SECTION I

RESEARCH IN PROGRESS

Mass of ^6He

R.G.H. Robertson, E. Kashy, W. Benenson, and A. Ledebuhr

With the exception of ^6He, the masses of all the light nuclei near the line of stability have been measured to a precision of the order of 1 keV or better. The mass of ^6He was measured in 1963 by Johnson, Pleasonton and Carlson[1], who examined the energy spectrum of ^6Li recoils following the β^- decay of ^6He and obtained a value for the decay energy accurate to 4 keV. No other measurement has approached that accuracy.

The ^6He mass is important in two respects. First, ^6He is a product of many reactions which lead to nuclei far from the line of stability, or serves in auxiliary calibration reactions, and its mass is becoming a limiting factor in the precision of some measurements of that type. Second, the ^6He β-decay is the fastest Gamow-Teller transition, and as such has received much attention in investigations of the renormalization of the axial-vector coupling constant in nuclear matter[2]. An accurate determination of the ft value for the decay depends on precise knowledge of the ^6He-^6Li mass difference.

We have completed a measurement of the ^6He mass by means of a comparison of the Q-values for the $^7Li(d,{}^3He){}^6He$ and the $^{19}F(d,{}^3He){}^{18}O$ reactions, the latter populating the first excited state of ^{18}O at 1.98216 MeV.

The method consisted of bombarding a natural LiF target with 20.8 MeV deuterons and observing outgoing ^3He particles on the focal plane of the Enge split-pole spectrograph. Groups from the $(d,{}^3He)$ reaction populating the ground state of ^6He and the first excited state of ^{18}O lay very close together (less than 30 keV apart) on the focal plane. Under these conditions the influence of the beam energy is negligible, and focal plane calibration to the required precision is straightforward. Use of a LiF target confers the advantages of a stable binary compound. Finally, to obviate the need to measure and control the reaction angle, the experiment was performed at 0^o, with the beam being stopped in a Faraday cup located between the first and second poles of the magnet. The experimental procedure was to cycle the spectrograph magnet and then record ^3He spectra at a series of spectrograph fields which moved the ^6He-$^{18}O^*$ doublet along the length of the focal-plane detector. Knowledge of the spectrograph calibration permitted the detector calibration to be determined, and the doublet separation could then be extracted with high precision. The detector calibration was assumed to be linear over small distances. The principal uncertainty is the possible occurrence of small-scale non-linearities in the detector (due for example to microscopic variations in wire diameter, dust on the wire, etc.), and such variations are presumed to average out in a set of measurements made at several locations on the detector. One of the doublet measurements, with the shape fitted by SAMPO[3], is shown in Fig. 1. The energy resolution

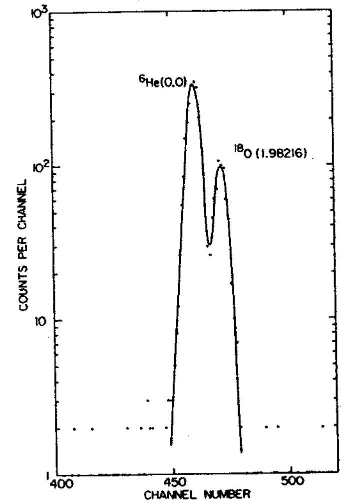

Fig.1.-Spectrum of ^3He particles resulting from 20.8-MeV deuteron bombardment of a LiF target.

is approximately 15 keV full width at half maximum in that spectrum. In all, thirteen measurements were taken, and the results are shown in Fig. 2.

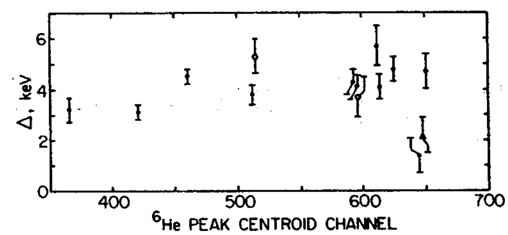

Fig. 2.-Plot of the quantity Δ measured at different locations on the focal plane, as a function of position.

