Exotic Nucleus Helium-9 and its Excited States

Kamal K. Seth, M. Artuso, D. Barlow, S. Iversen,[a] M. Kaletka,[b] H. Nann,[c] B. Parker, and R. Soundranayagam
Northwestern University, Evanston, Illinois 60201
(Received 8 December 1986)

The ground state and several excited states of ^{9}He, the most neutron-rich nucleus to date, have been identified by means of the reaction $^9\mathrm{Be}(\pi^-,\pi^+)^9\mathrm{He}$. The mass excess of the ground state has been measured and it is found that the nucleus is unbound against single-neutron decay by 1.13 ± 0.10 MeV only. It is found that the excited-state spectrum of this nucleus, which is very far from the valley of stability, is in good agreement with the predictions of "no-core" shell-model calculations whose parameters were optimized for the stable nuclei in the valley.

PACS numbers: 21.10.Dr, 21.60.Cs, 27.20.+n

The most demanding tests of models of nuclear structure are made by examining nuclear matter under extreme conditions. Well-known examples of this approach are provided by the studies of nuclear states with very large angular momenta,[1] and the present attempts to reach extremes of particle and energy densities in heavy-ion collisions. A similar opportunity is provided by the study of the stability and structure of nuclei far removed from the valley of stability.[2] For very light nuclei it becomes possible to make nuclear-structure calculations relatively free of model restrictions and one may hope that measurements on such exotic nuclei can shed light on some of the fundamental questions of nuclear physics, e.g., the existence of many-body forces.[3] In particular, in shell-model calculations one can test the extent to which effective interactions, which are optimized in the valley of stability, work for extremely neutron-rich (or neutron-deficient) nuclei.[4] The isotopes of helium offer a particularly rich opportunity for this purpose. The even isotopes ^{4}He, ^{6}He, and ^{8}He are all known to be particle stable. The odd isotopes of helium ^{5}He and ^{7}He are both known to exist. They are unstable against single-neutron emission, but by amounts considerably less than those suggested by the mass systematics of adjoining even-even isotopes. A local application of the transverse Garvey-Kelson relation,[5] with use of experimental masses of ^{6}He and ^{8}He, yields the prediction that ^{5}He and ^{7}He should be unbound for single-neutron emission by 1.3 and 2.3 MeV, respectively. In fact, they are found to be unbound by only 0.9 and 0.4 MeV, respectively, and have natural widths less than 1 MeV. Very little is known about ^{9}He and ^{10}He. Calculations based on mass systematics predict that ^{9}He may be unbound for one-neutron emission by anywhere from 2 to 4 MeV, and that ^{10}He may be unbound for two-neutron emission by as much as 5 MeV. Experimental attempts to detect either ^{9}He or ^{10}He have been uniformly unsuccessful so far.[6] Even if neither of these very exotic nuclei is bound, from the point of view of nuclear structure it is still very important to know how unbound these nuclei are, what level spectra they have, and what the widths and quantum numbers of their ground and excited states are. In this paper we report on the first successful observation of the ground state as well as several excited states of ^{9}He, the most neutron-rich nucleus ever identified ($N/Z = 3.5$).

The reaction $^9\mathrm{Be}(\pi^-,\pi^+)^9\mathrm{He}$ was studied at the EPICS channel at the Los Alamos Meson Physics Facility. The pion channel, the magnetic spectrometer, the special sweep magnet for double charge exchange (DCX), and the particle-detection system have been described before.[7] Particle identification was done by determination of time of flight through the spectrometer (~9-m distance), by a gas threshold Čerenkov counter to identify electrons, and by pion ranging in the focal plane. A high degree of electron, muon, and proton rejection was thus achieved. In order to take account of magnetic-field drifts, many four-hour miniruns were taken. Each minirun was separately analyzed for missing mass with use of the mean values of magnetic fields during that run. The missing-mass spectra were finally added without any shifts to obtain the overall missing-mass spectrum. The experiment was done in two different phases. The primary objective of the first phase was to identify the ^{9}He ground state (g.s.) and to measure its mass.[8] This experiment revealed a clear ground-state transition at the end of the phase space for two-body breakup of ^{9}He, and gave indications of the possible presence of several excited states. Accordingly, a second experiment was done with a thinner target which gave better energy resolution and led to unambiguous identification of at least three excited states. Figure 1 shows the spectrum obtained in this, the present run. The almost total absence of background for missing mass <0 should be noted.

