Brief Reports

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Search for the exotic nucleus ^{10}He

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A search has been conducted for the exotic neutron rich nucleus ^{10}He among projectile fragments produced by an $E/A = 30$ MeV ^{18}O beam. No $^{10}He^{2+}$ ions were observed. The upper limit on the production rate of ^{10}He is determined to be less than 3×10^{-5} that of ^{8}He.

Heavy-ion reactions at intermediate energies have proven to be a very effective means to make and study exotic nuclei far from the valley of stability.[1-3] Since the development of heavy ion cyclotrons for intermediate energies at Grand Accélerateur National d'Ions Lourds (GANIL) and Michigan State, a large number of new isotopes have been discovered.[4,5] In fact, all the proton rich isotopes with $Z<21$ that are predicted to exist have been observed, and on the neutron-rich side, all isotopes with $Z<8$ that are predicted to exist have been observed. On the proton-rich side of the valley of stability the limit of particle stability is quite sharp and well defined. By comparison, the fall off from the valley of stability on the neutron-rich side is much more gradual and the predicted limits of particle stability are not well defined. One consequence of this is that there have been several cases of neutron-rich nuclei such as ^{14}Be, ^{19}B, and ^{29}Ne, which were thought to be particle unstable and later found to be produced[6,7,4] when more prolific production mechanisms, such as heavy-ion projectile fragmentation, became available. The experiment discussed in this Brief Report was the first attempt to produce the previously unobserved nucleus ^{10}He using heavy ion projectile fragmentation.

Following the discovery of ^{8}He,[8] there were attempts to find ^{10}He among light fragments emitted in the spontaneous fission of ^{252}Cf.[9,10] Later attempts to produce ^{10}He used high-energy proton-induced[11] and deuteron-induced[12] spallation of uranium, or low-energy heavy-ion transfer reactions.[13,14] Although these experiments did not observe ^{10}He, it is important to note that they also did not observe ^{14}Be, ^{17,19}B, and ^{18,19,20,22}C, all of which were later found to be particle stable.

A summary is shown in Table I of predictions of the mass of ^{10}He and its one- and two-neutron separation energies. Most of the predictions indicate that ^{10}He is unbound by several MeV with respect to both one- and two-neutron emission. The result of Seth *et al.*[5] is based on their recent measurement of the mass of ^{9}He, and suggests that ^{10}He is much closer to being bound than previous calculations had suggested.

In the present experiment, the Michigan State University (MSU) reaction product mass separator (RPMS) was used to search for ^{10}He. Production was attempted by fragmentation of an ^{18}O beam incident on a 0.76 mm thick Sn target. The MSU RPMS is designed to separate exotic nuclei produced in intermediate-energy heavy-ion reactions in order that their decay properties can be studied. The RPMS is a "triply focusing device," which focuses in x and y position, and in velocity. It also disperses ions according to their mass-to-charge ratio, m/q. Ions of the mass-to-charge ratio of interest are focused onto a detector where they are identified, and their decay properties may be studied. The long target-to-focal plane distance (14 m) provides a clean environment for observation of rare isotopes.

A 540 MeV (30 MeV/A) ^{18}O beam from the K500 cyclotron at the National Superconducting Cyclotron Laboratory (NSCL) was used to measure the relative production probabilities of a variety of light neutron rich isotopes ^{6,7,8,9,11}Li, ^{4,6,8}He, and ^{2,3}H, as well as set limits on the production of ^{10}He. No candidate ^{10}He nuclei were observed. Upper limits on the production probability of ^{10}He were less than 3×10^{-5} of the measured production probability of ^{8}He. Previous experiments which have used the RPMS have been beta decay studies in which the ion of interest has been produced at rates of 10 to 10^3 ions per hour. The present experiment demonstrates the feasibility of searches at the few ions per experiment level for exotic nuclei.

The Sn target thickness, 0.76 mm, was chosen to stop the primary oxygen beam and degrade the energy of "projectile-like" ^{8}He and ^{10}He fragments so they could be

TABLE I. Summary of ^{10}He mass predictions.