The data comprise a measurement of the quantity $Q_6-Q_{18}{}^*$, where Q_6 and $Q_{18}{}^*$ are the Q-values of the $^7Li(d,{}^3He){}^6He$ and $^{19}F(d,{}^3He){}^{18}O$ (1.98216) reactions, respectively. However, to show the comparison between the present measurement and the previous one, the ordinate of Fig. 2 is the quantity

$$\Delta \equiv Q_6-Q_{18}{}^* - (Q_6-Q_{18}{}^*)_{1971}$$

where the last term is the Q-value difference that would be calculated using the 1971 mass table of Wapstra and Gove[4] (wherein the ^6He mass is essentially based on the measurement of Johnson et al.[1]). The error flags shown in the figure are the statistical uncertainties in the peak separations only, and the excess deviations from the mean are attributed to fluctuations in detector linearity. Two measurements made with an 8 $\mu g\text{-}cm^2$ LiF target are designated by open circles and one made with the 25 $\mu g\text{-}cm^{-2}$ LiF target reversed by a triangle. Combination of other uncertainties with the internal error in the data, 320 eV, leads to a final result

$$Q_6 - Q_{18}^* = 0.98(41)\ \text{keV}$$

and

$$M(^6\text{He}) = 17593.7(11)\ \text{keV}.$$

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Mass of ^{9}C

E. Kashy, W. Benenson, R.G.H. Robertson,
A. Ledebuhr and L. Robinson

The A=9 ground state isobaric quartet is of special interest as it is the only one that shows an experimentally significant deviation from the quadratic isobaric multiplet mass equation, i.e. a cubic coefficient of 5.8±1.5 keV is required. We are in the process of measuring the ^{9}C mass using the 70 MeV ^{3}He beam of the MSU Cyclotron. ^{6}He particles from the nuclear reaction $^{12}C(^{3}He,^{6}He)^{9}C$ are recorded on photographic plates simultaneously with ^{4}He and ^{3}He ions from the same target. Particle separation is essential to allow the rare ^{6}He particles to be seen in a strong ^{4}He background. This is achieved by means of an electrostatic deflector in the magnetic spectrograph, which at a given position on the focal plane gives a displacement proportional to $\frac{A}{Q}$. Thus only tritons can interfere with ^{6}He, and are differentiated via the track brightness. An important problem comes from the different energy dispersions on target for the various reactions. This forces the use of a beam with rather small total energy width. A set of exposures have been made, but the plates have not yet been scanned. It is expected that a mass with an accuracy of about 5 keV will be achieved, which is sufficient to test the accuracy of the previous measurement of the ^{9}C mass made by the $^{7}Be(^{3}He,n)^{9}C$ reaction to a precision of 3 keV.[2]

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Mass of Lowest T=2 State in ^{12}C

R.G.H. Robertson, T.L. Khoo, G.M. Crawley, A.B. McDonald,* E.G. Adelberger,** and S.J. Freedman+

The T=2 states in mass 12 show a number of interesting properties which have singled them out as remarkable. The lowest T=2 state in ^{12}C has a cross section in (p,t) an order of magnitude smaller than the corresponding cross sections in other 4n nuclei. The T=2 state in ^{12}N has been sought in the $^{15}N(^{3}He,^{6}He)$ reaction at MSU but has not been observed at the 50 nb level. There is a suggestion by Barker[1] that the first excited state in the A=12 T=2 system may be 0^+ and not 2^+. Finally, the lowest T=2 state in ^{12}C is unique in the 4n nuclei in that it has never been observed as an isospin forbidden resonance, despite almost 10 years of searches.

