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# Mass and Half-Life of $^9C$†

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The mass of $^9C$ has been measured by counting delayed protons near the $^7Be(^3He, n)^9C$ threshold. The data are consistent with an $s$-wave threshold at $E_{^3He} = 8980 \pm 5$ keV, giving a $^9C$ mass excess of $28\,907 \pm 4$ keV, and confirming the reported deviation of the $A = 9$, lowest $T = \frac{3}{2}$ quartet from the quadratic mass formula. The half-life of $^9C$, measured with a multiscaler, is $126.5 \pm 2$ msec.

The ground states of $^9C$ and $^9Li$ together with the $T = \frac{3}{2}$ excited states at 14.392 MeV in $^9Be$ and at 14.655 MeV in $^9B$ have been the subjects of considerable investigation because they form one of the few presently accessible isospin quartets. This experiment was undertaken to attempt to verify and improve the measurement of the $^9C$ mass. The experimental method of deducing that quantity from the threshold energy of the $^7Be(^3He, n)^9C$ reaction had been used previously by Barnes *et al.*[1]

A $^7BeO$ target, prepared for an earlier experiment[2] by evaporating under vacuum a $\frac{1}{8}$-in.-diam spot of $^7BeF_2$ onto a 1.2-mm-thick platinum bar and then oxidizing the layer in air, provided a surface density of $7 \times 10^{16}$ $^7Be$ atoms per cm$^2$. This number represents about half of the $^7Be$ present when the target was first prepared, the other half having decayed to $^7Li$, which, along with the oxygen and other impurities, contributed to a measured target thickness of 10 keV for the 9-MeV $^3He^{++}$ beam supplied by the Office of Naval Research-California Institute of Technology tandem Van de Graaff accelerator near the reaction threshold.

The target was mounted in a chamber[2] equipped with a solenoid-operated arm capable of switching the target between a beam line and a counting position in an 873-msec cycle. For the first 290 msec of each cycle, the target spot was exposed to $\sim\frac{1}{2}$ $\mu$amp $^3He$. If $^9C$ was formed, it would be expected to $\beta^+$ decay into the broad particle-unstable states of $^9B$, which almost immediately break up into a proton plus $^8Be$. Thus, in the second part of the cycle, after the beam had been deflected, the target was moved directly in front of a $\Delta E + E$ telescope consisting of an 11- and a 26-$\mu$m silicon detector, with a geometrical efficiency of ~15%. This arrangement of counters was necessary in order to be able to sort out the protons accompanying $^9C$ decays from the intense background of 478-keV $\gamma$ rays emitted by the 50 mCi of $^7Be$, as well as from the $\alpha$ particles and other activity induced by the $^3He$ bombardment. When a pulse from the $\Delta E$ counter consistent with a proton energy loss of 0.27–0.55 MeV arrived in coincidence with a pulse from the $E$ counter large enough to be distinguished from the $\gamma$-ray background, the sum was recorded by a multichannel analyzer. The natural radioactivity of the target restricted both the choice of detector volume and the smallest $\Delta E$ (largest proton energy) that could be accepted. Two successive counting periods of 229 msec each were recorded separately to provide a check of the half-life.

Figure 1 shows the sum of the spectra obtained during the 16 threshold runs. The broad group of protons with 0.75–3.0-MeV energy loss in the counters is clearly separated from the constant $\gamma$-ray background at the low-energy end. Because some of the delayed protons had ranges greater than the total thickness of the two detectors and/or values of $\Delta E$ outside our 0.27–0.55-MeV window, the shape of the observed spectrum is essentially determined by the coincidence requirements rather than by the actual distribution of proton energies.

During a typical 40-min run, the target was exposed to an integrated beam current of 300 $\mu$C. The yield, taken as the sum of the counts accumulated in channels 27 through 100, varied with $^3He^{++}$ bombarding energy as shown in Fig. 2. If one assumes that $l = 0$ neutrons are emitted near threshold, then the cross section is expected to vary as $(E - E_T)^{1/2}$, where $E_T$ is the threshold energy. The solid curve, fit to the data points in an interval ~200 keV around the threshold, combines the effect of such an $s$-wave dependence with the effects of the measured target thickness and the observed 2 counts/300-$\mu$C background. It defines a nominal threshold energy to ±1 keV. The beam-analyzing magnet was calibrated immediately after these runs by locating the threshold of the $^6$Li($\alpha$, $n$)$^9$B reaction ($E_T$ = 6624.6 ± 2 keV)[3] on a freshly evaporated $^6$Li target, oxidized in air. (The required magnetic field differed by less than 1% from that used in the $^9$C measurement.) Neutrons were detected with a NE402 scintillator at 0°, with results as shown in Fig. 3.

