Mass of ^8He[‡]

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A new precision measurement of the mass of ^8He has been performed by observing ^8He events from the reaction $^{64}Ni(^4He,^8He)^{60}Ni$ at an incident beam energy of 80 MeV. The Q values and mass excess are determined to be $Q = -31.796 \pm 0.008$ MeV and mass excess = 31.593 ± 0.008 MeV. The new ^8He mass allows for a more stringent test of the isobaric multiplet mass equation in the $A = 8$ quintet. A significant deviation from the quadratic mass equation persists.

[NUCLEAR REACTIONS $^{64}Ni(^4He, ^8He)$. Measured reaction Q value and mass excess. Deduced coefficients of IMME for the $A=8$ isobaric quintet.]

INTRODUCTION

Q-value measurements of multinucleon transfer reactions have proven to be an extremely useful way to probe nuclear properties far from the valley of stability. The four neutron transfer (^4He, ^8He) has been used to determine nuclear masses of several proton-rich nuclei. In order for the (^4He, ^8He) reaction to be a useful spectroscopic tool, it is important to have an accurate determination of the ^8He mass. Previously four ^8He mass measurements have been performed. Their results are summarized in Table I where we note that the previous best single measurement determined the ^8He mass to an uncertainty of 17 keV.

An additional motivation for obtaining an accurate ^8He mass excess is that it represents the $T_Z=2$ member of the $A=8$ isobaric quintet. $A=8$ is the only isobaric quintet in which the masses of all five members have been determined. The quadratic isobaric multiplet mass equation (IMME), which predicts that the masses of isobaric multiplets are related by $M=a(A, T)+b(A, T)T_Z+c(A, T)T_Z^2$ with a, b, and c constant for a given multiplet,[1] does not provide a good fit to the $A=8$ quintet. Indeed the previous experimental results suggest possible T_Z^3 and T_Z^4 contributions to the IMME.[2,3] Isospin quartet tests have verified that the quadratic IMME is sufficient to account for their experimental masses except in the case of the ground state $A=9$ quartet, where a T_Z^3 term must be added.[4] The size of the deviation suggested in $A=8$ is comparable to that observed in $A=9$. Possible causes of such a breakdown of the quadratic IMME in $A=8$ have been discussed previously in Refs. 2 and 3.

TABLE I. Summary of previous ^8He mass measurements.

Reaction	Mass excess (MeV)	Reference
$^{26}Mg(^4He,^8He)^{22}Mg$	31.65 ±0.12	10
$^{26}Mg(^4He,^8He)^{22}Mg$	31.57 ±0.03	11
$^{18}O(^4He,^8He)^{14}O$	31.600 ±0.025	12
$^{64}Ni(^4He,^8He)^{60}Ni$	31.613 ±0.017	13

The experiment reported here has been optimized to perform a precision measurement of the ^8He mass. The new result significantly reduces the uncertainty in the ^8He mass excess and allows for a more stringent test of the IMME in the $A=8$ isospin quintet.

EXPERIMENTAL PROCEDURE

The ^8He mass was determined by measuring the Q value of the $^{64}Ni(^4He, ^8He)^{60}Ni$ reaction with an 80 MeV α beam from the Texas A & M University 88 inch cyclotron. ^8He events were observed by a 10 cm single-wire gas proportional counter backed by a 5-cm × 1-cm × 600-μm Si solid-state detector, in the focal plane of an Enge split-pole magnetic spectrograph. Particle identification was determined from the three constraints: (1) $(dE/dx)_{gas}$, (2) E_{Si}, and (3) time of flight relative to the cyclotron rf. Particle position was found by charge division performed by an on-line computer. In previous experiments, the gas proportional counter, solid-state detector combination has been shown to be sensitive to ^8He cross sections of less than 500 pb/sr.[5] In the present experiment, this sensitivity corresponds to no observable background in the ^8He spectrum.

In addition to the gas proportional counter-solid-state detector, a second particle detector was placed in the focal plane at lower ρ in order to monitor inelastic α events. The second detector was a 20-cm single wire gas proportional counter backed by a plastic scintillator. Particle identifi-