Author	Model	Mass excess (MeV)	B_n (MeV)	B_{2n} (MeV)
Seth *et al.*[a]	Local GK[f]	49.18	−0.31	−1.44
Thibault, Klapisch[b]	Regional GK	52.75	−3.88	−5.00
Beiner *et al.*[c]	Energy density method	47.20	+1.67	+0.55
Janecke[d]	Global GK	50.13	−1.26	−2.38
Jelley *et al.*[e]	Regional GK	51.00	−2.13	−3.26
Jelley *et al.*[e]	Shell-model systematics	52.34	−3.47	−4.59

[a]Reference 15.
[b]Reference 16.
[c]Reference 17.
[d]Reference 18.
[e]Reference 19.
[f]GK stands for Garvey-Kelson relation.

focused in the RPMS. This allowed the RPMS to be operated at 0°. Reaction products were separated according to their mass-to-charge ratio, m/q, and detected in a focal plane detector consisting of a position-sensitive single-wire gas proportional counter followed by a detector telescope consisting of four 700 mm^2, 1 mm thick lithium drifted silicon detectors. The single-wire gas proportional counter measured the horizontal position by resistive charge division and the vertical (dispersive) position by electron drift time.

The RPMS contains a Wien EXB filter, which acts as a velocity filter, passing ions in an 8% wide velocity window through to the focal plane. The selection of the velocity window is adjustable by changing the ratio of the electric to magnetic field in the Wien filter. The velocity window in the present experiment was selected to optimize the collection efficiency for ^{10}He, by focusing the RPMS for $m/q=4$ and adjusting the velocity window to maximize the count rate of ^{8}He. The count rate of ^{8}He was not very sensitive to small variations (10%) in the velocity window. This suggests that a velocity window optimized for ^{8}He is probably nearly optimal for ^{10}He. The velocity window chosen was centered on $E/A=15$ MeV, which resulted in most ^{8}He nuclei stopping in the third silicon detector in the telescope. This meant that any ^{10}He nuclei selected by the velocity window would stop in the third and fourth silicon detectors in the telescope.

The dispersion of the RPMS is sufficiently large that only a single helium isotope was focused on the focal plane detector at a time. When the RPMS was tuned for $m/q=3$ isotopes to be centered in the telescope, $m/q=2$ isotopes were just off the top edge of the telescope, and $m/q=4$ isotopes were just off the bottom edge. When the RPMS was focused for $m/q=5$ isotopes to search for ^{10}He, there was, of course, no observables $m/q=5$ line, since there are no known particle stable $m/q=5$ isotopes. In order to be sure we were looking in the right focal plane location for ^{10}He we extrapolated from the locations of ^{4}He, ^{6}He, and ^{8}He. This was done by focusing the RPMS successively at $m/q=2$, $m/q=3$, and $m/q=4$ and determining the location of ^{4}He, ^{6}He, and ^{8}He in the focal plane when the ion was in focus. It was found that ^{8}He was in the same location at an $m/q=4$ setting as ^{6}He was for an $m/q=3$ setting. It was then assumed that the ^{10}He focus at an $m/q=5$ setting would be in the same location as ^{8}He was when the RPMS was focused at $m/q=4$. By this means, it was possible to set position gates on the focal plane position of ^{8}He when the RPMS was focused for $m/q=4$ and use the same gates for ^{10}He when the RPMS was refocused to $m/q=5$.

The four element silicon telescope was used to provide isotope identification of the light isotopes independent of the RMPS mass information. Two particle identification functions, PID1 and PID2, were constructed from the energy signals $E1$, $E2$, $E3$, and $E4$ from the four silicon detectors. First, taking the front silicon detector as the ΔE signal and the sum of $E2+E3+E4$ as the E signal we obtained a particle identification function PID1

