SECTION I

RESEARCH IN PROGRESS

Mass of ^{6}Li in its Ground and 0+T=1 States

R.G.H. Robertson and J.A. Nolen

Experiments are now in progress searching for the resonant capture of α-particles by deuterium at the energy of the 3.56 MeV state in ^{6}Li. The process is forbidden by parity and isospin conservation, but can occur if a hadronic parity-violating ΔT=1 force acts in nuclei.

In searching for a very weak narrow resonance superimposed on a continuum, it is imperative that the search range be reduced to the extent possible in order that adequate statistics be obtained over the resonance. In this particular case, the mass excess of ^{6}Li (3.56) must be known (relative to the alpha particle and the deuteron) to a precision of ±0.3 keV if that uncertainty is not to dominate the choice of search range. The excitation energy has been measured in three recent experiments[1,2,3] with an overall uncertainty of 0.5 keV, but one measurement[3] disagrees with the other two by 6 keV. The ground state mass is known only to 0.9 keV,[4] a result also obtained by averaging reaction Q-value measurements which disagree. No direct mass spectroscopy of Li has ever been performed. We have carried out two experiments to improve on this situation.

I. Excitation energy of the 3.56 MeV State

The 3.56 MeV state has a large radiative width and can therefore be excited readily in photon scattering. This method of excitation reduces Doppler broadening of the 3.56 MeV γ-ray line, compared to other nuclear reaction techniques.

The experiment made use of bremsstrahlung from the University of Illinois superconducting microtron. The photon beam (end point 7 MeV) irradiated a 10 gm isotopic ^{6}Li metal target, and fluorescent γ-rays were observed at a scattering angle of 126.3° in a Ge(Li) detector.

A hardener of lead and copper was interposed between the detector and the target, and the detector itself was enclosed in a large lead shielding cave.

The 3.56 MeV line from ^{6}Li lies very close to the 3547.891 keV line from ^{56}Co. The energy of the latter line was recently redetermined for this measurement by Dr. R.C. Greenwood,[5] and has an overall energy uncertainty of 34 eV. Part of the γ-ray spectrum is shown in Fig. 1.

Five runs were taken in which beam current, amplifier and ADC gains, shielding and relative source strength were varied. The separations between ^{56}Co (3547.891) and the ^{6}Li line from each run are shown in Fig. 2. The error bars are only statistical, and the excess deviations may be attributed to ADC differential non-linearity. We take the weighted mean using standard deviations increased by the appropriate factor to bring χ^2 to 1. After correcting for recoil we find E_x=3562.89 ± 0.10 keV. Fig. 3 shows our present result compared with previous work. There is good agreement with both the ^{6}Li(p,p') measurement of Nolen and Barker,[1] and the ^{9}Be(p,αγ) work of Kim et al,[2] and evidence that the result of Wessels et al.[3] should be rejected.

II. Ground State Mass Excess of ^{6}Li

The ^{6}Li(p,α)^{3}He reaction provides a basis for a mass measurement of ^{6}Li, because all the masses involved are well known except for the target. At E_p=10.5 MeV with a mixed isotope ^{6,7}Li F target on carbon and Formvar there is a convenient grouping of reaction products of similar magnetic rigidity which provides simultaneous calibration of the spectrograph focal plane, beam energy and reaction angle. Four plate exposures were taken, two at 11° and one each at 10° and 12°, with an 11° exposure shown in Fig. 4. The numbered peaks are as follows: 1, 2, 3, 5-^{19}F(p,α)^{16}O (6.050, 6.13043, 6.9171, 7.11685), 4-^{7}Li(p,d)^{6}Li, 6-^{6}Li(p,α)^{3}He, 7-elastic protons, 8-^{19}F(p,p')^{19}F (0.19724) 9-^{1}H(p,p)^{1}H, 10-^{7}Li(p,p')^{7}Li (0.477611), 11-^{6}Li(p,^{3}He)^{4}He, 12-^{19}F(p,p')^{19}F (1.34567). The presence of both the ^{6}Li(p,α) and (p,^{3}He) lines on the plate gives two (partially correlated) measurements from each exposure.

The data have been analyzed with the linearized least-squares fitting program DOALL, with the results shown in Fig. 5. At 12° the ^{6}Li(p,α) peak merges with the elastic protons and cannot be used. The solid circles are (p,α) points, the open circles (p,^{3}He). Also shown on the figure are the two points which presently fix the ^{6}Li mass, one consisting of the Notre Dame measurements[6] of Q-values involving ^{9}Be, ^{8}Be and ^{6}Li, the other being the average of four ^{6}Li(p,α) measurements. The ordinate is ΔQ, the measured Q-value minus the 1977 Mass Table value (4020.0 ± 0.8 keV). Our result for ΔQ is -3.3 ± 0.8 keV or -2.6 ± 0.8 keV, depending on whether the discrepant 12° point is omitted or included (respectively).

