Mass of ^{67}Ni†

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The three nucleon pickup reaction ^{70}Zn(^{4}He,^{7}Be)^{67}Ni has been employed to observe the $T_z = 11/2$ ^{67}Ni nucleus. The ^{67}Ni mass excess is found to be -63741 ± 22 keV. Comparison is made to recent predictions.

[NUCLEAR REACTIONS ^{70}Zn(^{4}He,^{7}Be)^{67}Ni; Q value measured, mass excess inferred.]

Recently it was suggested to us by C. N. Davids that the accepted value for the mass of ^{67}Ni might be in error by an amount exceeding the assigned uncertainty. He was led to this belief by the failure of the modified shell model mass equation (MSMME) when the ^{67}Ni mass was employed. Our interest in mass measurements as a test of mass predictions and Davids' suggestion led us to investigate the ^{70}Zn(^{4}He, ^{7}Be)^{67}Ni reaction as a means of measuring the mass of ^{67}Ni. In recent years the mass relationships of Garvey and Kelson[1,2] based on an independent particle model has encouraged accurate mass measurements to test the model. The new data have in turn led to modifications of the G-K method[3-6] and to predictions based on the shell-model and Hartree-Fock methods.[7] Recently Maripuu has compiled several mass predictions including those for ^{67}Ni.[8]

The Q value of the ^{70}Zn(^{4}He, ^{7}Be)^{67}Ni reaction was measured to obtain the mass excess of the $T_z = \frac{11}{2}$ nucleus ^{67}Ni. The Princeton University AVF cyclotron was used with the quadrupole-dipole-dipole-dipole (QDDD) spectrograph (14.5 msr solid angle), including a detector consisting of two resistive-wire gas-proportional counters and a plastic scintillator. This detector gives position, two energy loss measurements, and a scintillator signal for use in particle identification, with particle trajectory and time-of-flight as additional constraints.[9,10] Data were recorded event mode and were analyzed on a Data General Eclipse computer using the Princeton acquisition code ACQUIRE.

A 80% enriched ^{70}Zn target of 117 μg/cm^2 thickness evaporated on a 30 μg/cm^2 carbon foil was employed. Table I lists the isotopic composition of the ^{70}Zn and the 104 μg/cm^2 natural Zn targets used. An 80 μg/cm^2 ^{12}C target and a 76 μg/cm^2 ^{25}Mg target (evaporated on a 20 μg/cm^2 thick carbon foil) were used to obtain a focal plane calibration. Target thicknesses of the ^{70}Zn and ^{25}Mg targets were determined to 10% with the cyclotron-QDDD system by measuring the change in energy loss of the ^{7}Be particles from the ^{12}C(^{4}He, ^{7}Be)^{9}Be reaction upon rotation of the targets by 180°.

The spectrograph angle was obtained by comparing the ^{12}C(^{4}He, ^{4}He)^{12}C 4.44 MeV state and the ^{1}H(^{4}He, ^{4}He)^{1}H ground state at 8.5°. The larger angle at which the mass measurement was made was obtained by relying on the surveyed angle marking on the spectrograph track to obtain the difference between the two angles. The ^{4}He beam energy and focal plane calibration was obtained by demanding consistency of energies for the reactions ^{12}C(^{4}He, ^{4}He)^{12}C 4.44 MeV, ^{12}C(^{4}He, ^{7}Be)^{9}Be ground and 431 keV states, ^{12}C(^{4}He, ^{6}Li)^{10}B ground and 716 keV states, and ^{25}Mg(^{4}He, ^{7}Be)^{22}Ne ground and 1277 keV states. These measurements gave the beam energy to be 56.11 ± 0.05 MeV and the scattering angle as $16.5° \pm 0.1°$.

A run was made on the ^{70}Zn target, with matching runs on the ^{25}Mg calibrant at the same field and without adjusting the kinematic focusing. A spectrum was also obtained from a natural zinc target. Other calibrants listed above required changing the QDDD focusing. Figure 1 shows the resulting position spectra from the ^{70}Zn and natural Zn targets. The ^{70}Zn(^{4}He, ^{7}Be)^{67}Ni spectrum shows a ground state peak of about 190 nb/sr cross-section above background. The spectrum from natural zinc shows some structure, but it does not correlate with the ^{67}Ni spectrum. The scale of the spectrum from the natural zinc has been normalized to the charge used with the ^{70}Zn target.

TABLE I. Isotopic composition of the zinc targets used in the (^{4}He, ^{7}Be)reaction.