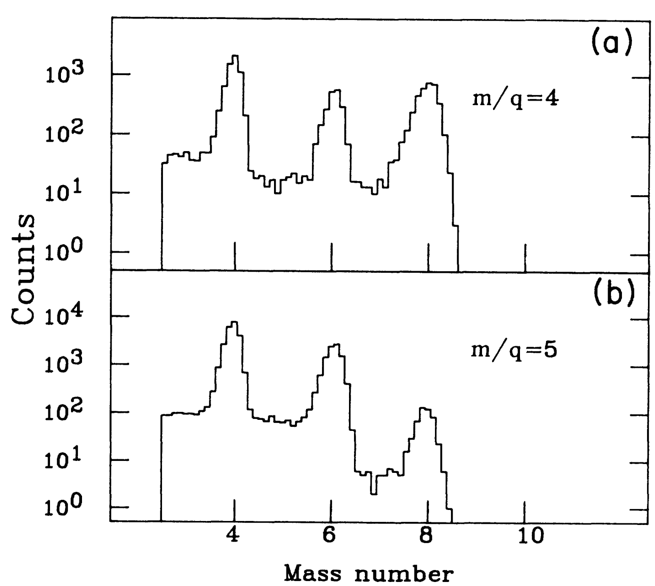

FIG. 1. Mass distribution of helium isotopes obtianed from runs at RPMS settings of $m/q=4$ and 5. The total integrated beam currents for the runs were 180 and 2200 μC, respectively. Note that there are no counts in the region of ^{10}He.

$=(E1+E2+E3+E4)^{1.78}-(E2+E3+E4)^{1.78}$. The second particle ID function was defined using the sum of the first two detectors as a ΔE signal and the sum of the last two detectors, $E3+E4$, as the E signal. This gave the second particle identification function PID2 $=(E1+E2+E3+E4)^{1.78}-(E3+E4)^{1.78}$. Ions which reached at least the third detector element and did not undergo a nuclear interaction within the detector stack should have consistent particle identification values PID1 and PID2. For ^{10}He ions the event was required to have the right position in the focal plane and consistent particle identification signals PID1 and PID2 in order for the event to be accepted. Figure 1 shows plots of the accepted helium events taken at $m/q=4$, and 5 RPMS settings. The integrated beam current of $^{18}O^{5+}$ for the two runs was 180 and 2200 μC, respectively. For the $m/q=4$ and 5 runs, clear peaks are seen for ^{4}He, ^{6}He, and ^{8}He. These ions, although present at the $m/q=5$ RPMS setting have count rates which are greatly suppressed because the RPMS is tuned for $m/q=5$. However, there are no counts which are near the location of ^{10}He. In order to obtain a limit on the production rate of ^{10}He by comparison with the production rates of other exotic light nuclei, we made a series of short runs at m/q settings ranging from $m/q=2$ to $m/q=4$ to measure the relative production rates of ^{2,3}H, ^{4,6,8}He, and ^{6,7,8,9,11}Li. This comparison is shown in Fig. 2. Individual elements show a smooth trend of yields falling roughly exponentially with increasing neutron excess. By extrapolating the yields of the helium isotopes to the location of ^{10}He it is possible to make an empirical "prediction" of the ^{10}He yield. This prediction of the ^{10}He yield is about 1000 times larger than the limit obtained in the experiment. The limit obtained for ^{10}He production is less than 3×10^{-5} of the production rate of ^{8}He. No experiment can, on the basis of the nonobservation of ^{10}He, prove that it is unbound to particle decay. This experiment, however, strongly suggests that ^{10}He is unbound to particle emission. Since the mass of ^{9}He has been recently measured,[15] a precise measurement of the mass of ^{10}He would definitively answer the question of the stability of ^{10}He. Since the recent measurement of the mass of ^{9}He indicates that ^{10}He is nearly bound, it may have a ground state of finite width and, therefore, a direct measurement of the mass of ^{10}He may be possible, perhaps by heavy-ion transfer reactions such as ^{10}Be(^{9}Be,^{9}C)^{10}He.