The result is still quite preliminary, but it appears that there may be a significant error in the presently accepted value for the ^{6}Li mass.

1. J.A. Nolen and P.H. Barker, to be published.
2. J.C. Kim, P. Depommier, W. del Bianco, and S. Kundu, Nucl. Inst. Methods 143 (1977) 371.
3. B. Wessels, M. Parrott, D. Ercegovic, D. Justice, and W. Miller, Nucl. Inst. Methods 141 (1977) 157.
4. A.H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19 (1977) 175.
5. R.C. Greenwood, private communication.
6. F.H. O'Donnell and C.P. Browne, Phys. Rev. 158 (1967) 957.

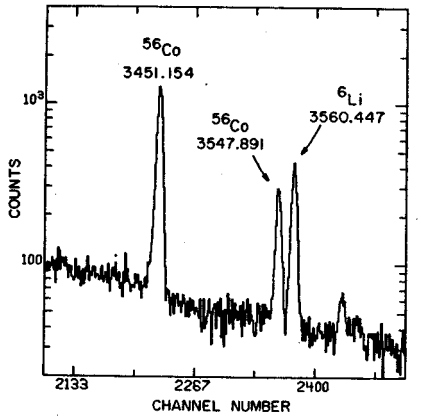


Fig. 1. Portion of γ-ray spectrum showing 3.56 MeV fluorescent line from the ^{6}Li(γ,γ)^{6}Li reaction together with calibration lines from a ^{56}Co source.

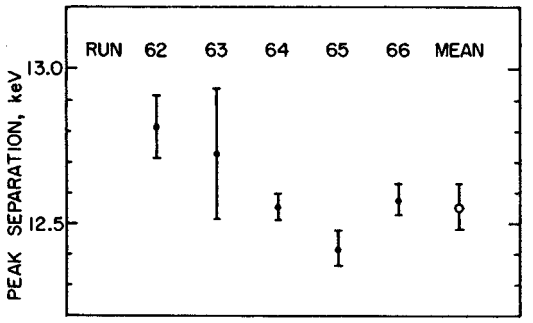


Fig.2. Doublet separations between ^{6}Li resonance line and ^{56}Co (3547.891) calibration line, for five runs.

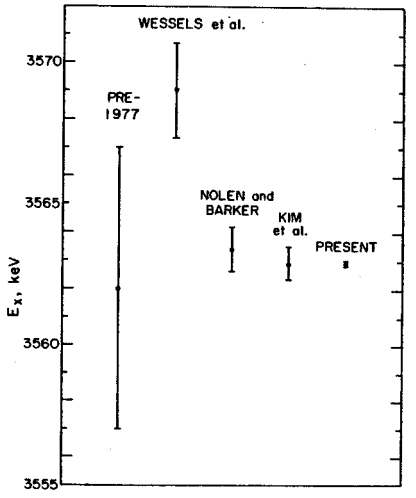


Fig. 3. Summary of measurements of excitation energy of 0^+, T=1 state in ^{6}Li.

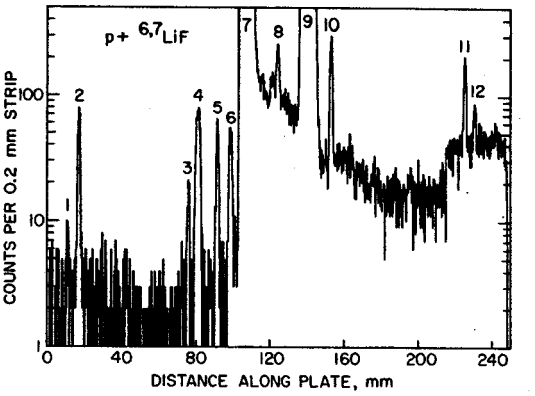


Fig. 4. Plate spectrum resulting from 10.5 MeV proton bombardment of 8μg - cm^{-2} Li F target containing equal isotopic abundances of ^{6}Li and ^{7}Li.

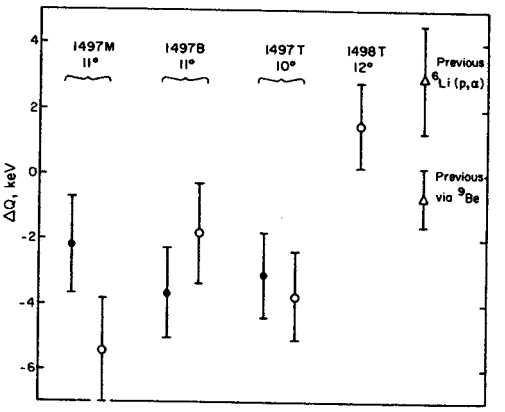


Fig. 5. Summary of values for Q-value of ^{6}Li(p,α) reaction, relative to accepted value.