	Percent abundance	
Isotope	^{70}Zn target	Natural Zn target
^{70}Zn	79.64 ± 0.10	0.62
^{68}Zn	6.24 ± 0.10	18.6
^{67}Zn	1.02 ± 0.05	4.1
^{66}Zn	5.20 ± 0.10	27.8
^{64}Zn	7.90 ± 0.10	48.9

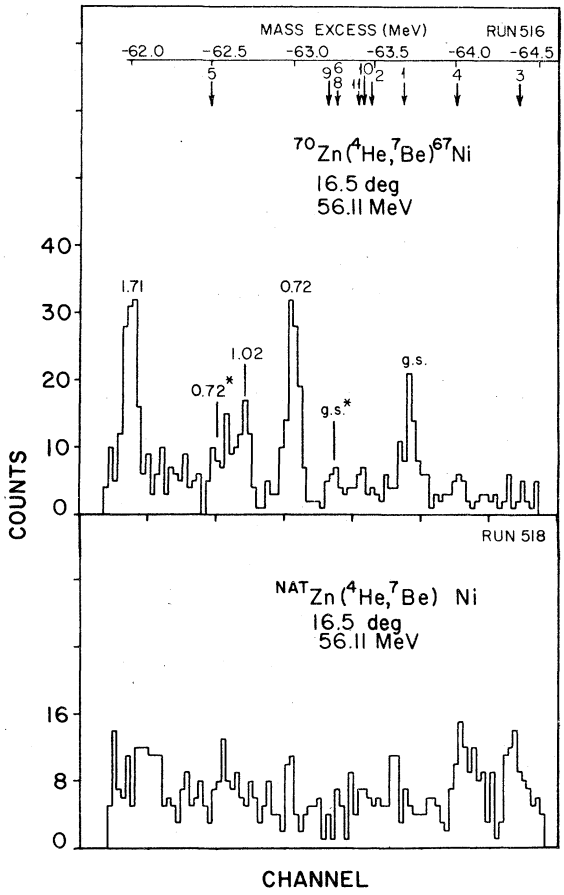

FIG. 1. Spectra from natural zinc and ^{70}Zn targets showing the Q value scale and indicating mass predictions from Table III. Asterisks mark peaks from the ^{7}Be first excited state.

The relativistic kinematics computer program CALIB [11] was used to obtain the ^{67}Ni mass. This code is capable of using a set of calibrant peaks to calibrate the spectrograph focal plane and give the Q values for other states of interest, including corrections for target thickness and QDDD dispersion changes. In the measurement, the ^{22}Ne calibrants were taken with the same QDDD optics as the ^{67}Ni spectra, so that no dispersion correction was needed. Though slightly defocused, the angular distribution of the ^{22}Ne states has a negligible effect on their centroids as shown by the consistency of all calibrant reactions.

TABLE II. Error analysis where values are keV contributions to the ^{67}Ni mass uncertainty.

Peak centroid uncertainty	8
Target thickness uncertainty	8
Beam energy uncertainty	9
Scattering angle uncertainty	12
Calibrant uncertainty	12
Root mean square error	22

TABLE III. Comparison of this measurement with model predictions and previous values for ^{67}Ni mass excess in MeV.

Present	−63.74(2)
Previous (Ref. 12)	−63.47(9)
Meyers (Ref. 8)	−64.38
Groote and Takahashi (Ref. 8)	−63.99
Seeger and Howard (Ref. 8)	−62.5
Liran and Zeldes (Ref. 8)	−63.26
Beiner, Lombard and Mas (Ref. 8)	−61.2
Janecke (Ref. 8)	−63.26
Comay and Kelson (Ref. 8)	−63.22
Janecke and Eynon (Ref. 8)	−63.42
Monahan and Serduke (Ref. 13)	−63.39

The ^{70}Zn(^{4}He, ^{7}Be)^{67}Ni spectrum of Fig. 1 shows excited states at 0.72, 1.02, and 1.71 MeV. Also indicated by asterisk are the locations of the ground and 0.72 MeV states associated with the ^{7}Be being left in its 0.431 MeV first excited state. We do not see excited states of ^{67}Ni between the ground state and 0.72 MeV state above about 20 nb/sr. We feel it unlikely that we have misidentified an excited ^{67}Ni state as the ground state, but it is conceivable that the ground state could be off the spectrum or could be weakly excited (less than about 20 nb/sr).

This measurement gives a result for the Q value of −19 164 ± 22 keV measured relative to the Q value of −18 512 ± 2 keV (Ref. 12) for ^{25}Mg(^{4}He, ^{7}Be) ^{22}Ne. Using −69 560 ± 3 keV for the ^{70}Zn mass excess,[12] this gives a ^{67}Ni mass excess of −63 741 ± 22 keV. The 22 keV error in our result, summarized in Table II, received almost equal contributions from centroid, target thickness, beam energy, scattering angle and calibrant uncertainties.

Table III compares the current result to the various predictions and to the previous results. It is interesting to note that ^{67}Ni is more bound than most of the predictions. The previously reported mass excess of ^{67}Ni(−63 470 ± 90 keV) (Ref. 12) seems to be in error by 271 keV. However, while Davids' suggestion concerning the mass of ^{67}Ni was correct, it now seems that the failure of the MSMME is more subtle than simply the use of an incorrect mass value.

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