The calibrated energy of the $^7$Be($^3$He, $n$)$^9$C threshold was thus found to be 8980 ± 5 keV. The quoted error reflects the uncertainty in the two threshold measurements and in the reproducibility of magnet flux settings, and the possibility of an undetected 1-keV carbon layer on the surface of either target (carbon accumulated during earlier use of the $^7$Be target had been previously removed by briefly heating to redness in air). Translating the threshold energy into the center-of-mass system and using the latest atomic masses[3] one infers a $^9$C mass excess of 28 907 ± 4 keV, slightly lower than the 28 916 ± 5 keV reported previously by Barnes *et al.*[1] and the recent value 28 911 ± 9 keV of Trentelman, Preedom, and Kashy.[4]

The theoretical fit to the threshold data follows the higher-energy yields for more than an MeV above threshold. At the highest energies, however, there is a systematic tendency for the cross section to fall off, presumably owing to the opening of additional channels for the decay of the compound nucleus. A bombarding energy near the peak at ~11 MeV was used to produce $^9$C for the half-life measurement.

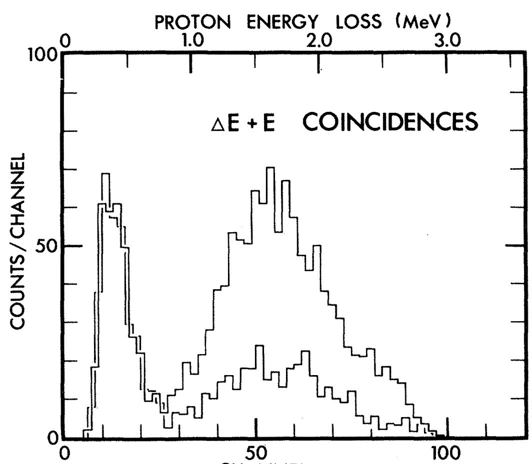


FIG. 1. The pulse-height-sum spectra recorded from the counter telescope in two successive 229-msec time bins after repetitive beam bursts, showing the energy distribution and dwindling intensity from delayed protons following $^9$C decay. The rise below channel 20 is due to the intense $\gamma$-ray flux from the radioactive target. These spectra were accumulated during runs at bombarding energies in the range 8.9 $E_{^3\mathrm{He}} \leq 11.0$ MeV; the individual runs were summed above channel 25 to give the yields plotted in Fig. 2.

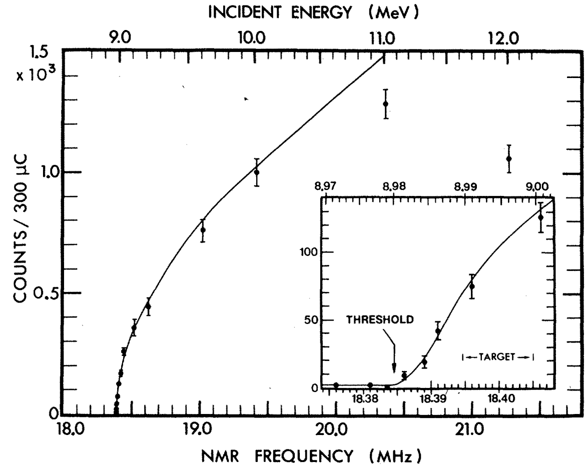


FIG. 2. Observed yield of delayed-proton counts vs bombarding energy, fitted with a curve calculated for an $s$-wave threshold at 8980 keV, 10-keV target thickness, and a background of 2 counts per 300 $\mu$C. The inset shows an expanded view of the threshold data.

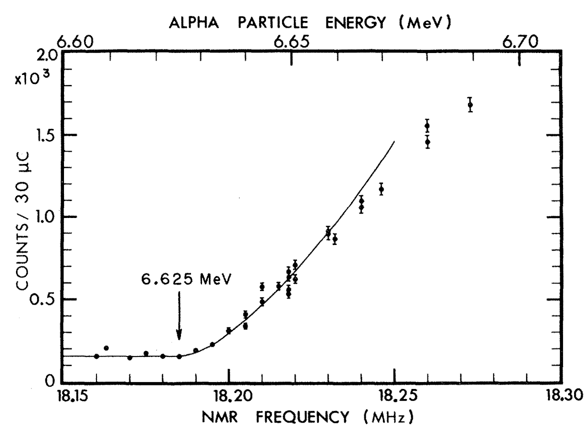


FIG. 3. The neutron yield at 0° vs $E_\alpha$ from the $^6$Li($\alpha$, $n$)$^9$B neutron near threshold. The calculated curve assumes the expected $s$-wave threshold for a thick target and a constant background, and fits the data below 18 240 kHz for a threshold at $\nu$ = 18 185 ± 2 kHz. The magnetic-analyzer constant derived from this measurement is in excellent agreement (<150 ppm) with three earlier calibrations extending over 5 yr.

