Mass of ^{57}Cu

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The ground state Q value of the reaction ^{58}Ni(^{7}Li, ^{8}He)^{57}Cu has been measured [$Q=-29.564(50)$ MeV]. The cross section for this reaction was found to be 130(30) nb/sr at 5.0 deg in the laboratory. This is the first report of the use of the (^{7}Li,^{8}He) reaction and the first measurement of the ^{57}Cu mass excess. The deduced ^{57}Cu atomic mass excess is $-47.35(5)$ MeV. The implications of this result with respect to Coulomb displacement energy anomalies and nucleosynthesis of elements with $A>56$ by the rp process are discussed.

I. INTRODUCTION

In a simple shell model the nucleus ^{57}Cu has one proton outside the ^{56}Ni $N=Z=28$ closed core. Because of the role closed shell nuclei play in nature and hence in nuclear theory, knowledge of the binding energy and structure of ^{57}Cu is important. The mass excess of ^{57}Cu is a direct input into the Garvey-Kelson charge symmetric mass relation.[1] In conjunction with its mirror nucleus ^{57}Ni, ^{57}Cu provides data on the Nolen-Schiffer anomaly[2] and hence possible evidence for charge symmetry breaking of the nuclear force. Finally, models of the rp process, which is hydrogen burning at temperatures in the range of 10^9 K, need the atomic mass excess and level structure of ^{57}Cu to be able to predict the rate of nucleosynthesis of elements with $A>56$.[3] The rp process also provides a model for x-ray bursts which depend on the details of ^{57}Cu as well.[4] Despite the interest in this nucleus, only highly excited states of ^{57}Cu have been observed previously[5] in a study of β-delayed proton emission starting from ^{57}Zn. In this paper we report the first mass measurement of ^{57}Cu and the first use of the (^{7}Li,^{8}He) exotic transfer reaction.

II. EXPERIMENTAL PROCEDURE

The measurements were performed at the National Superconducting Cyclotron Laboratory (NSCL) with the S320 spectrograph, which has a quadrupole-quadrupole-dipole-sextupole configuration and a solid angle of 0.5 msr. The mass of ^{57}Cu was measured by determining the Q value of the reaction ^{58}Ni(^{7}Li,^{8}He)^{57}Cu relative to known Q values. The 173.6 MeV ^{7}Li beam was provided by the K500 cyclotron. The target was a 3.77 mg/cm^2 foil of 99.93% enriched ^{58}Ni. The focal plane detector consisted of two position sensitive proportional wires separated by 40 cm and two ion chambers for ΔE information. The detector was backed with a 7.5 cm thick plastic scintillator used for an event trigger, light output information, and a start signal for time-of-flight against the cyclotron rf. The S320 focal plane was calibrated with ^{58}Ni(^{7}Li^{3+},^{7}Li^{2+}) elastic scattering. The ratio of ^{7}Li^{2+} to ^{7}Li^{3+} was found to be approximately 9×10^{-5}. The calibration was checked by comparing the known excited states in ^{59}Cu (Ref. 6) with ones measured via the ^{58}Ni(^{7}Li,^{6}He)^{59}Cu reaction. The rms deviation of this comparison was 20 keV due mostly to uncertainties in resolving states in ^{59}Cu and magnet scaling. The ^{7}Li beam energy was measured by the difference in focal plane position between the ^{7}Li^{2+} elastic peak and the ^{8}He peak from the reaction ^{27}Al(^{7}Li,^{8}He)^{26}Si(g.s.), and was accurate to 200 keV. Furthermore, since the ^{27}Al(^{7}Li,^{8}He)^{26}Si Q value is well known,[7] and the magnetic fields were the same as used for the ^{58}Ni(^{7}Li,^{8}He)^{57}Cu reaction, this also provided a Q value calibration for the ^{57}Cu mass measurement.