The mass measurement experiment was done at $T(\pi) = 194$ MeV and $\theta(\mathrm{lab}) = 15°$. A 2.40-g/cm^2-thick target of metallic beryllium was used for the study of the reaction $^9\mathrm{Be}(\pi^-,\pi^+)^9\mathrm{He}$, and a 0.93-m/cm^2 target of graphite was used for the study of the calibration reac-

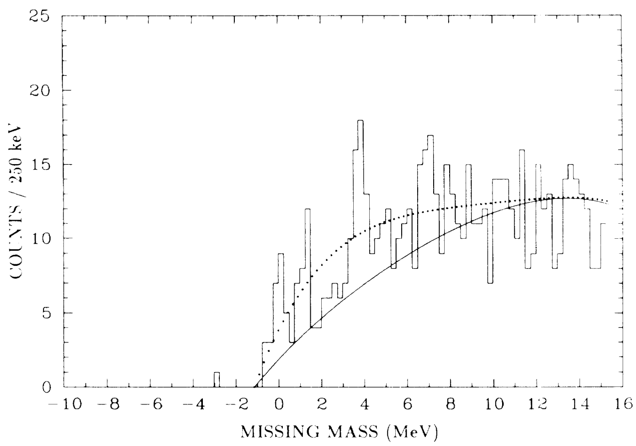

FIG. 1. Missing-mass spectrum for the reaction $^9Be(\pi^-, \pi^+)^9He$ for $T(\pi^-)=180$ MeV, $\theta(\text{lab})=15°$. The dotted curve illustrates the best fourth-order-polynomial fit to the full data (maximum likelihood: 45%). The solid curve illustrates the polynomial part of the fit when the data are fitted with a polynomial plus four Lorentzian peaks at 0, 1.2, 3.8, and 7.0 MeV (maximum likelihood: 95%).

tion $^{12}C(\pi^-,\pi^+)^{12}Be$(g.s.). The measurements with both the ^9Be and ^{12}C targets were done with the same undisturbed settings of the channel and the spectrometer magnets. The ^9He(g.s.) and ^{12}Be(g.s.) were clearly observed. The observed energy resolution for ^9He(g.s.) was FWHM ≈ 1 MeV. The differential cross section for the production of ^9He(g.s.) was found to be 40 ± 10 nb/sr, as normalized to the known $\pi^+ p$ elastic-scattering cross section.

The known Q value for the reaction $^{12}C(\pi^-, \pi^+)^{12}Be$(g.s.), $Q = -25.077 \pm 0.015$ MeV, provided the absolute reference point for the missing-mass scale. The scale calibration, kiloelectronvolts per channel, was determined by our keeping the spectrometer totally unchanged but tuning the channel for a 164-MeV π^+ beam so that ^{12}C elastic and inelastic scattering (from the 4.439-MeV state) could be measured with a thin CH_2 target. The resulting absolute scale for missing mass leads to the atomic $Q_0(^9He(\text{g.s.})) = -29.45 \pm 0.10$ MeV. This Q value corresponds to an atomic mass excess of 40.80 ± 0.10 MeV, which implies that the ground state is unstable against single-neutron decay by 1.13 ± 0.10 MeV. The quoted errors arise from the following, rather conservative estimates of uncertainties: ^9He(g.s.) centroid determination, ± 65 keV; ^{12}Be centroid determination, ± 55 keV; relative energy loss in targets, ± 50 keV; total of all other sources, $\leq \pm 20$ keV.