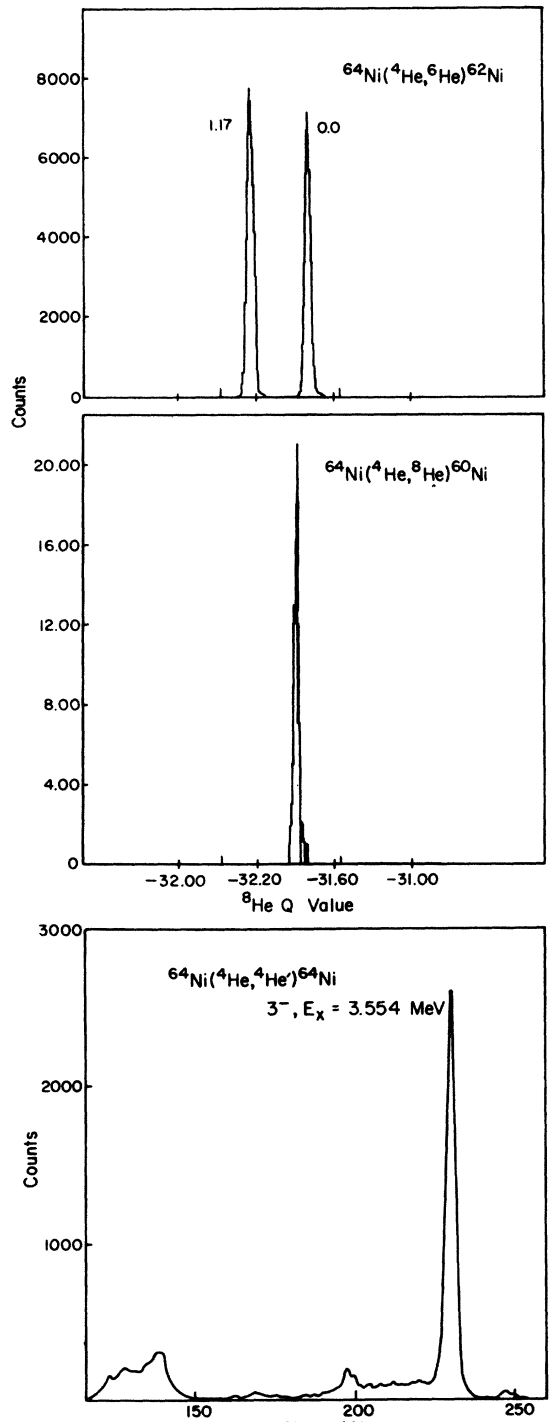

FIG. 1. ^{6}He and ^{8}He spectra obtained at $\theta_{lab} = 7°$ with a 2 msr solid angle. The inelastic α peak was obtained with a 0.5 msr solid angle at the same laboratory angle.

cation was determined by electronic windows set on the $(dE/dx)_{gas}$, and $(E)_{plastic}$ signals. Particle position was again determined by charge division performed by the on-line computer. The vertical acceptance of the 20 cm counter was limited to ~0.2 mm in order to reduce the particle event rate. In addition, a 2-cm horizontal slit was placed around a strong inelastic peak ($E_x = 3.55$ MeV) thus eliminating the elastic scattering events from the detector. The combination of the two slits provided a system monitor with an acceptable count rate into the computer.

In order to perform a precision mass measurement in a magnetic spectrograph, care must be taken in the choice of the calibration reaction. The natural calibration reaction for the ^{8}He measurement was the ^{64}Ni(^{4}He, ^{6}He)^{62}Ni reaction. The incident α beam energy was chosen so that ground state ^{8}He events would occur on the focal plane between the ground and first excited state ^{6}He events from the calibration reaction. Typical ^{6}He and ^{8}He spectra are shown in Fig. 1. Also included in the figure is an inelastic α spectrum obtained in the second counter. Using the ^{6}He groups as calibrants minimizes the uncertainty in the mass determination due to target thickness, incident beam energy, and scattering angle uncertainties. The ^{8}He Q value becomes quite sensitive to the ^{6}He Q value and correspondingly to the focal plane calibration, however.

The ^{64}Ni(^{4}He, ^{8}He)^{60}Ni cross section is quite small, thus necessitating long runs in order to obtain statistical accuracy for the peak centroid. Beam energy and magnetic field drifts were potential systematic errors unless carefully monitored. The ^{6}He peak centroids in the ^{8}He detector and the inelastic α particles in the second detector were checked as a function of time during the ^{8}He acquisition. The system stability was found to be quite good over extended periods (i.e., less than 4-keV drifts were observed during 12-h runs). As an additional check, a low count rate precision pulse generator was used to monitor the stability of the electronics.

The incident beam energy was found by comparing elastic deuterons with tritons from the ^{12}C(d, d)-^{12}C and ^{12}C(d, t)^{11}C reactions, with a deuteron beam accelerated to the same magnetic rigidity as the incident ^{4}He beam. A momentum match between the (d, d) and (d, t) reactions from ^{12}C is very sensitive to the scattering angle. Thus the angle was determined directly by inserting a Formvar target and measuring ^{12}C(d, d)^{12}C vs H(d, d)H. Including uncertainties due to target thickness, scattering angle and peak centroids, the deuteron beam energy was determined to an uncertainty of ~5 keV.