III. RESULTS

The spectra obtained from the ^{58}Ni(^{7}Li,^{8}He)^{57}Cu and ^{27}Al(^{7}Li,^{8}He)^{26}Si reactions are shown in Fig. 1. The absence of counts below the lowest observed state in ^{57}Cu indicates good ^{8}He particle identification, which is shown in Fig. 2. Assuming the state at lowest excitation energy is the ^{57}Cu ground state, we measured a Q value of $-29.564(50)$ MeV, which leads to a mass excess for ^{57}Cu of $-47.35(5)$ MeV. This value agrees with the Janecke-Garvey-Kelson[8] mass excess prediction of -47.43 MeV. The error in the measurement comes primarily from the statistical uncertainties in the centroid of the ^{26}Si g.s. and ^{57}Cu g.s. peaks. These uncertainties added in quadrature give 36 keV. The other two major sources of error are 24 keV from uncertainty in the beam energy, and 20 keV from the uncertainty in the focal plane calibration.

Figure 3 shows the measured levels of ^{57}Cu relative to its mirror nucleus, ^{57}Ni. The $\frac{1}{2}^-$ and the $\frac{5}{2}^-$ states are expected to lie within 50 keV of each other according to calculations of the displacement energies of these states and the structure of the mirror nucleus. The calculations of the displacement energies reproduce quite well the trends in nearby nuclei and will be discussed in the following in connection with the Nolen-Schiffer anomaly. A statistical analysis of the peak at 1.04 MeV shows that its width is identical to that expected from the spectrograph

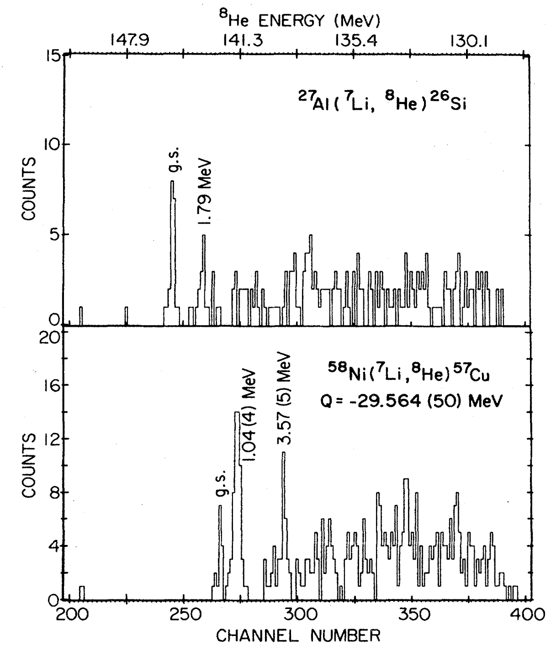

FIG. 1. Position spectra for the measured ^{8}He nuclei.

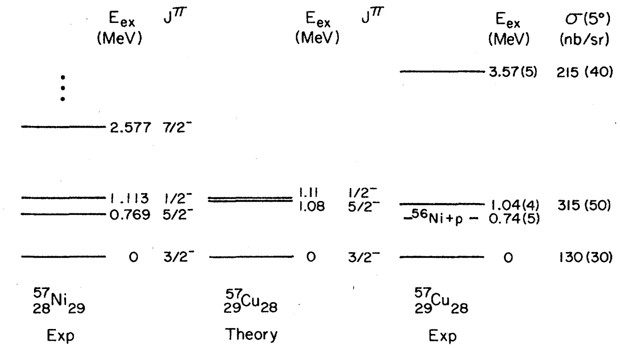

FIG. 3. Level diagrams for ^{57}Ni and ^{57}Cu. The theory used to predict the structure of ^{57}Cu is described in the text. The measured state in ^{57}Cu at 1.04(4) MeV is probably the $\frac{5}{2}^-$ and $\frac{1}{2}^-$ states unresolved.