One possible explanation of the non-observation of the state would be an error in its excitation energy. Three previous measurements[2,3,4] are in general agreement and give for the excitation energy an average value of 27.603±0.014 MeV. We have made a new measurement of this quantity using the $^{14}C(p,t)$ reaction. Tritons from that reaction were detected in the focal plane of the Enge split-pole spectrograph along with precisely known calibration lines from (p,p') (p,d) and (p,α) reactions induced on ^{12}C and ^{14}C. Nuclear emulsions are mandatory for the highest accuracy in this type of experiment because of their linearity and the independence of centroid positions on ionization. Simultaneous observation of unknown and calibration lines eliminates the influence of time-dependent changes in beam energy, reaction angle, etc., and removes the need to know the spectrograph field as a function of NMR frequency.

The use of plates for a reaction as weak as $^{14}C(p,t)$ ($\sigma \sim 5\mu b\ sr^{-1}$) would ordinarily be impossible because of the presence of much more intense groups of protons, deuterons and alphas. We have therefore added to the split-pole magnet an electrostatic deflector which vertically separates into bands particles having different charge-to-mass ratios.

Figure 1 shows the spectra obtained from the three bands on a plate. The tritons are clearly separated and can be scanned without difficulty. The plates have all been scanned with the MSU automatic plate scanner. (The broad feature in all three spectra is a diffuse group of protons arising from scattering in the target chamber.)

Analysis of three runs gives a preliminary result for the excitation energy of

$$E_x = 27.5949 \pm 0.0029 \text{ MeV}$$

The total width of the state is

$$\Gamma_{tot} < 30 \text{ keV}$$

Many attempts were made with thin targets to obtain a narrower line, but the state was not

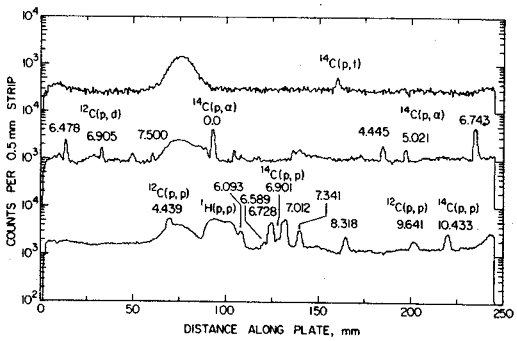

FIG. 1.--Spectra of tritons, alphas and deuterons, and protons, observed in a nuclear emulsion with 45 MeV protons incident on a 250 μg-cm^{-2} ^{14}C target. The separation into three bands was achieved by means of electrostatic deflection.

seen at all. It is possible that the width is not much less than 25 keV. There remain two checks that must be made before the excitation energy can be finalized--a more detailed analysis of the uncertainties, and a test that the electrostatic deflector does not introduce a significant centroid shift.

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A=15 and 29 Mass Quartets

W. Benenson, E. Kashy, A. Ledebuhr and L.W. Robinson

During the past year we have studied ^{15}F, the one missing T_z=-3/2 nucleus in the series from ^{7}B to ^{37}Ca. This nucleus was expected to have properties similar to ^{11}N[1] since it is predicted to be unbound by about the same amount and should have an $1/2^+$ ground state (like its mirror ^{15}C). In ^{11}N the broad peak observed was interpreted to be the mirror of the ^{11}Be first excited state, and the $1/2^+$ ground state was assumed to be unmeasurably broad. As can be seen in Fig. 1, the situation in ^{15}F is similar except that the peak observed appears to be quite narrow. In fact the peak marked with an arrow has a width of ∿220 keV which is close enough to the instrumental resolution to prevent an accurate determination of the width of the state.

