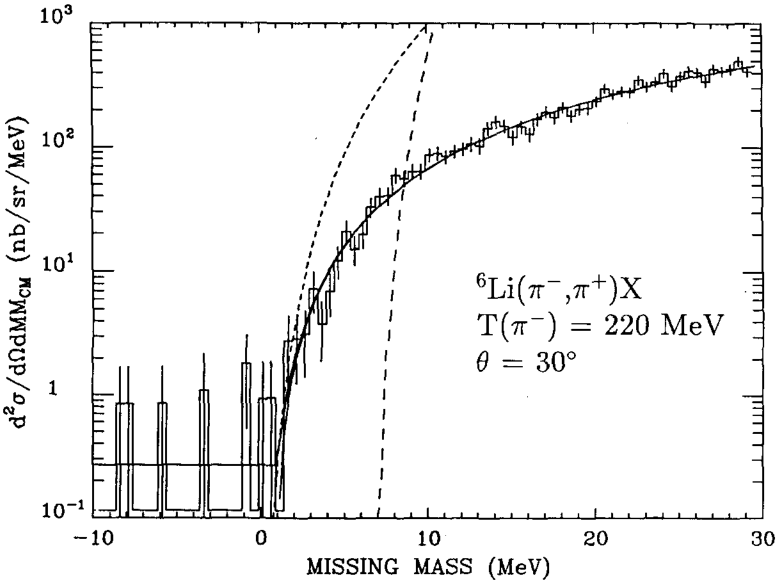

Fig. 2. Missing mass spectrum for the reaction $^6Li(\pi^-, \pi^+)X$ at $T(\pi^-) = 220$ MeV, $\theta = 30°$. The short-dashed curve corresponds to the phase-space distribution for $X = {}^3H + n + n + n$, and the long-dashed curve corresponds to the phase-space distribution for $X = {}^2H + n + n + n + n$. The solid curve is the best fit obtained with a third-order polynomial. The error bars shown on the data are statistical only.

this paper only the data from the central region, in which the acceptance was $\geqslant 50\%$ of the maximum, were used.

It was the purpose of the present experiment not only to look for possible ^6H enhancements in the immediate vicinity of the $^3H + 3n$ (3n = three unbound neutrons) threshold, but to search for possible enhancements deeper into the continuum. Investigation of a large region of phase space is also necessary in order to be able to compare the observed missing mass spectrum with phase-space predictions in a more reliable manner than was done in the heavy ion experiments [6,7]. For these reasons the reaction was studied with two different settings of the central-ray momentum of the spectrometer. In the first setting the $^3H + 3n$ threshold was put at $\delta = -2.5\%$; this setting emphasizes the threshold and bound regions. In the second setting the $^3H + 3n$ threshold was put at $\delta = +4.5\%$; this setting emphasizes the threshold and unbound regions. It was found that the acceptance-corrected missing mass (MM) spectra from the two settings agreed very well with each other (within $\pm 1\%$) in the region of overlap. Accordingly, the two data sets were combined, and the combined data were used in all subsequent analysis. The resulting $^6Li(\pi^-, \pi^+)X$ double differential cross sections as a function of the missing mass ($\equiv$ MM) are shown in fig. 2. The zero of the missing mass scale is set to be that due to the breakup $X = {}^3H + n + n + n$. We note that the background due to errors in particle identification and due to the contributions of trace impurities in the target is very small, < 0.3 nb/sr MeV in the region $MM \leqslant 0$ MeV. We also note that there are no clear and obvious peaks in the data, neither in the bound region ($MM \leqslant 0$ MeV), nor in the unbound region ($0 \leqslant MM \leqslant 30$ MeV). In order to reach more quantitative conclusions a more detailed analysis of the data was done. We describe it below.

In order to search for a resonance peak we have to fit the continuum data on which the presumed peak rides. In fig. 2 we show arbitrarily normalized curves for the phase-space distributions (PSD) for $X = {}^2H + n + n + n + n$ (long dashes) and $X = {}^3H + n + n + n$ (short dashes). Both of these rise very rapidly from their thresholds and are definitely ruled out by the data. The PSD for $X = p + n + n + n + n + n$ would rise even faster and is also ruled out. We conclude that no PSD, or combination of PSDs, with final states containing only nucleons or stable nuclei can be made to fit these data. We have chosen therefore to simply fit our data with a low-order polynomial, and to examine systematic departures from the fit for evidence of a "peak" or a "resonance". In fig. 2, the solid curve shows the best fit to our data obtained with a third-order polynomial. The value of $\chi^2/\mathrm{d.o.f.}=68/55=1.24$ indicates that the fit is quite good and that no resonances are required by these data.