The finite solid angle of the magnetic spectrograph introduces a possible systematic error since the peak shape is affected by the reaction angular distribution. This effect is, of course, minimized at the kinematic focus but it is not necessarily

TABLE II. Experimental uncertainties and results for the present ^{8}He mass measurement.

Source of uncertainty	Estimated error (keV)
Beam energy	2.5
Reaction angle	< 1
Target thickness	3
Centroid uncertainty[a]	3.7
Focal plane calibration	4.2
$\sigma(\theta)$	4
Other masses	2

Experimental results

θ_{lab}	$\left(\frac{d\sigma}{d\Omega}\right)_{lab}$	Q value[b]
5	36 ±8 nb/sr	−31.797 ±0.005
7	44 ±8 nb/sr	−31.795 ±0.005

Accepted values including all uncertainties
$Q = -31.796 \pm 0.008$ MeV
Mass excess = 31.593 ±0.008 MeV

[a] ^{6}He centroid plus Q-value uncertainties.
[b] Includes centroid, beam energy, and calibration (centroid) uncertainties.

eliminated. ^{8}He data were obtained with horizontal apertures corresponding to angle integration (solid angles) of 3° (~2 msr) and 6° (~4 msr). The two spectra, which had sufficient statistics to provide separate mass determinations, had identical centroids within their statistical uncertainties. Thus an upper limit for a centroid shift was determined. The ^{6}He centroids did shift slightly as a function of acceptance angle. Thus the aperture was reduced to a 0.5° horizontal acceptance for the actual ^{6}He calibration runs.

In addition to the solid angle checks, which were carried out at a 7° laboratory angle, a separate mass measurement was performed at $\theta_{lab} = 5°$. The 5° measurement was performed with a solid angle of ~2 msr corresponding to a horizontal acceptance of ~3°. The results of the 5° and 7° measurements were in excellent agreement as is indicated in Table II. The laboratory cross sections, averaged over the 2-msr solid angle were 36 ± 8 nb/sr at 5° and 44 ± 8 nb/sr at 7°. The cross section uncertaihties include charge integration, vertical acceptance, target thickness, and statistical uncertainties.

The uncertainties in the mass measurement for the narrow aperture determination at 7° are summarized in Table II. The focal plane calibration uncertainty includes both the ^{64}Ni(^{4}He, ^{6}He)^{62}Ni Q value and ^{6}He peak centroid uncertainties. The target thickness was determined both by weighing and by an ^{241}Am α energy loss measurement. The two methods were in good agreement and the target thickness quoted in the table is an average of the two measurements. The centroid uncertainty is quoted for one standard deviation $\sigma/\sqrt{N}$.

The final values for the reaction Q value and mass excess are $Q = -31.796 \pm 0.008$ MeV, mass excess = 31.593 ± 0.008 MeV. The new result is based upon mass excesses from the 1976 preliminary revision to the Wapstra-Gove mass table[6] and the ^{64}Ni(^{4}He, ^{6}He)^{62}Ni calibration reaction Q value of −17.800 ± 0.005 MeV.

DISCUSSION

The new ^{8}He mass measurement is in excellent agreement with the previous determinations given

TABLE III. Summary of the $A = 8$ isobaric quintet properties. Uncertainties are listed in parentheses.

	T_Z	Mass excess (MeV)	E_x (MeV)	Width $\Gamma_{c.m.}$
^{8}C[a]	−2	35.096(0.026)	0.0	230 ±50
^{8}B[b]	−1	33.542(0.009)	10.619(0.009)	32 ±25
^{8}Be[c]	0	32.4360(0.0017)	27.4942(0.0016)	12 ±3
^{8}Li[b]	1	31.7694(0.0054)	10.8219(0.0055)	< 12
^{8}He[d]	2	31.596(0.007)	0.0	Bound

Predicted coefficients in units of MeV for the IMME

a	b	c	d	e	χ^2
32.4349(16)	−0.8826(41)	0.2295(25)	0	0	8.1
32.4356(17)	−0.8946(63)	0.2254(29)	0.0058(23)	0	1.5
32.4360(17)	−0.8820(41)	0.2134(69)	0	0.0043(17)	1.7
32.4360(17)	−0.8901(73)	0.2171(74)	0.0038(28)	0.0026(21)	···

[a] Weighted average of Ref. 2 (revised) and Ref. 3.
[b] Reference 14.
[c] Weighted average of Refs. 14–16.
[d] Weighted average of present results along with Refs. 11–13.