Mass of $^{9}C^{+}$

E. Kashy, W. Benenson, J.A. Nolen, Jr., and R.G.H. Robertson

The properties of analog levels in nuclei have been of considerable interest in studies of microscopic and macroscopic nuclear properties. For example, the mixing of T levels with background T levels in the first instance and the determination of nuclear radii in the second. When three or more analog states are involved, it is expected[1] that the energies of the states in the various nuclei obey a quadratic relation, i.e., that the respective masses are described by the isobaric multiplet mass (IMME) equation:

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

To test that relation, four or more masses must be measured, which is the case when the isospin T is greater than or equal to 3/2. A recent review of experimental results for quartets and quintets of states showed that only for the A = 9 quartet is a highly significant deviation from the quadratic dependence observed.[2] The present measurement then represents an effort to reduce the chance of an experimental error as the source of the effect. Previous measurements of the ^{9}C mass include the $^{7}Be(^{3}He,n)^{9}C$ threshold measurements by Barnes et al.[3] and Mosher et al.[4] with accuracies of ∿5 keV and the Q-value of the $^{12}C(^{3}He,^{6}He)^{9}C$ reaction measured by Trentelman et al.[5] with an accuracy of ∿8 keV. The possibility of improving the latter measurements by using a magnetic spectrograph, electrostatic particle separation, and photographic emulsions led to the present measurement.

In the present work, a 60 $\mu g/cm^2$ target was made from a uniform mixture of carbon isotope, 40% of ^{13}C and 60% of ^{12}C. The incident beam was 72 MeV ^{3}He from the Michigan State University Cyclotron. The reaction products, i.e., ^{3}He, ^{4}He, and ^{6}He, were detected in the focal plane of the 90 cm Enge split-pole spectrograph, using nuclear emulsions as track recorders. In order to separate the rare ^{6}He from the abundant ^{4}He, an electrostatic deflector was used in the region between the poles of the spectrograph.[6] The ensuing deflection was then proportional to m/q for a given position in the focal plane, with the ^{6}He getting the largest displacement. Since the abundant ^{3}H have the same m/q as ^{6}He, they are subject to the same electric deflection, but can be differentiated from the ^{6}He by the difference in their specific ionization, i.e. their track brightness.

In this measurement, we compared the $^{13}C(^{3}He,^{6}He)^{10}C^{*}$ reaction leading to the 3.350 MeV level of ^{10}C with the $^{12}C(^{3}He,^{6}He)^{9}C$ g.s. reaction. These two Q-values are closely tied, with change of 1.0 keV in the first reaction resulting in a 1.2 keV in the second. Thus a change in the mass excess of $^{10}C^{*}$ would result in an adjustment of the present results. We note that the key advantage of the photographic emulsion in this work lies in the simultaneous recording of the various particles of interest. The results of three plate exposures, yield an average Q-value of -31.5762(30) MeV for the $^{12}C(^{3}He,^{6}He)^{9}C$ reaction. The assumed Q was -18.5898 MeV for C^{*} reaction leading to the first excited state of ^{10}C at 3.350 MeV.

The results for all the precise mass measurements of ^{9}C are shown in Table I, and are in rather good agreement with each other. A weighted average yields a mass excess of 28913.4 (2.2) keV for ^{9}C in its ground state. Table II shows the results of the fitting to the IMME. The quadratic IMME fit has a ^{2} of 14.4. If a cubic term of T_z^3 is added, we have d=5.7 1.5 keV, with the dominant contribution to the uncertainty coming from the inner members of the quartet, $^{9}Be^{*}$ and $^{9}B^{*}$.

Table I. Mass excess of ^{9}C (keV).

28918.2(5.1)	Barnes et al.[3]
28909.1(4.0)	Mosher et al.[4]
28915.6(8.0)	Trentelman et al.[5+]
28913.8(3.2)	Present work
28913.4(2.2)	Weighted mean

Bertsch and Kahana[7] have calculated possible contributions to a d-term and obtain d +3.6 keV from 3-body Coulomb and Coulomb plus charge dependent forces. Since the analog states in ^{9}Be and ^{9}B are extremely narrow, i.e. 0.38 and 0.40 keV respectively,[8] it is unlikely that they are shifted differentially in a significant way due to mixing with background levels, and this effect would not then contribute significantly to the observed d-term. We conclude that, at least in A=9, we have a multi-body interaction whose effect is reflected in the experimental results.