If the T=3/2 levels in ^{15}O were known, it would be straightforward to use the isobaric multiplet mass equation to determine which states in ^{15}C are mirrors of the observed peaks. In the absence of this information one can use coefficients taken from systematics (b=-2500 keV c=240 keV), and the equation then shows that the peak indicated with an arrow is the mirror of the $5/2^+$ first excited state of ^{15}C and that the T=3/2 state in ^{15}O which is its analog should lie at E_x=12.27 MeV. Using the ^{17}O(p,t) reaction we have searched for this state and found a weak, broad L=0 peak at the appropriate energy. However, the state is somewhat obscured by narrow T=1/2 states and ^{12}C(p,t)^{10}C. Consequently we are planning to observe the state in coincidence with its proton decay, which should go entirely to the T=1, 2.31 MeV state in ^{14}N and therefore enhance the peak relative to the others. We are also planning another ^{20}Ne(^{3}He,^{8}Li) run at a different angle to help verify the identification of the peaks shown.

The experiment[2] to measure ^{29}S was one of the first in the series of T_z=-3/2 nuclei in the s,d shell and, because of target problems, one of the least precise. Using the target techniques developed for the ^{32}S(^{3}He,^{8}Li)^{27}P experiment[3] we have remeasured ^{29}S and observed its energy levels for the first time as can be seen in Fig. 2. The analogs of the excited states of ^{29}S in ^{29}Si and ^{29}P are unknown, so a search for them will be made with the (p,t) and (p,^{3}He) reactions on ^{31}P. The ^{29}S mass measured with data like that shown in Fig. 2 will have an error of about 20 keV and therefore will represent a meaningful test of the isobaric multiplet mass equation.

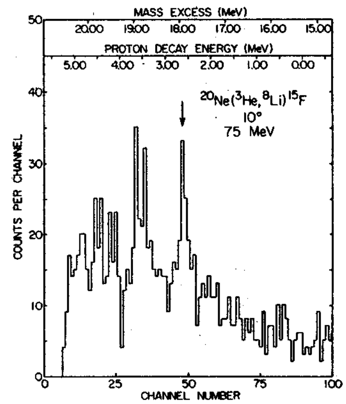

Fig. 1.--Spectrum from the ^{20}Ne(^{3}He,^{8}Li)^{15}F reaction.

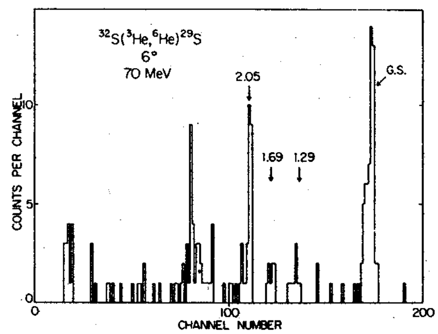

Fig. 2.--Spectrum from the ^{32}S(^{3}He,^{6}He)^{29}S reaction.

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Search for the Isotope ^{57}Cu

E. Kashy, W. Benenson, B.A. Brown,
A. Ledebuhr and L. Robinson

The reaction $^{58}Ni(^{12}C,^{13}B)^{57}Cu$, a charge exchange plus neutron pick-up, was used to look for ^{57}Cu and measure its mass. Since ^{57}Cu is expected to be a single $p_{3/2}$ proton outside the N=Z=28 doubly closed-shell core, its mass yields an important displacement energy when it is compared to the mass of ^{57}Ni. A calculation of the binding energy of ^{57}Cu, based upon an estimate of the charge dependence of the effective nuclear force $[(V_{pn}-V_{NN})/V_{nn} \approx 1.7\%$ for $J=0]$, a $p^{n}_{3/2}$ model and the masses of $^{56,57,58}Ni$ and of ^{58}Cu yields a binding energy of 484.70 MeV which corresponds to a Q value of -29.48 MeV for the above reaction.

Measurements were carried out with 75 MeV ^{12}C using, in the split-pole spectrograph, a detection system which consisted of a resistive wire position sensitive gas proportional counter backed by a 5 cm long Si detector. The four quantities, ΔE in the gas, E in the Si detector, position along the focal plane and time-of-flight through the spectrograph were recorded on magnetic tape. In the later runs, a set of plates produced on electric field parallel to the magnetic field and deflected the particles of given magnetic rigidity according to their A/Q. This, while it would appear at first to be redundant with time-of-flight information, greatly reduced the number of unwanted particles being detected by sweeping them away from the counter aperture. This technique resulted in a large reduction in the count rate, and therefore reduced the pile-up substantially at 8° and 20°, the angles used in this search.