resolution and the finite target thickness. However, a strong selectivity of the (^{7}Li,^{8}He) reaction for one of these states and not the other is not expected because the states are both single particle in composition. Also, since the angular momentum mismatch between the incoming and outgoing particles is only 1.4$\hbar$, there should not be the preference for high spin states which is usually the case for heavy-ion-induced reactions.[9] Therefore, for the purposes of analysis, we will assume the $\frac{1}{2}^-$ and the $\frac{5}{2}^-$ states both lie at 1.04(4) MeV excitation. The quoted uncertainty in the excitation energy of these states is larger than the statistical error because of uncertainty in separating the states. It is possible that only one of the states is populated, in which case the excitation of the other would be unknown.

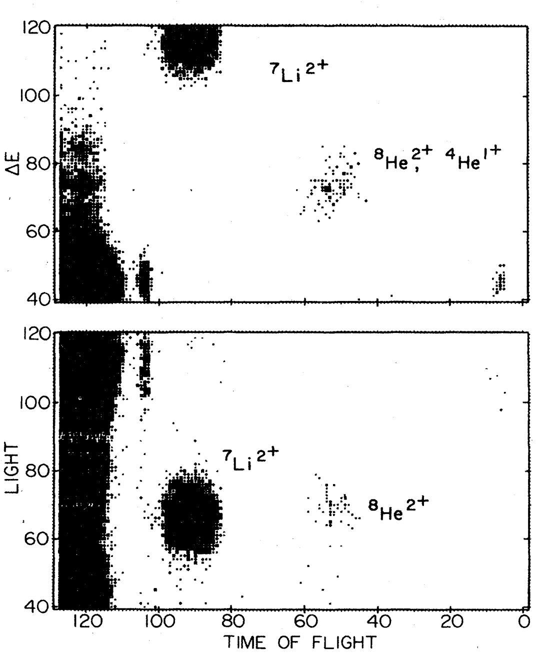

FIG. 2. Particle identification for the ^{8}He reaction products. The units are arbitrary with the time axis corresponding to ~ 1 nsec/channel.

IV. DISCUSSION

The mirror pair ^{57}Ni-^{57}Cu permits a test for the Nolen-Schiffer anomaly. The Nolen-Schiffer anomaly is the systematic discrepancy between the Coulomb displacement energy calculated from theory, assuming charge symmetry of the nuclear force, and the displacement energy measured experimentally. For mirror systems the Coulomb displacement energy is defined as:

$$E_C = Z_> - Z_< + \Delta_{nh} \, ,$$

where $Z_>$ and $Z_<$ are the atomic mass excesses of the proton rich and the neutron rich members of the pair, respectively, and Δ_{nh} is the neutron-hydrogen mass difference. The anomaly is particularly surprising because the Coulomb force is well known, and its effect on nuclear binding energies should be calculable. Two possible explanations for this anomaly are nuclear structure effects not included in the calculations and charge symmetry breaking in the nucleon-nucleon force. A case such as the $A=57$ pair provides valuable data because the closed ^{56}Ni core allows detailed nuclear structure calculations to be made, as has been done for other single particle or single hole nuclei.[10–13]

It is interesting to compare the present displacement energy and those of other mirror states from $A=41$ to 59 to a standard theoretical model which takes into account the Coulomb interaction between the valence and core nucleons along with some well-understood corrections. The direct part of the Coulomb interaction between the valence proton and the core protons was calculated using the radial wave functions obtained in a spherical Hartree-

Fock (HF) calculation carried out with the SGII potential of Sagawa and van Giai.[14] For this calculation we assume a closed $f_{7/2}$ shell for ^{56}Ni and valence particles in the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ orbits. The separation energies between ^{57}Cu and ^{56}Ni were constrained to the experimental values in the HF calculation by multiplying the central HF potential by an appropriate factor. According to the prescription of Ref. 15 the direct term should be calculated with ground state wave functions which reproduce the rms charge radius of ^{57}Ni. A correction was made for the small difference between the experimental and calculated rms charge radius of ^{57}Ni using the harmonic oscillator model. These finite-well HF calculations represent an improvement over the harmonic-oscillator calculations used in Ref. 15 and remove most of the orbit dependence in the ratio of the experimental to theoretical displacement energies of the $f_{7/2}$ and $p_{3/2}$ orbits found in Ref. 15.