Table II. Parameters of the IMME for the lowest A = 9 quartet (values and uncertainties in keV).

	a	b	c	d	2
Quadratic fit	26337.7(1.6)	-1320.7(0.9)	265.1(1.0)	----	14.4
Cubic fit	26339.4(1.6)	-1332.4(3.2)	264.3(1.0)	5.7(1.5)	----

1. E.P. Wigner, in Proceedings of the Robert A. Welch Foundation Conferences on Chemical Research, Houston, Texas 1957, edited by A. Milligan, The Structure of the Nucleus, p. 67.
2. W. Benenson and E. Kashy, Reviews of Modern Physics, 51, 527 (1979).
3. C.A. Barnes, E.G. Adelberger, D.C. Hensley, and A.B. McDonald, in Nuclear Physics: Internation Conference, edited by R.L. Becker, C.D. Goodman, P.H. Stelson, and Z. Zucker (Academic Press Inc., New York, 1967) p. 261.
4. J.M. Mosher, R.W. Kavanagh, and T.A. Tombrello, Phys. Rev. C 3, 438 (1971).
5. G.F. Trentelman, B.M. Preedom, and E. Kashy, Phys. Rev. C 3, 2205 (1971).
6. R.G.H. Robertson, T.L. Khoo, G.M. Crawley, A.B. McDonald, E.G. Adelberger, and S.J. Freedman, Phys. Rev. 17, 1535 (1978).
7. G. Bertsch and S. Kahana, Phys. Lett 33B, 193 (1970).
8. P.A. Dickey, P.L. Dyer, K.A. Snover, and E.G. Adelberger, Phys. Rev. C 18, 1973 (1978).

Mass of ^{146}Gd and ^{147}Gd and Shell Closure at Z = 64

R.C. Pardo, S. Gales, R.M. Ronningen and L.H. Harwood

Recent studies by Kleinheinz et al.[1] and Ogawa et al.[2] have shown that the first excited state at 1579 keV in ^{146}Gd is the 3^- octupole state and the first 2^+ state is located at the relatively high excitation energy of 1971 keV. Only ^{208}Pb is known to have a similar level structure. These results, together with other indirect information, indicate that the energy gap at Z = 64, N = 82 between the $1g_{7/2}$ and $2d_{5/2}$ proton orbitals and the $1h_{11/2}$ orbital is unusually large.

The nuclear masses needed to address the question of the magnitude of the gap at Z = 64, N = 82 are ^{145}Eu, ^{145,146,147}Gd, and ^{147}Tb. Only the masses of ^{145}Eu and ^{147}Gd have been reported in the literature. Recently Firestone, Pardo, and McHarris[3] have measured the mass excess of ^{145}Gd to be -72.87 ±0.06 MeV. In this paper, we report the values of the mass excess for ^{146}Gd and ^{147}Gd deduced from Q-value determinations in the reactions ^{144}Sm(^{12}C,^{10}Be) ^{146}Gd and ^{144}Sm(^{12}C, ^{9}Be)^{147}Gd.

The MSU sector-focused Cyclotron provided 75-MeV $^{12}C^{4+}$ ions with beam current intensities ranging from 150 na to over 1 μa on target. Typical intensities were 250 na. The higher intensities were obtained using hafnium metal as the ion source cathodes. These buttons resulted in source lifetimes of from 12 to 36 hours. Machine stability was also significantly improved as compared to when tantalum metal cathodes were used.

Reaction products were detected in the focal plane of an Enge split-pole spectrograph by a two-wire charge-division transmission gas proportional counter.[4] This counter was backed by a stopping scintillator which gave total energy and time-of-flight information. The resulting ΔE, E, and TOF data gave excellent identification of the $^{10}Be^{4+}$ and $^{9}Be^{4+}$ ions. The resolution obtained in this experiment was as good as 90 keV for short runs. Due to the combined effects of ion source instabilities and target effects more typical resolutions were 100 - 120 keV. The targets used were approximately 100 μgm/cm^2 ^{144}Sm (96.5%) evaporated onto a 20 μgm/cm^2 ^{12}C foil backing. Similar thickness ^{92}Mo (98.3%) targets were used to calibrate the spectrograph.

Calibration of the spectrograph was achieved using the ^{92}Mo(^{12}C,^{10}Be)^{94}Ru (Q = -14.703 ± 0.013 MeV) reactions. The Q-values of these reactions are such that both $^{9}Be^{4+}$ and $^{10}Be^{4+}$ ion groups are simultaneously accepted by our detector. In fact, $^{10}Be^{4+}$ ions populating the ^{94}Ru ground state are focused only 9 mm from the focus for the $^{10}Be^{4+}$ ions populating the ^{146}Gd ground state. Likewise the ^{95}Ru ground state is only 7.5 mm from the ^{147}Gd ground state in the spectra of $^{9}Be^{4+}$ events. Therefore, no change in the spectrograph field is required in going from the calibration runs to the data runs. This choice of calibration reactions reduces all sources of error in our measurement to small kinematic effects, except for target thickness uncertainties.

Data were taken at 20°, 25°, and 30° in the laboratory system. A series of short runs confirmed DWBA predictions that the angular distributions was essentially bell-shaped and centered at the grazing angle (θ_g = 30°). The experiment was performed by a sequence of calibration run, data run, calibration run for each data point.

Spectra of $^{10}Be^{4+}$ and $^{9}Be^{4+}$ ions for the reaction leading to the residual nucleus ^{146}Gd and ^{147}Gd, respectively, are shown in Fig. 1. The mass excess of ^{146}Gd was determined to be -76.096 ±0.025 MeV while the mass excess of ^{147}Gd was found to be -75.48 ±0.03 MeV.