The program EVEN, written by Au and Mueller, was modified by Au to allow for more data manipulation. EVEN allows the user to "replay" the experiment as if it were live and set digital gates in any one or two dimensions, i.e. E, ΔE, TOF and position. The modification allows correction of all of the parameters to permit viewing of the particles groups during the replay. For example, in the transformation of E as 1.7E + .3ΔE + 500 the first factor makes better use of the 128 x 128 display by expanding the data for better visibility. The second corrects for energy loss in the counter gas and windows. The constant term is useful in centering the region of interest on the screen and also permits the two-dimensional display to become a lens which magnifies the region of interest since data is taken with a resolution of 4096 channels. A fortran program written by D. Johnson allows the user to make a fit of the positions of the easily identified prolific particle groups and then gives the expected positions of other groups, according to their Z, Q and A. Figure 1 shows a two dimensional plot of ΔE vs. E for 75 MeV ^{12}C on ^{27}Al.

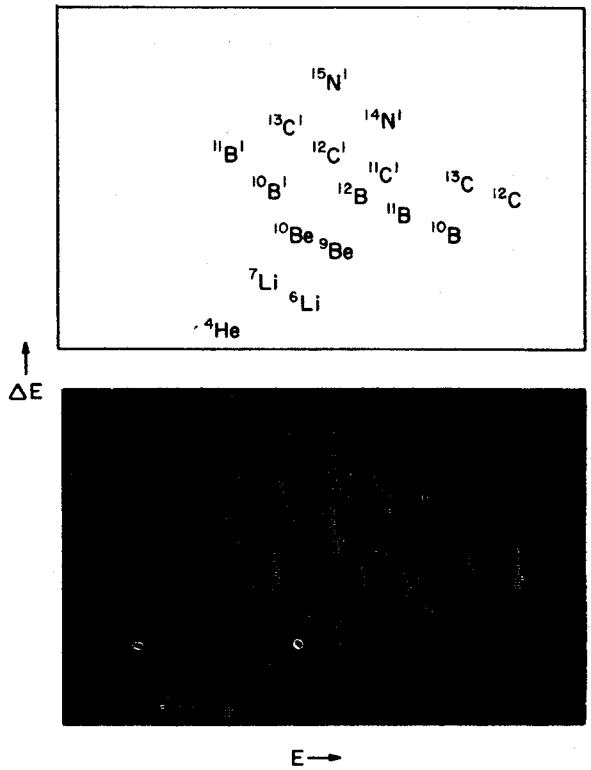

Fig. 1.--Plot of ΔE vs. E. The axes are transformed as ΔE = 1.2ΔE and E = 1.75E + .3ΔE (Tape 1527). The symbol $^{12}C^{1}$ indicates a ^{12}C ion which is not fully stripped and has one atomic electron when leaving the target.

The results so far indicate a cross section ≤10 nb/sr for the $^{58}Ni(^{12}C,^{13}B)$ reaction. This low cross section appears to reflect, in addition to the complexity of the reaction, the rather strong Q-mismatch caused by the very negative Q-value of the reaction. We are considering the $^{54}Fe(^{14}N,^{11}Be)^{57}Cu$ reaction for the next experiment.