In order to put an upper limit on the area of a resonance which could be forced on the data in the region MM = 0–10 MeV, we have made the following additional analysis. The data in the region MM = 0–10 MeV were separately fitted with a second order polynomial. The best fit was found to have $\chi^2/\mathrm{d.o.f.}=17.5/18$ (likelihood = 50%). Once again this indicates that no "peak" is needed. A peak of width 1.8 MeV was then added to the polynomial and the best fit for the combination was obtained. The procedure was repeated with the peak scanned in 0.25 MeV steps between MM = 0 and 5 MeV. The entire procedure was repeated with the extreme peak widths of 1.3 and 2.3 MeV also. The best fit χ^2/d.o.f. through all these scans ranged from 14/17 to 17/17, i.e., no meaningful improvement in the overall quality of the fit was obtained. The most likely value of the permissible resonance area was found to oscillate equally between positive and negative values, and the 95% confidence upper limits of the areas ranged from 0 to 5 nb/sr. In particular, at MM = 2.7 ± 0.4 MeV, the 95% confidence upper limit of the resonance area was found to be 5 nb/sr. The χ^2/d.o.f. for the best fit in this case was 17/17, i.e., essentially identical to that for the no-resonance case.

Since there are no reliable theoretical models for the pion or heavy-ion induced DCX transitions to non-analog states even in "normal" nuclei, the only way in which we can put the present results in some perspective is to compare them with the experimental results for the production of another "exotic" nucleus. DCX experiments for the production of the exotic nucleus ^{9}He allow us to make such a comparison, albeit only in qualitative terms.

In our study of the $^9\mathrm{Be}(\pi^-, \pi^+)^9\mathrm{He}$ reaction at $T(\pi^-)=194$ MeV, $\theta=15°$ the ^{9}He(g.s.) production cross-section was measured as 40 ± 10 nb/sr [10]. In a recent study of the $^9\mathrm{Be}(^{13}\mathrm{C}, ^{13}\mathrm{O})^9\mathrm{He}$ reaction at 30 MeV/nucleon the corresponding production cross-section was found to be 45 ± 18 nb/sr [12]. Thus, a heavy-ion DCX reaction, which is optimized for momentum matching, has approximately the same sensitivity as our (π^-, π^+) experiments. On the other hand, the heavy-ion DCX experiment of Belozyorov et al. [7], was done at an extremely momentum-mismatched energy of 8 MeV/nucleon. We therefore expect that the sensitivity for the production of ^{6}H(g.s.) in our present experiment is higher than in the experiment of Belozyorev et al.

A similar conclusion for the sensitivity of the present experiment is obtained by estimating the production cross section for ^{6}H on the basis of our ^{9}He result. The $^9\mathrm{Be}(3/2^-)\to{}^9\mathrm{He}(1/2^-)$ transition is $L=2$, which is expected to peak at $\theta>25°$ (the $^{18}\mathrm{O}(\pi^+, \pi^-)^{18}\mathrm{Ne}(2+)$ transition was found to peak at $\sim 25°$) [5], and therefore have a peak differential cross-section larger than the 40 ± 10 nb/sr measured at $\theta=15°$. The $^6\mathrm{Li}(1^+)\to{}^6\mathrm{H}_{\mathrm{g.s.}}(2^-$ or $1^-)$ transition is $L=1$. It is expected to have its peak at $\theta\sim 30°$. We therefore estimate that if ^{6}H(g.s.) exist its production cross-section in our experiment should be substantially larger than 40 nb/sr. We therefore believe that our 95% confidence upper limit of 0–5 nb/sr for the production cross section of ^{6}H(g.s.) casts serious doubt on the existence of ^{6}H.

In summary, we do not find in our data evidence for the existence of ^{6}H anywhere from the $^3\mathrm{H}+\mathrm{n}+\mathrm{n}+\mathrm{n}$ threshold to 30 MeV unbound. The 95% confidence upper limits for the production cross section for ^{6}H is placed at 0–5 nb/sr in the 0–5 MeV unbound region, and it is argued that this casts serious doubts on the existence of ^{6}H.

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