The mass excess of ^{146}Gd found in this study is 186 keV more negative than that predicted by the mass systematics of Wapstra and Bos.[5] A recent measurement of the Q-value of the ^{144}Sm (^{3}He,n) by Alford, et al.[6] results in a mass excess (-76.081 ±0.030 MeV) which is in excellent agreement with our value.

With the results of this experiment and the recent measurement of Firestone et al.[3] four of the five nuclei whose masses are needed in order to experimentally address the shell structure around ^{146}Gd have been determined. Only ^{147}Tb remains to be studied along with its metastable state, ^{147}Tb.

For ^{146}Gd we find the odd-even mass differences to have values of:

$\delta^p(^{146}Gd)$ = 3.75 MeV

$\delta^n(^{146}Gd)$ = 3.84 MeV

These are quite similar to those for the observed proton and neutron gaps in $^{208}Pb_{128}$, 3.43 MeV and 4.21 MeV, respectively.

The approximate cross sections observed in these reactions are compiled in Table 1. Since similar previous experiments[7] at this energy and DWBA calculations predict little, if any, structure to angular distributions, no attempt was made to carefully normalize these results. Even so, a few interesting points can be made concerning the observed population of excited states.

The low-lying 3^- and 2^+ states[1,8] at 1.58 and 1.97 MeV are populated with the 2^+ more weakly excited. The remaining states observed are in the negative parity band up to $J^\pi = 9^-$.

A state not populated in γ-ray studies is observed at 3.67 ± 0.010 MeV followed by the 10^+, 3.86 MeV level. Past the 10^+ level at 3.86 MeV little strength exists to any state, although two new levels, at 4.74 MeV and 6.47 MeV, excitation energy are observed.

As we do not observe the 8^- states[8] at 3.183 and 3.294 MeV, it would appear that only natural parity states are populated. This would be consistent with the assumption that the protons are transferred in a relative s-state. Although our data provides no direct spin/parity information, based on the above assumption one could propose the states at 3.67, 4.74 and 6.74 MeV have natural parity.

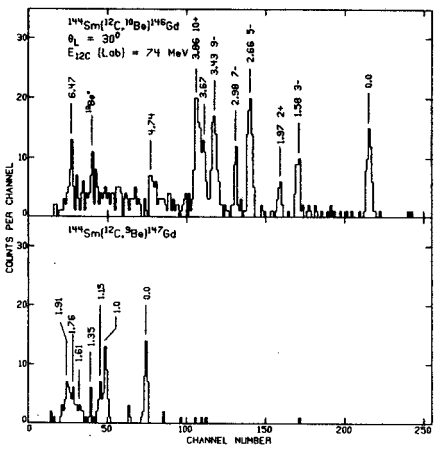


Fig. 1. Spectra of events observed in the ^{144}Sm(^{12}C,^{10}Be)^{146}Gd and ^{144}Sm(^{12}C,^{9}Be)^{147}Gd reactions.

Table I. Excited states observed in the reactions ^{144}Sm(^{12}C,^{10}Be)^{146}Gd and ^{144}Sm(^{12}C,^{9}Be)^{147}Gd. Approximate cross section at 30° (lab) are included.

Final Nucleus	E^x(MeV)	dσ/dΩ (μb/sr) at 30°(lab)
^{146}Gd	0.0	60
	1.58	38
	1.97	19
	2.66	86
	2.98	35
	3.43	70
	3.67 ± .010	50
	3.86	82
	4.74 ± .030	24
	6.47 ± .030	35
^{147}Gd	0.0	
	1.00	45
	1.15	25
	1.35	9
	1.61	13
	1.76	24
	1.91	34

1. P. Kleinheinz, S. Lundardi, M. Ogawa, and M.R. Maier, Z. Physik A284, 351 (1978).
2. M. Ogawa, R. Broga, K. Zell, P.J. Daly, P. Kleinheinz, Phys. Rev. Lett. 41, 289 (1978).
3. R. Firestone, R.C. Pardo, W.B. McHarris, Bull. Am. Phys. Soc. 23, 626 (1978), and to be published.
4. L.W. Robinson, MSU Annual Report 1977-78 p. 77.
5. A.W. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 177 (1977), 1977 Atomic Mass Evaluation, Part I.
6. W.P. Alford, R.E. Anderson, P.A. Batay-Csorba, R.A. Emigh, D.A. Lind, P.A. SMith, and D.C. Zafiratos, to be puslished in Phys. Rev.
7. W. von Oertzen, H. Homeyer, B.G. Harvey, D. Hendrie, and D. Kovar, Z. Phys., A279, 357 (1976).
8. P. Kleinhneiz, R. Broda, P.J. Daly, S. Lunardi, M. Ogawa, and J. Blomquist, Z. Physik, A290, 279 (1979).