The Energy Levels of ^{60,61}Zn and the Mass of ^{61}Zn

G.M. Crawley, D.J. Weber, W. Benenson and E. Kashy

The zinc isotopes have been the subject of a recent shell model calculation of van Hienen, Chung, and Wildenthal[1] involving the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbitals outside of an inert ^{56}Ni core. The calculation predicts seventeen positive parity levels below 5 MeV of excitation in ^{60}Zn. For ^{61}Zn, a higher level density is predicted, with about 20 levels below 2 MeV of excitation. The ^{60}Zn nucleus has so far only been studied by the ^{58}Ni(^{3}He,n) reaction[2–4] with an energy resolution of 350-500 keV F.W.H.M. and by a (^{3}He,nγ) experiment[5] which measured the energies of four excited states with high precision. For ^{61}Zn, no excited states are known and the accepted mass[6] is known only to 200 keV. In fact two separate mass measurements[7,8] for ^{61}Zn differ by 510 keV. With the recently acquired capability to accelerate heavy ions at the Michigan State University cyclotron however, ^{60}Zn and ^{61}Zn can be studied with the reactions ^{58}Ni(^{12}C,^{10}Be) and ^{58}Ni(^{12}C,^{9}Be). For ^{60}Zn, the heavy ion reaction provides information about the nucleus not available in the previous (^{3}He,n) studies since angular momentum and Q-value matching conditions in the heavy ion transfer reaction lead to a selective population of high spin states in ^{60}Zn. In addition, a better energy resolution, ~150 keV F.W.H.M., is obtained over a wide range of excitation energies. For ^{61}Zn, this work represents the first information concerning the energy levels of this nucleus.

A 77 MeV $^{12}C^{4+}$ beam was scattered from a 324 μg/cm^2 isotopically enriched ^{58}Ni target. A detector consisting of two resistive wire proportional counters backed by a thin plastic scintillator was placed in the focal plane of an Enge split pole spectrograph. This gave position, energy loss, light output, and time of flight information which resulted in unambigious particle identification of ^{12}C, ^{9}Be, and ^{10}Be ions. The spectra were calibrated by varying the spectrograph field to move the $^{12}C^{5+}$ elastically scattered particles from ^{58}Ni across the detector. The calibration was corrected for the differential energy loss of the different ions in the target. Spectra for ^{60}Zn and ^{61}Zn are shown in Figure 1 and 2. The energy levels observed are compared with the predictions of van Hienen in Figure 3 and 4. Angular distributions for the states seen in ^{60,61}Zn are shown in Figure 5-8.

Except for levels in ^{61}Zn above 4 MeV of excitation which exhibit some forward angle structure there is little or no structure observed in any of the angular distributions. Furthermore, since all of the angular distributions are similar in shape, no spin assignments can be made on

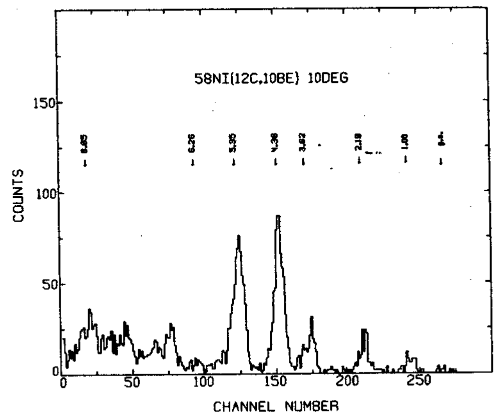

FIG. 1.--An energy spectrum for the reaction ^{58}Ni(^{12}C,^{10}Be) at 77 MeV.

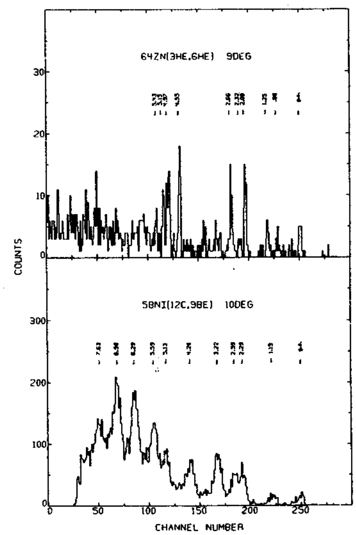

FIG. 2.--An energy spectrum for the reaction ^{58}Ni(^{12}C,^{9}Be) at 77 MeV (bottom) and an energy spectrum for the reaction ^{64}Zn(^{3}He,^{6}He) at 70 MeV (top).