One interesting consequence of this mass measurement is that if it is used in the local Garvey-Kelson transverse relationship, it predicts that the doubly magic nucleus ^{10}He is unstable against one-neutron decay by 0.31 ± 0.14 MeV and against two neutron decay by 1.44 ± 0.14 MeV. These numbers are much smaller than any of the earlier predictions. They give us the hope that if ^{10}He can be searched for in the missing-mass spectrum of a two-body reaction, it is quite likely that it will be found that its ground state does not have too large a width. Unfortunately, one cannot think of too many such reactions; $^{10}Be(\pi^-,\pi^+)$ appears to be a rather unique but remote possibility!

In Table I, we note that the application of transverse Garvey-Kelson relations predicts ^9He(g.s.) unbound by amounts ranging from 3.55 to 2.36 MeV depending on whether one uses only masses of the adjoining five nuclei, or uses parameters optimized over more extended mass regions. In Table I we also list the results of recent shell-model calculations due to Glaudemans and collaborators at Utrecht. These calculations are notable in the fact that they do not assume any "closed core" and they use a translationally invariant interaction which allows them to avoid the problem of spurious states due to

TABLE I. Our experiment and a summary of ^9He mass predictions (GK stands for the transverse Garvey-Kelson relation).

Author (Ref.)	Model	Mass excess (MeV)	B_n (MeV)
This paper	Experiment	40.80 ± 0.10	-1.13 ± 0.10
This paper (from 8, 9)	Local GK	43.22 ± 0.25	-3.55 ± 0.25
Thibault, Klapisch (10)	Regional GK	42.75	−3.08
Jelly *et al.* (11)	Regional GK	42.61	−2.94
Janëcke (12)	Global GK	42.03	−2.36
Jelly *et al.* (11)	Shell-model systematics	43.49	−3.82
Beiner, Lombard, and Mas (13)	Energy density method	38.0	+1.67
Van Hees and Glaudemans (4)	$(0+1)\hbar\omega$ shell model (A)	43.08	−3.31
Poppelier, Wood, and Glaudemans (4)	$(0+1)\hbar\omega$ shell model (B)	40.88	−1.21
Poppelier, Wood, and Glaudemans (4)	$(0+2)\hbar\omega$ shell model (C)	44.08	−4.41

center-of-mass motion. Results of calculations using two different interactions have been reported. In the first calculation (A) in the $(0+1)\hbar\omega$ space, Van Hees and Glaudemans[4] determined the two-body matrix elements empirically from a fit to the energies of 136 levels in $A=4-16$ nuclei. In the second calculation, by Poppelier, Wood, and Glaudemans,[4] both the $(0+1)\hbar\omega$ space (B) and the $(0+2)\hbar\omega$ space (C) were used. The two-body matrix elements were derived from the realistic Reid soft-core potential and the mass-independent differences between the effective and the free nucleon-nucleon interactions were obtained by a fit to 146 energy levels. As we note in Table I the $(0+1)\hbar\omega$ calculation of Poppelier, Wood, and Glaudemans (calculation B) predicts the binding energy almost exactly, while the other two calculations, A and C, predict a much more unbound ^{9}He. Obviously it is necessary to examine other predictions of these calculations in order to determine if any of them is indeed markedly superior to the others.