The Mass and Excited States of ^{89}Mo

R.C. Pardo, L.W. Robinson, W. Benenson, E. Kashy and R.M. Ronningen

We have used the (^{3}He, ^{6}He) reaction to measure the mass and excited states of the isotope ^{89}Mo. The M.S.U. Cyclotron provided 70 MeV ^{3}He beams with intensities around 700 nA on target. Reaction products were identified[1] in the focal plane of an Enge split-pole spectrograph with two single wire charge division proportional counters (position, ΔE) plus a scintillator for energy and time-of-flight information.

A target of 260 μg/cm^2 thickness was produced by electron-sputtering 98.3% enriched ^{92}Mo onto a 20 μg/cm^2 carbon foil reinforced by a 2 μg/cm^2 layer of Formvar. Calibration of the spectrograph and detector was accomplished using the ^{27}Al(^{3}He,^{6}He) and the ^{26}Mg(^{3}He,^{6}He) reactions. The resolution obtained was about 60 keV. Our results are based on data taken in 5 separate runs during two independent experiments at lab angles of 7° and 10°. Using the masses of Wapstra and Bos[2] we determined the Q-value of the ^{92}Mo(^{3}He,^{6}He) reaction to be -14.474 ± .015 MeV, corresponding to a mass excess of -75.008 ± .015 MeV for ^{89}Mo.

The β^+-decay of ^{89}Mo was first reported by Butement and Qaim.[3] They reported an activity of 7 min. half-life based on the observation of positrons with energies greater than 3.6 MeV. The β^+-endpoints observed were 4.05 MeV and 4.95 MeV. No γ-rays were observed in the decay. The results of our work show that the maximum β^+-decay energy available in the decay of ^{89}Mo is 4.59 MeV. Therefore, the 4.95 MeV activity observed could not have been ^{89}Mo. Much later, Hagenauer *et al.*[4] attempted to study ^{89}Mo. Using three different targets, two projectiles, and seven energies they reported no activities which could be identified as ^{89}Mo. Systematics in this region predict a half-life of 1-2 minutes for ^{89}Mo. Based on these considerations we believe our data contains the first observation of ^{89}Mo.

The systematics of nearby odd -A, N=47 nuclei indicate that the ground state of ^{89}Mo should be $9/2^+$. The first excited states in ^{83}Kr, ^{85}Sr, and ^{87}Zr have $J^\pi=7/2^+$ and occur at 0.0094 MeV, 0.232 MeV and 0.210 MeV respectively. The second excited states in these nuclei have $J^\pi=1/2^-$ and are located at 0.0416 MeV, 0.240 MeV and 0.336 MeV. The first excited state of ^{89}Mo is identified at 0.124 MeV. Although weakly populated, a second excited state is located at 0.40 MeV. Systematic trends imply that the 0.124 MeV state has $J^\pi=7/2^+$ and the tentative level at 0.40 MeV has $J^\pi=1/2^-$. Other excited states are listed in table 1.

The cross section for populating the ^{89}Mo ground state was observed to be 51 nb/sr. The maximum observed cross section to any level was 83 nb/sr to the 1.74 MeV state. This agrees well with the cross section observed in the ^{90}Zr(^{3}He, ^{6}He)^{87}Zr reaction in ref. 1.

1. R.C. Pardo, E. Kashy, W. Benenson, and L.W. Robinson, Phys. Rev. C18, 1249 (1978).
2. A.H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 177 (1977), 1977 Atomic Mass Evaluation, Parts I and II.
3. F.D.S. Butement and S.M. Qaim, J. Inorg., Nucl. Chem. 26, 1491 (1964).
4. R.C. Hagenauer, G.D. O'Kelley, and E. Eichler, J. Inorg, Nucl. Chem. 37, 1111 (1975).

Table I. Identified excited states of ^{89}Mo from the ^{92}Mo(^{3}He,^{6}He) reaction.

Excitation energy		J^π*
0.0		$9/2^+$
0.124	.010	$7/2^+$
(0.40	.04)	$1/2^-$
1.25	.015	
1.74	.015	
2.11	.015	
5.34	.025	
5.48	.025	

*Assignments of J^π are based only on nuclear systematics.

A Study of the A=24, T=2 States with a Recoil Mass Analyzer and Cryogenic He-jet

A.G. Ledebuhr, R.G.H. Robertson, L.H. Harwood and T.J. Bowles*

In a previous paper,[1] the description of a cryogenic (liquid-nitrogen cooled) helium jet coupled to a recoil time-of-flight mass analyzer for use in observing short-lived β-delayed particle emitters was presented. This apparatus was used at Princeton University in an attempt to observe ^{24}Si. Results tentatively suggested that protons from the decay of this nucleus had been observed and that the mass of the T=2 state in the daughter nucleus ^{24}Al was consistent with the prediction from the quadratic form of the isobaric multiplet mass equation (IMME). With these promising results, an improved apparatus was constructed at Michigan State University with the intent of observing ^{24}Si and other T_z=-2 nuclei. Except as noted below, the apparatus is as described in ref. 1.