the basis of their shapes. This is borne out by the similarity of shapes of DWBA calculations for L transfers of 2,3 and 4 which are shown (with arbitrary normalization) for states of known spin in ^{60}Zn. DWBA calculations have also been performed on ^{61}Zn for L tranfers of 1/2, 3/2, and 5/2. Again no spin assignments can be made on the basis of the shapes of the angular distributions, although the data do not seem to exhibit the rapid oscillations of the calculations for the lower L transfers. Some information on spins may be available from a calculation of relative spectroscopic factors. Work is proceding on this problem. The matching conditions do suggest however that the strongest states observed have high spin. The state at 4.36 MeV in ^{60}Zn could therefore be the 6^+ state predicted by van Hienen at 4.23 MeV. The state at 3.62 MeV in ^{60}Zn is a doublet probably comprised of the known 3^- level at 3.50 MeV and a new high spin state near 3.7 MeV. This new state may correspond to Van Hienen's 4^+ state predicted to lie at 4.03 MeV.

The calibration indicated an error in the accepted mass of ^{61}Zn of 350±50 keV. However, although angular momentum and Q-value mismatches were not so severe for this case as for ^{60}Zn, a very weak cross section to the ground state could not be ruled out. Since the mass appeared to be larger than the accepted value, it was possible that the first state seen in ^{61}Zn might therefore be the first excited state. To eliminate this possibility, the reaction $^{64}Zn(^{3}He,^{6}He)$ was studied at 70 MeV. In this lighter ion reaction, the ground state would be expected to appear strongly. In addition, a better resolution would be obtainable with which to measure the mass of ^{61}Zn. A spectrum for $^{64}Zn(^{3}He,^{6}He)$ is also shown in Figure 2. This spectrum was calibrated using the reaction $^{56}Fe\ (^{3}He,^{6}He)$ to known states of ^{53}Fe. The position of the ground state indicated that the accepted mass was in fact low by 375±20 keV, and verified that the first state seen in the reaction $^{58}Ni(^{12}C,^{9}Be)$ was indeed the ground state of ^{61}Zn. The new mass excess for ^{61}Zn was determined to be -56205±20 keV. The energies of the excited states seen in $^{64}Zn(^{3}He,^{6}He)$ are shown in Figure 4.

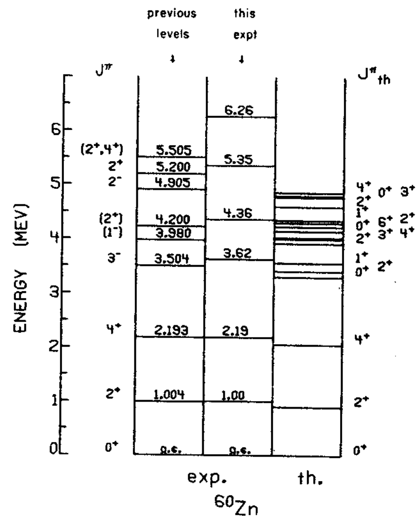

FIG. 3.--Energy levels of ^{60}Zn. The levels observed in this experiment are shown in the center. They are compared with the previous level energies and spins which are shown to the left and the calculated energies and spins of van Hienen et al.[1] which appear to the right.

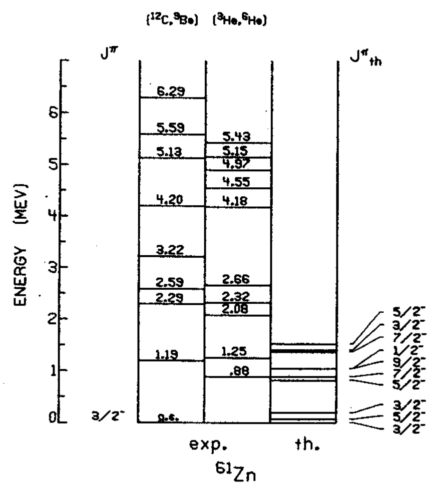

FIG. 4.--The energy levels of ^{61}Zn observed in this experiment. The levels on the left are those observed in the reaction $^{58}Ni(^{12}C,^{9}Be)$; those in the center were seen in the reaction $^{64}Zn(^{3}He,^{6}He)$. Theoretical predictions are shown on the right.