TABLE IV. Proton separation energies for the lowest $T=2$ states of ^{8}Be, ^{8}B, and ^{8}C.

Neutrons	S_{1p} (MeV)	S_{2p} (MeV)
^{8}Be	−10.2	+0.26
^{8}B	−0.53	+1.33
^{8}C	−0.13	+2.14

in Table I. Thus using a weighted average of the four best measurements we find the mass excess to be 31.596 ±0.007 MeV. This represents a 7-keV shift from the previous value of 31.603 ± 0.013 MeV which was a weighted average of the last three entries in Table I. The new ^{8}He mass causes a shift in the ^{8}C mass determined by the ^{12}C(^{4}He, ^{8}He)^{8}C reaction.[2] The adjusted ^{8}C mass when combined with a separate measurement via the ^{14}N(^{3}He, ^{9}Li)^{8}C reaction[3] yields the mass excess 35.096 ± 0.026 MeV.

The adjusted $A=8$ masses are given in Table III where the properties of the $A=8$ isobaric quintet members are reviewed. Also included in the table are the coefficients for quadratic, cubic, and quartic IMME fits. The quadratic fit is not good as evidenced by the total $\chi^2=8.1$. We should note, however, that the deviation between the predicted and observed ^{8}Li mass excess contributes 5.5 to the χ^2. The four parameter fits with $d=0$ or $e=0$ are of comparable quality. The full five parameter fit gives $d=3.8\pm2.8$ keV and $e=2.6\pm2.1$ keV.

In the $A=8$ system, two effects could give rise to non-negligible second order contributions in the IMME and hence introduce cubic and quartic coefficients. The perturbation caused by isospin mixing in ^{8}Be has been discussed previously by Robertson *et al.*[3] Particle decays of the $T=2$ state in ^{8}Be suggest $\Delta T=0$ and possibly $\Delta T=1$ isospin mixing. This second order effect would give rise to a nonzero quartic coefficient in the IMME. For a simple two-state mixing, the size of the deviation suggested by the e coefficient in Table III would require nearly degenerate unperturbed eigenstates and a modest Coulomb matrix element of ~50 keV.

The other dominant perturbation is the size-alternation that is induced by binding energy differences. In Table IV the one and two proton separation energies are listed for the ^{8}Be, ^{8}B, and ^{8}C members of the quintet. We note that these three members are all unbound to two proton decay and the threshold for single proton emission drops to only 130 keV for the ^{8}C system. The small nuclear binding should result in somewhat more diffuse wave functions for the proton-rich members of the quintet and hence reduced Coulomb energies relative to tightly bound systems. Bertsch and Kahana[7] considered a similar size-alternation perturbation and found rather small ($d \leq 1$ keV) contributions to the IMME. More recently Benenson *et al.*[8] discussed the binding energy effect in the $A=27$ isospin quartet. In $A=27$ the valence nucleons are $(d_{5/2})^2(S_{1/2})$. For the same binding energy, the radial wave function of a $d_{5/2}$ proton is much larger in the interior than a corresponding $S_{1/2}$ wave function. In Ref. 8 the authors predicted substantial energy shifts for the proton-rich members of the quartet based upon a quite simple single-particle shell model picture that included the difference in the radial wave functions. Due to a cancellation, the energy shifts did not produce a d coefficient, however. We have extended the calculation by simply increasing the masses of all the multiplet members by the ^{27}P binding energy (hence ^{27}P becomes approximately unbound), and recalculating an expected d coefficient. The result is still consistent with $d=0$ even though the single-particle Coulomb energy is changing rather rapidly. This simple calculation suggests that treated as a perturbation, the effect of the binding energy would be to change the coefficients of the quadratic IMME without involving significant higher order terms. A similar result has been suggested for other perturbations.[9]

In $A=8$, the number of nucleons is so small that a single-particle calculation based upon a nuclear core is not reasonable. Instead a somewhat more careful analysis is required to estimate the Coulomb energy shift. The data suggest that the second order effect should be sizable in this system. It would be quite interesting to determine if a sizable d coefficient could be accommodated theoretically.

Finally we note that the apparent deviation from the quadratic IMME in $A=8$ arises almost entirely from the ^{8}Li mass excess. If this mass is removed from the quintet, a quadratic fit to the four remaining masses produces a $\chi^2=0.1$. A four parameter fit to these masses predicts a d coefficient of $d=1.2\pm4.4$ keV. Albeit the uncertainty is large, this result would not suggest a serious breakdown of the quadratic IMME. Since the IMME fits are so sensitive to the ^{8}Li mass excess, it would be quite useful to verify the present result.

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