It is a feature of this apparatus that mass identification and background reduction can be obtained with only a single Si detector (rather than a counter telescope) to detect the protons. The improved resolution and linearity, as well as the simultaneous recording of strong calibration groups, enable us to obtain a more precise value for the mass of the T=2 state in ^{24}Al than was obtained by Aysto, et al. In addition, we can report the first direct measurement of the half-life of ^{24}Si.

A 1-2.5 μA beam of 70 MeV ^{3}He particles from the Michigan State University Cyclotron bombarded a 5 mg/cm^2 target of ^{24}Mg, producing ^{24}Si via the ^{24}Mg(^{3}He,3n) reaction. The ^{24}Si nuclei recoiling out of the ^{24}Mg target were thermalized in the cold He gas, which was at a temperature of 77° K and a pressure of 0.7 atm. The atoms were then swept into a 1.8 mm-diameter polyethylene capillary tube and transported 2.4 m to the recoil time-of-flight mass analyzer. The activity exitted the capillary 2-3 mm from a skimmer cone. A 140 l/s Roots blower backed by a 80 l/s mechanical pump removed a large fraction of the He gas. The transported atoms passed through the skimmer and were deposited on a 10-12 μg/cm^2 thick Formvar catcher foil. The main chamber was pumped on by a 1500 l/s turbo molecular pump backed by a 16.5 l/s mechanical pump and a 25 l/s mechanical pump connected in parallel.

Six catcher foils are mounted on a vertically aligned foil wheel. The foil wheel was stepped at a rate of 5 Hz with a high-torque hollow-rotor D.C. motor. The wheel was connected to the motor by a ferrofluidic shaft seal. This seal allows for high shaft accelerations while maintaining vacuum integrity. The activity was allowed to collect for 200 ms, minus ~20 ms stepping time. The wheel was then moved to its next position, where the newly deposited activity was placed between the particle detectors. After β-decay to particle-unstable states, both the particle emitted and the recoiling ion were observed in coincidence. Fig. 1 illustrates this arrangement.

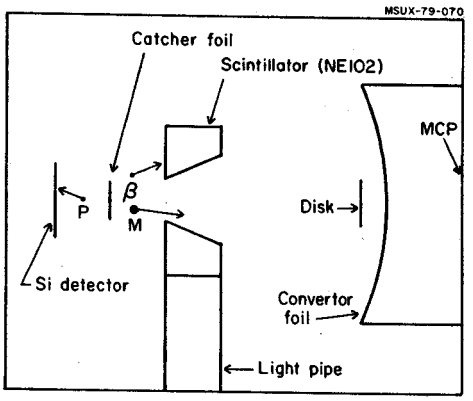


Fig. 1 shows the geometry of the detector arrangement (not to scale). The activity was deposited on the right side of the catcher foil.

Protons (or alphas) passed through the thin catcher foil and were detected using a single 150 mm^2, 300 μm deep Si detector. The residual nucleus is ejected off the surface of the foil. The recoil ions have enough energy to pass through a thin converter foil, placed opposite the Si detector. Secondary electrons from the converter were observed by a pair of Microchannel Plates (MCP). The 50.8 mm-diameter converter foil served also to isolate the MCP from the .14 torr pressure in the main detector chamber. This allowed the operation of the channel plates in a clean, high vacuum of 10^{-6} - 10^{-7} torr provided by another 1500 l/s turbo molecular pump.

The converter foil was shaped as a section of a sphere with an 80 mm radius of curvature. When placed 80 mm from the catcher foil, this curvature reduced the time spread of the recoil ions. Both the Si detector and converter foil subtended a solid angle of 2.6% of 4π. The converter foil consisted of a ~30 μg/cm^2 layer of Formvar on a curved wire screen. Onto this Formvar surface a ~10 μg/cm^2 layer of gold and a ~10 μg/cm^2 layer of CsI were evaporated. The layer of gold was used to prevent the converter foil from charging up. The CsI, with its supposed higher secondary emission coefficient,[3,4] was used to improve the detection efficiency of the recoils.

A start signal from the proton or alpha in the Si detector and a stop signal from the MCP gave a value for the time-of-flight of the recoil ion. This time, combined with the particle energy in the Si detector, was used to derive the recoil mass.

The β-decay recoil determines the mass resolution in these measurements. For ^{25}Si, which was produced in a competing reaction, this β-recoil limited the mass resolution to 7%, a value nevertheless adequate for mass identification.