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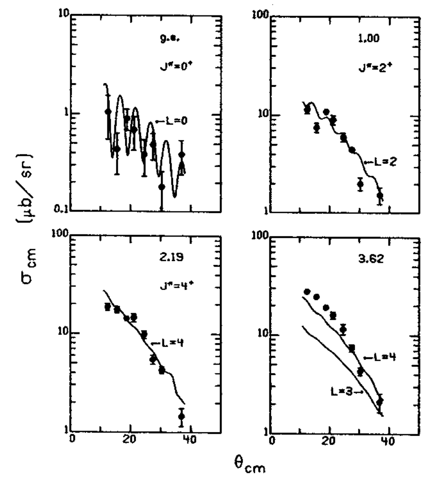

FIG. 5.--Angular distributions for low lying states seen in $^{58}Ni(^{12}C,^{10}Be)^{60}Zn$. Arbitrarily normalized DWBA calculations appear for states of known spin.

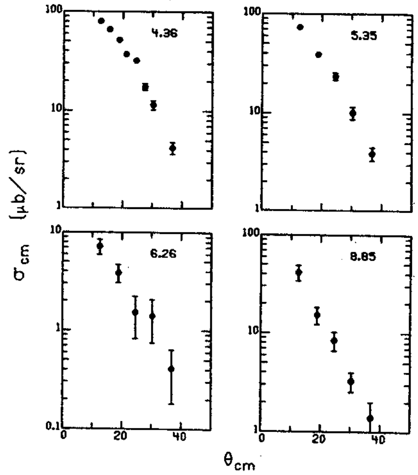

FIG. 6.--Angular distributions for highly excited states seen in the reaction $^{58}Ni(^{12}C,^{10}Be)^{60}Zn$.

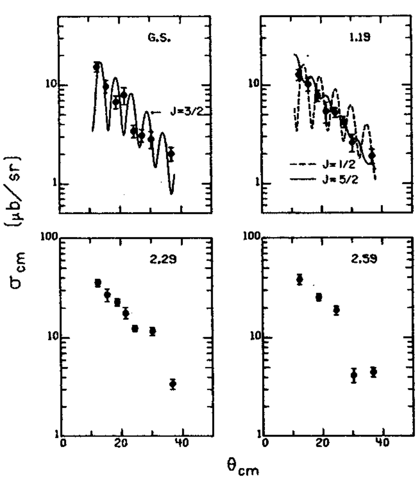

FIG. 7.--Angular distributions are shown for levels excited in the reaction $^{58}Ni(^{12}C,^{9}Be)$. Arbitrarily normalized finite range DWBA calculations for various j transfers are shown together with the data.

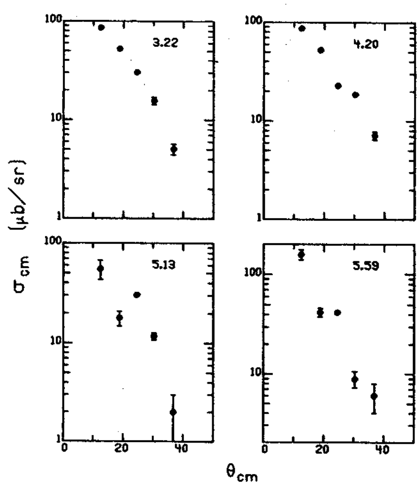

FIG. 8.--Angular distributions are shown for highly excited levels seen in the reaction $^{58}Ni(^{12}C,^{9}Be)$.