The excited-state spectra predicted by the three calculations are shown in Fig. 2. We note that all calculations predict the $\frac{1}{2}^-$ ground state and a state at ~1.5-MeV excitation. However, there are notable differences

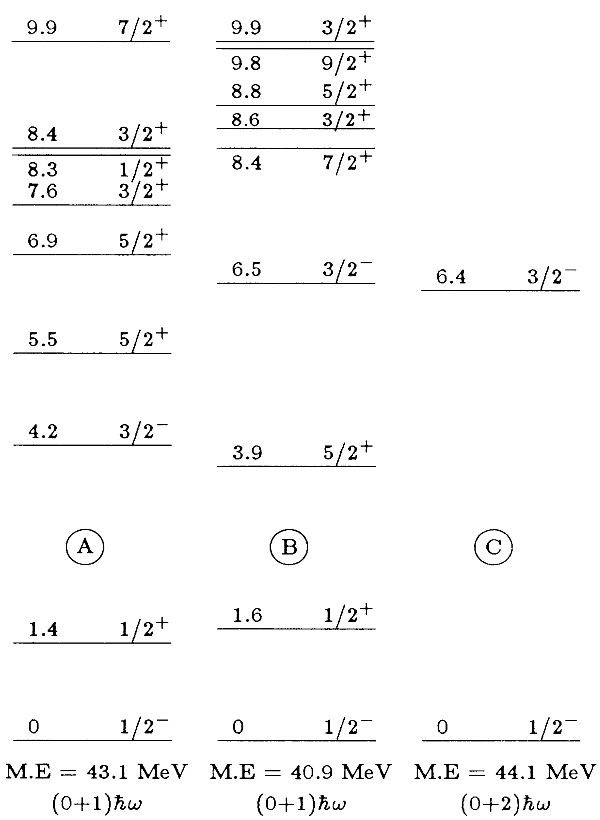

FIG. 2. Predicted excited-state spectra for ^{9}He. (A), Van Hees and Glaudemans (Ref. 4); (B) and (C), Poppelier, Wood, and Glaudemans (Ref. 4).

beyond that point. For example, between the two $(0+1)\hbar\omega$ calculations, A and B, there is a dramatic inversion of the $\frac{3}{2}^-$ and $\frac{5}{2}^+$ states. The agreement between the results of calculation B and the predictions of the $(0+2)\hbar\omega$ calculation C (which does not contain positive-parity levels) again suggests that calculation B is to be preferred over A.

In our mass-measurement experiment, which had an energy resolution FWHM ≈ 1.0 MeV, we had some evidence for states near 2- and 4-MeV excitation, deep in the continuum. However, no firm conclusions could be drawn. The predictions of the aforementioned shell-model calculation prompted us to make a new measurement with better energy resolution. An almost factor-2 thinner ^{9}Be target (0.928 g/cm^2) and a factor-2 higher-intensity beam ($\sim 3.5\times10^7$ π/sec) were used at $T(\pi^-) = 180$ MeV, $\theta(\mathrm{lab}) = 15°$. All other details of this experiment were the same as those for the earlier experiment. A companion elastic-scattering measurement provided an estimate of the overall experimental energy resolution as 420 ± 10 keV. The observed $^9\mathrm{Be}(\pi^-,\pi^+)X$ missing-mass spectrum is shown in Fig. 1. In this spectrum we can identify at least three peaks with widths $\gtrsim 420$ keV over and above the continuum. In order to determine the level of statistical significance for this conclusion, we have made a χ^2-based likelihood analysis of the data. As the shape for the nonresonant continuum spectrum we have used both a fourth-order polynomial and a mixture of three-body ($^8\mathrm{He}+n+\pi^+$) and four-body ($^7\mathrm{He}+2n+\pi^+$) phase spaces. We find that for the different constraints on the shape of the continuum spectrum, the hypothesis of no peaks in the data has a maximum likelihood of ~(40–50)%, whereas introducing four Lorentzian peaks at 0 MeV (FWHM $=420\pm100$ keV), 1.2 MeV (FWHM $=420\pm100$ keV), 3.8 MeV (FWHM $=500\pm100$ keV), and 7.0 MeV (FWHM $=550\pm100$ keV), leads to a very significant increase in the maximum likelihood, to ~95–98%. We therefore conclude that the states at 0, 1.2, and 3.8 MeV are certain, and the 7.0-MeV state is highly probable. The correspondence of the experimental level spectrum with the predictions of both calculations A and B is very good (perhaps fortuitously), and we are tempted to identify the first three states with the predicted sequence of the $\frac{1}{2}^-$, $\frac{1}{2}^+$, and ($\frac{5}{2}^+,\frac{3}{2}^-$) states. The broad structure at ~7-MeV excitation appears to correspond to the ($\frac{3}{2}^-,\frac{5}{2}^+$) state predicted at ~6.7 MeV. If our identifications are correct it is indeed remarkable that shell-model calculations whose parameters are optimized in the valley of stability should work so well so far from the valley.