We have estimated the binding energy of ^{10}He from a new shell-model calculation of the He isotopes. The calculation was carried out in the $0p$ shell-model space, and all $0p_{3/2}-0p_{1/2}$ configurations were taken into account. The effective interaction was based upon the G matrix of Hosaka *et al.*[20] The interaction was then improved by varying the central components, making use of the spin-tensor decomposition method described in Refs. 21 and 22. For the $T=1$ part of the interaction there are only three independent central matrix elements. The optical values for the strength of these three matrix elements together with the two single-particle levels were determined by an iterative least-squares fit to the binding energies of the eight experimentally known states: ^{4}He 0^+, ^{5}He $\frac{3}{2}^-$, ^{5}He $\frac{1}{2}^-$, ^{6}He 0^+, ^{6}He 2^+, ^{7}He $\frac{3}{2}^-$, ^{8}He 0^+, and ^{9}He $\frac{1}{2}^-$ (the latter experimental binding energy was taken from Ref. 15). Excluding the very broad ^{5}He $\frac{1}{2}^-$ excited state, the root-mean-square deviation in the fit was about 70 keV. In Fig. 3 we show the experimental binding energies compared to the fitted values. In this figure we also show the predicted binding energies of ^{9}He $\frac{3}{2}^-$ and ^{10}He 0^+ states from the same interaction. For ^{10}He 0^+ we thus obtained $B_n=-0.04(14)$ MeV and $B_{2n}=-1.18(14)$

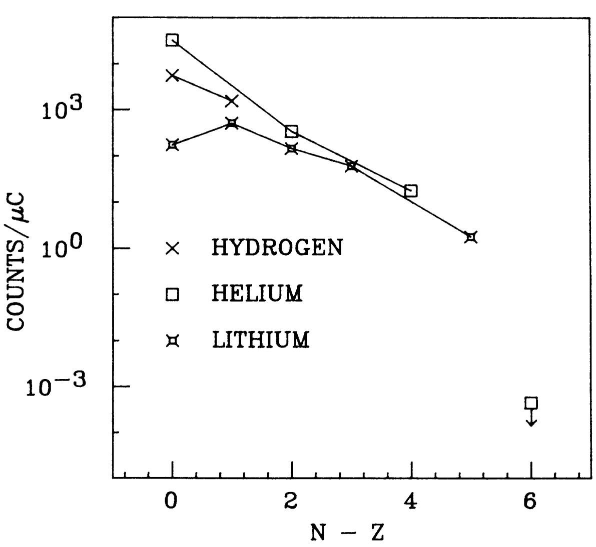

FIG. 2. Relative yields of neutron rich H, He, and Li isotopes plotted against neutron excess.

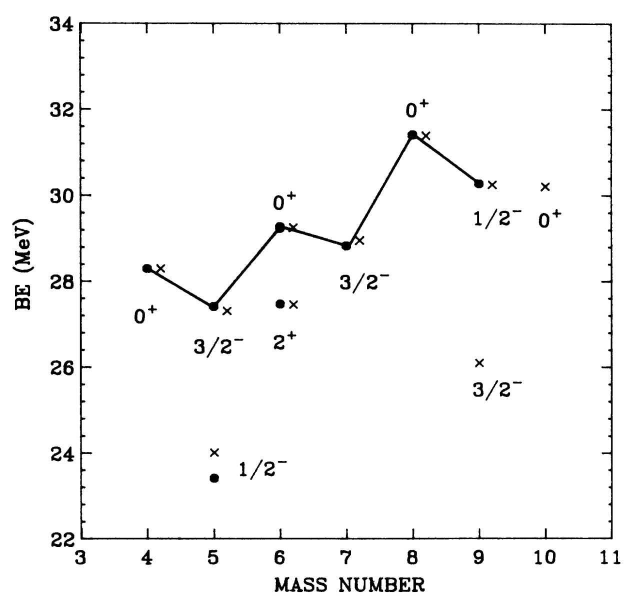

FIG. 3. Binding energies of states of the He isotopes. The experimental energies are shown by circles and experimental ground state binding energies are connected by a line. The calculated energies (see text for details) are shown by the crosses (slightly offset to the right in the case when they are close to the circles).

MeV, where the errors are the present theoretical estimates. These are close to the estimates obtained by Seth *et al.*[15] from the local Garvey-Kelson model (see Table I) and confirm the expectation that ^{10}He should be unbound, at least by two neutron emission.

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