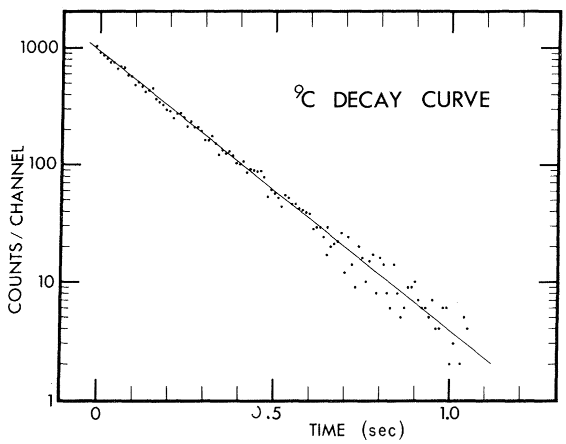


FIG. 4. Delayed-proton counts per 10-msec time bin in a cyclic multiscaler. The curve is a least-squares fit of the form $Ne^{-t/\tau}+C$, with $\tau=126.5\pm1.7$ msec and $C=0.1\pm1.7$; $\chi^2=1.2$ per degree of freedom.

In measuring the half-life, the coincident pulses arriving in the proton group were sorted into 10-msec time bins, with a multiscaler controlled by a quartz-crystal oscillator. The cycle period was also increased from 0.9 to 2.2 sec to provide a longer look at the decaying activity. The result of 4000 $\mu$C of beam is shown in Fig. 4, where the points represent the total counts accumulated in the successive 10-msec intervals. A least-squares fit, including the possibility of a constant background level, indicates a half-life of $126.5\pm2$ msec, in agreement with the $127\pm3$ msec reported previously by Hardy *et al.*[5]

The masses of the $A=9$ isospin-quartet states may be used to test the quadratic mass formula

$$M(T_z)=a+bT_z+cT_z^2.$$

Such a law leads to the prediction that

$$M(^9\mathrm{C})-M(^9\mathrm{Li})=3[M(^9\mathrm{B}^*)-M(^9\mathrm{Be}^*)].$$

Measurements[1,6] of the $Q$ values for $^7$Li($^3$He, $n$)$^9$B* and $^7$Li($^3$He, $p$)$^9$Be* indicate that

$$M(^9\mathrm{B}^*)-M(^9\mathrm{Be}^*)=1330.4\pm7\ \mathrm{keV}.$$

TABLE I. The masses used in the comparison with the quadratic and cubic mass formulas for the lowest $T=\frac{3}{2}$ states of the $A=9$ nuclei.

| Level | $T_z$ | Mass and error (keV) | Reference |
|---|---|---|---|
| $^9$Li | $\frac{3}{2}$ | 24 965 ± 5 | 7 |
| $^9$Be* | $\frac{1}{2}$ | 25 743 ± 5 | 6 |
| $^9$B* | $-\frac{1}{2}$ | 27 074 ± 5 | 1 |
| $^9$C | $-\frac{3}{2}$ | 28 910 ± 3 | Average of 1, 4, and the present work |

[An attempt to utilize the unique properties of our half-$^7$Be–half-$^7$Li target to reduce the uncertainty in this quantity by simultaneously observing protons from the reactions $^7$Li($^3$He, $p$)$^9$Be* and $^7$Be($^3$He, $p$)$^9$B* was thwarted by background problems.] The mass excess of $^9$Li has been measured to be $24965\pm5$ keV.[7] Hence the predicted mass excess of $^9$C is $28956\pm22$ keV, exceeding the experimental value reported here by $49\pm22$ keV. (That the four measured masses fit the quadratic law has a probability of only 2%.)

Table I summarizes the best values of the four $A=9$ masses, and in Table II the corresponding parameters of the quadratic and cubic mass formulas are given. Since the value obtained for the coefficient of $T_z^3$ ($d=8\pm4$) is of roughly the same magnitude as the fine-structure constant times the coefficient of $T_z^2$, there is no obvious indication from these results of an isotensor component to the electromagnetic interaction.[1,8]

Recent calculations by Jänecke[9] demonstrate that the magnitude of the deviation from the quadratic formula would imply either a large amount of isospin mixing in the $|T_z|=\frac{1}{2}$ members of the quartet (~15% in intensity) or large off-diagonal elements of the vector Coulomb-energy operator. Either of these alternatives involves sufficient isospin mixing so that they are probably inconsistent with the observed value for the width of the lowest $T=\frac{3}{2}$ state in $^9$Be, $\Gamma=0.8\pm0.3$ keV.[6,10] Because of this result it is obviously worth considering other effects that might also account for the deviation. One such effect is that proposed by Thomas[11] and by Ehrman[12] due to the differing two-body binding energies across the multiplet.