In order to put our conclusions on a firmer basis it is necessary to measure the J^π of the various states of ^{9}He. However, since this nucleus is only produced in an exotic reaction such as double charge exchange, it is rather unlikely that even the L transfers can be determined, except in one case. One can attempt to determine whether any of these states have identifiable $L=0$ components in their angular distributions and therefore $J^{\pi}=\frac{3}{2}^{-}$. This may allow a choice to be made between the different interactions of calculations A and B. In order to investigate this possibility and to investigate higher-lying narrow states it is planned to make a high-resolution, high-statistics investigation of the reaction $^{9}Be(\pi^{-},\pi^{+})^{9}He$ at several forward angles in the near future.

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

[(a)]Now at EG&G, Santa Barbara, CA 93102.

[(b)]Now at Massachusetts Institute of Technology, Cambridge, MA 02139.

[(c)]Now at Indiana University, Bloomington, IN 47405.

[1]See, for example, M. J. A. de Voigt, J. Dudek, and Z. Szymanski, Rev. Mod. Phys. **55**, 949 (1983).

[2]See, for example, Proceedings of the Fourth International Conference on Nuclei Far from Stability, edited by P. G. Hansen and O. B. Nielsen, CERN Report No. CERN 81-09, 1981 (unpublished).

[3]V. R. Pandharipande and R. B. Wiringa, Rev. Mod. Phys. **51**, 821 (1979); V. R. Pandharipande, private communication.

[4]A. G. M. Van Hees and P. W. M. Glaudemans, Z. Phys. A **314**, 323 (1983), and **315**, 223 (1984); N. A. F. M. Poppelier, L. D. Wood, and P. W. M. Glaudemans, Phys. Lett. **157B**, 120 (1985).

[5]G. T. Garvey and I. Kelson, Phys. Rev. Lett. **16**, 197 (1966); G. T. Garvey *et al.*, Rev. Mod. Phys. **41**, 51 (1969).

[6]S. L. Whetstone, Jr., and T. D. Thomas, Phys. Rev. **154**, 1174 (1967); S. W. Cosper, J. Cerny, and R. C. Gatti, Phys. Rev. **154**, 1193 (1967); A. A. Vorobiev *et al.*, Leningrad Nucleon Physics Institute Report No. 232, 1969 (unpublished); G. G. Beznogikh *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 323 (1979) [JETP Lett. **30**, 349 (1979)]; R. Bayer *et al.*, Czech. J. Phys. **31**, 1273 (1981); Y. T. S. Ognesyan *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 104 (1982) [JETP Lett. **36**, 129 (1982)].

[7]K. K. Seth *et al.*, Phys. Lett. **173**, 397 (1986), and references therein.

[8]A preliminary report of this measurement was presented earlier. See K. K. Seth, in Ref. 2.

[9]A. H. Wapstra and G. Audi, Nucl. Phys. **A432**, 1 (1985).

[10]C. Thibault and R. Klapisch, Phys. Rev. C **6**, 1509 (1972).

[11]N. A. Jelly, J. Cerny, D. P. Stahel, and K. H. Wilcox, Phys. Rev. C **11**, 2049 (1975).

[12]J. Jänecke, At. Data Nucl. Data Tables **17**, 455 (1976).

[13]M. Beiner, R. J. Lombard, and D. Mas, Nucl. Phys. **A249**, 1 (1975).