Additional corrections to the direct interaction which have been included are discussed in Ref. 15. Finally, we consider the core-polarization correction.[16] This correction arises from the change in the radial wave functions of the core protons due to the interaction with the valence neutron or proton. There is an orbit dependence in this correction due to the fact that the core protons can be "pulled out" or "pulled in" depending on the shape and size of the valence radial wave function. This correction was obtained by carrying out the spherical HF calculation separately for ^{57}Cu and ^{57}Ni and then finding the difference between the total Coulomb energy of the core protons in each nucleus.

The ratios of the experimental displacement energies over those calculated with the above-mentioned assumptions are shown in Fig. 4. We include in this comparison the displacement energies of other states in the $A>39$ mass region which can be considered as single-particle or single-hole states. A similar comparison based on calculations without the finite-well or core-polarization corrections had been made previously in Ref. 15. The core-polarization correction increases the ratio of experiment over theory for the $d_{3/2}$ orbit by about 4% up to 1.05—1.07 and decreases the ratio for the fp orbits by 1—2% down to 1.09—1.11 and thus removes about half of the orbit dependence in the ratio of the $d_{3/2}$ and fp orbits found in Ref. 15. Some authors[11,13] have considered the effects of core excitations of higher order than those included in HF. They find that these corrections tend to increase the anomaly for hole states and decrease it for the particle states. This may account for the remaining orbit dependence of the anomaly but cannot account for the anomaly. Hence the persistence of the anomaly despite the inclusion of all the known important corrections suggests the presence of a charge symmetry breaking force. For a summary of charge symmetry breaking forces see Ref. 17.

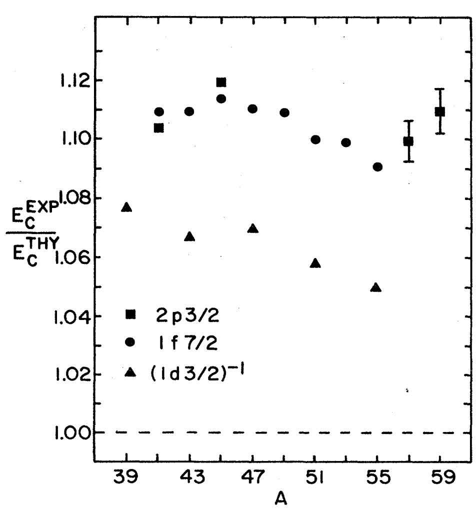

FIG. 4. The ratio of experimental displacement energies to those calculated with the model described in the text plotted vs A.