The lowest $A=9$ quartet is not expected to be strongly affected by this type of shift, because the dominant configuration[13] of the states involved [(32)$^2$P] is not that of the nearest threshold [$A=8$ ($T=1$) + nucleon]. However, since we are dealing with only a small discrepancy, a Thomas-Ehrman shift is not obviously negligible. The model used for this investigation consists of the interaction of a two-body configuration by means of a Woods-Saxon nuclear potential and the Coulomb potential produced by a trapezoidal charge distribution matched to the Woods-Saxon shape

TABLE II. The parameters (in keV) obtained using the masses listed above in the mass formula $M_{T_z}=a+bT_z+cT_z^2+dT_z^3$.

| $a$ | $b$ | $c$ | $d$ | $\chi^2$ |
|---|---|---|---|---|
| 26 342 ± 4 | −1333 ± 8 | 264.5 ± 2 | 8.0 ± 3.7 | ... |
| 26 342 ± 4 | −1316 ± 2 | 264 ± 2 | 0.0 (fixed) | 4.6 |

TABLE III. The values of $V_0$ in MeV for the states of the lowest $T=\frac{3}{2}$ multiplet in the $A=9$ nuclei using the configuration, $[A=3]+[A=6\ (T=1)]$, with $R=3.0$ fm and $a=0.70$ fm.

| $^{9}$Li ($^{6}$He$+t$) | ($^{6}$Li$^*+t$) $\frac{2}{3}$ | $^{9}$Be* Weighted average | ($^{6}$He$+^{3}$He) $\frac{1}{3}$ | ($^{6}$Be$+t$) $\frac{1}{3}$ | $^{9}$B* Weighted average | ($^{6}$Li$^*+^{3}$He) $\frac{2}{3}$ | $^{9}$C ($^{6}$Be$+^{3}$He) |
|---|---|---|---|---|---|---|---|
| | 27.71 | | 28.44 | 27.59 | | 28.07 | |
| 28.03 | | 27.95 | | | 27.91 | | 27.97 |

TABLE IV. The values of $V_0$ in MeV for the states of the lowest $T=\frac{3}{2}$ multiplet in the $A=9$ nuclei using the configuration, nucleon$+[A=8\ (T=1)]$, with $R=3.0$ fm and $a=0.52$ fm.

| $^{9}$Li ($^{8}$Li$+n$) | ($^{8}$Li$+p$) $\frac{1}{3}$ | $^{9}$Be* Weighted average | ($^{8}$Be$^*+n$) $\frac{2}{3}$ | ($^{8}$B$+n$) $\frac{1}{3}$ | $^{9}$B* Weighted average | ($^{8}$Be$^*+p$) $\frac{2}{3}$ | $^{9}$C ($^{8}$B$+p$) |
|---|---|---|---|---|---|---|---|
| | | | (16.63) [a] | | | (16.63) [a] | |
| | | | 35.49 | | | 35.01 | |
| | 35.49 | | (16.93) [a] | 35.49 | | (16.93) [a] | |
| | | | 36.04 | | | 35.62 | |
| 35.76 | | 35.67 | | | 35.37 | | 34.96 |

[a] The two separate values given for $^{8}$Be*+nucleon result because the $T=1$ strength in $^{8}$Be is approximately equally divided between the states at 16.63 and 16.93 MeV.

$$V_{\rm nuclear}(r)=\frac{-V_0}{1+e^{(r-R)/a}}\ ,$$

where $R$ is the "nuclear radius" and $a$ is the surface diffuseness. The justification for this model has been given previously[14] and will not be repeated here.

Two different configurations were investigated: an $A=3$ particle bound to an $A=6$ $(T=1)$ nucleus – closely representing the dominant configuration of the $A=9$ quartet states; and a nucleon bound to an $A=8$ $(T=1)$ core – representing the nearest two-body threshold. Using the masses given in Table I, the $V_0$'s were varied until each of the members of the quartet lay at the correct binding energy relative to the threshold. The results are summarized in Tables III and IV.

The agreement of the values of $V_0$ for the $[A=3]+[A=6\ (T=1)]$ configuration is what one would expect from the charge symmetry of nuclear forces. However, the spread in the values of $V_0$ for the configuration, nucleon$+[A=8\ (T=1)]$, indicates that even a small admixture of this configuration would easily produce a Thomas-Ehrman shift large enough to account for the mass discrepancy observed. If, for example, the value of $V_0(1+8)$ obtained for $^{9}$Li is used for $^{9}$C, the binding energy of $^{9}$C would be overestimated by 0.38 MeV. With an admixture of approximately 10% (in intensity) for the nucleon$+[A=8]$ configuration,[13] a shift comparable in magnitude with the observed deviation is obtained. It therefore seems more reasonable for the moment to attribute the coefficient of $T_z^3$ to this source, rather than to isospin mixing or corrections to the Coulomb interaction itself.

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