Finally, the structure of ^{57}Cu is interesting because of its importance in the rp process in element production with $A>56$. The rp process is proton burning via the (p,γ) reaction at temperatures between $T_9=0.10$ and 2.0, where T_9 is the temperature in units of 10^9 K. A detailed study of the rp process by Wallace and Woosley[3] found that the nucleus ^{57}Cu is an important branch point from lower- to higher-A nuclei because of the stability and long stellar half-life of ^{56}Ni. The rate of higher-A production may also be a critical factor in energy production from x-ray bursts which result from hydrogen accreted onto the surface of white dwarfs or neutron stars.[18,19] The crucial reaction, ^{56}Ni(p,γ)^{57}Cu, will be dominated by (p,γ) resonances, and therefore the reaction rate is sensitive to the proton energy of these resonances. The present experiment shows that the nucleus ^{57}Cu is proton bound by 0.74(5) MeV, hence there is an $l=1$ resonance at 0.30(4) MeV. There is also an $l=3$ resonance at about the same energy, but the larger angular momentum barrier will significantly reduce its importance. Wallace and Woosley also included a resonance at 1.752 MeV on which our study has no information. However, photodisintegration of ^{57}Cu dominates its production at the higher temperatures at which this resonance would be important. At temperatures up to $T_9=0.8$, only the lower energy resonance is important. The $l=1$ resonance energy is only 0.12 MeV different from that originally assumed by Wallace and Woosley, but leads to a significant deviation from the previously calculated ^{56}Ni(p,γ)^{57}Cu rate. A further correction to the ^{57}Cu production rate will be due to the influence of the inverse reaction, ^{57}Cu(γ,p)^{56}Ni. With the new mass excess for ^{57}Cu we calculate the Q value for the ^{57}Cu(γ,p)^{56}Ni reaction to be $-0.74(5)$ MeV instead of the -0.69 MeV assumed by Wallace and Woosley. This implies a decrease in the (γ,p) photodisintegration rate. The ratio of the recalculated ^{56}Ni(p,γ)^{57}Cu rate to the previously calculated rate[3] versus temperature is shown in Fig. 5. The dashed curves were calculated for the resonance energy changed by ± 40 keV. The ratio plotted is defined as

$$R=\frac{\lambda_{p\gamma}^{N}}{\lambda_{p\gamma}^{O}} ,$$

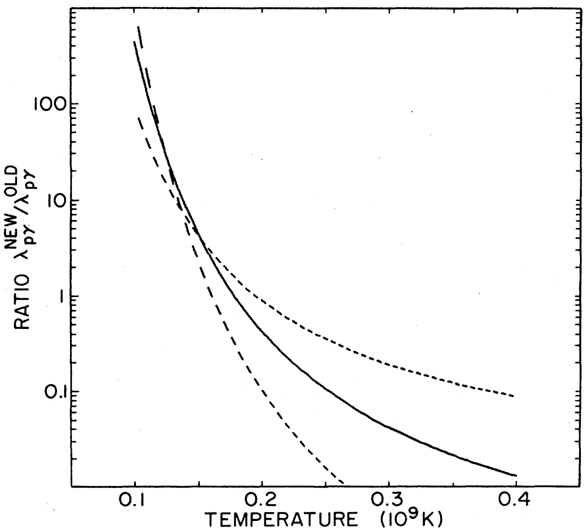

FIG. 5. The ratio of the recalculated $^{56}Ni(p,\gamma)^{57}Cu$ rate in units of cm^3/mole sec to the previously calculated rate versus temperature. The dashed lines were calculated by varying the resonance energy by the uncertainty in the measurement, ± 40 keV.

where $\lambda_{p\gamma}$ is the rate in units of cm^3/mole sec, and the superscript O or N denotes the old or the new reaction rate calculations, respectively. The deviation from unity shown in Fig. 5 is due to the narrower proton decay width of the resonance, and the decreased resonance energy.

V. CONCLUSIONS

In conclusion, the ^{57}Cu mass excess and level structure deduced from this experiment yield two diverse and significant results. First, there is additional evidence on the Nolen-Schiffer anomaly which may indicate charge symmetry breaking of the nuclear force in mirror systems. When detailed nuclear structure calculations are performed, they fail to reproduce the measured Coulomb energy shift by about 10% for single particle states, and at least 5% for hole states. If indeed all significant structure effects have been included, then the most probable cause of the anomaly must be charge asymmetric forces. Second, the measured Coulomb shifts of the levels in ^{57}Cu suggest that recalculations of the rp process will change the production rates of elements with $A > 56$.

Note added in proof. In a recent publication, T. Shinozuka *et al.*, Phys. Rev. C **30**, 2111 (1984), the β^+ decay of ^{57}Cu was reported and the mass excess deduced. The measured value of $-47.34(13)$ MeV agrees with our result.

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