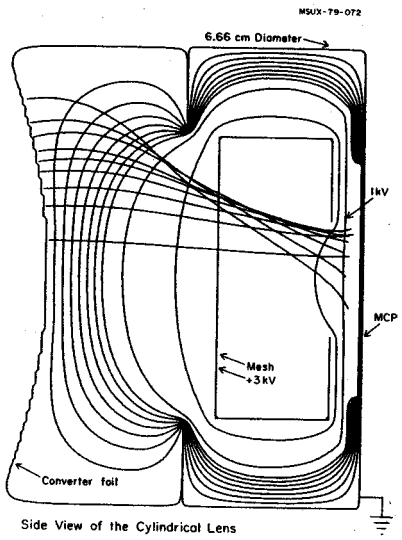
In initial experiments, it was found that the double coincidence data (between Si detector and MCP) showed two different recoil mass groups for the same particle energy. The second (slower) group was delayed by ~9 ns and was attributed to recoil ions directly striking the MCP but failing to produce secondary electrons in the converter foil. In order to remove these ghost groups, which were producing a background in the region of interest, the design of an electrostatic lens was undertaken. It was hoped that a design could be found which would both stop the recoils from striking the channel plates while still allowing the electrons to do so.

Lens designs were first modeled using the method of successive overrelaxation to solve Laplace's equation.[5] A program was developed which allowed the testing of many different geometric configurations. This program also calculated particle trajectories through the lens.

A gridded lens design, illustrated in fig. 2, that focused the electrons to the central region of the channel plates was chosen. This design required only the central portion of the MCP to be used. The outer regions were masked off, and a small disk placed in front of the converter foil prevented the recoil ions from hitting the channel plates. A loss of only 7% in solid angle resulted from this arrangement, and a significant reduction in the background was achieved.

As in the previous apparatus,[1] an annular plastic scintillator was used to observe the initial β-decay of the parent nuclei. This scintillator was placed opposite the Si detector and subtended a solid angle of ~37% of 4π. Recoil ions traveled through a conical hole in the scintillator to the converter foil. The triple coincidence data, though useful in reducing the background and improving the mass resolution for the verification of weak groups, was not directly used in obtaining the proton energy. This was because the beta-induced recoil of the daughter had a component of its velocity toward the Si detector. Thus, the particles detected in the Si detector were shifted up in energy. Therefore, only double coincidence data (between Si detector and MCP) were used to obtain the proton energy.

Many different activities are produced by the beam in the target and several delayed particle emitters were observed in our experiments. Due to the mass identification capability, we recorded data in the event mode and, upon subsequent playback, extracted proton and alpha energy spectra for different recoil mass bands. Figure 3 shows proton spectra for a recoil band of 22-24 amu.



Side View of the Cylindrical Lens

Fig. 2 shows the model lens upon which the actual lens was based. Eleven equipotentials and nine particle trajectories are shown. The particles were started from rest near the surface of the convertor foil. The inner and outer trajectories are at 0.5 cm and 2.54 cm respectively. A time difference of 3.1 ns was calculated for these two paths. The mass resolution is still limited by β-recoil before the particle emission.

The two large peaks were from protons from the decay of the β-delayed proton emitter ^{25}Si. This was produced in the ^{24}Mg(^{3}He,2n) with a much higher yield than the ^{24}Si. The proton groups from this nucleus provided us with well-known calibration lines. The energies of these two groups were derived from the results of Rogers et al.[6,7] and are 4089±2 kev and 5402±2 kev respectively. We obtained a value for the proton energy of the decay of the T=2 state in ^{24}Al of 3911.2±3.6 kev. This agrees well with the 3914±9 kev result of Aysto, et al.[2] The recent measurement of the mass of ^{24}Si by Tribble et al.[9] completes this A=24, T=2 isospin quintet.

The half-life of ^{24}Si was measured by recording the time of occurrence of an event after the foil wheel step. By comparison with other delayed-particle activities, such as ^{20}Na(445 ms), ^{21}Mg (122 ms), and ^{25}Si(220 ms), the half-life of ^{24}Si could be directly measured. The value we obtained was 136±56 ms. This agrees with both the predicted value of 115 ms[8] and with the estimate from Aysto, et al[2] of 100^{+90}_{-40} ms.

A paper describing in detail our results for the mass excess of the T=2 state in ^{24}Al and of the half-life of ^{24}Si, along with a fit of all five masses with the IMME, is being completed.

* Argonne National Laboratory, Argonne, IL.

1. R.G.H. Robertson, T.J. Bowles and S.J. Freedman, Nucl. Instr. and Meth. 147 (1977) 361.
2. J. Aysto, D.M. Moltz, M.D. Cable, R.D. Von Dincklage, R.F. Parry, J.M. Wouters, and J. Cerny, Phys. Lett. 82B (1979) 43.
3. J.C. Faivre, et al., Tran. IEEE, NS24 (1977) 299.
4. R. Burgei, M. Grand, R. Maillard and A. Papinean, Saclay CEA-N-2026 (1977) 256.
5. M. Distasio and W.C. McHarris, Am. J. Phys. 47(5) (1979) 440.
6. D.W. Rogers, N. Anyas-Weiss, S.P. Dolan, N.A. Jelley, and T.K. Alexander, Can. J. Phys. 55 (1977) 206.
7. A.H. Wapstra and K. Bos, At. Data and Nucl. Data Tebles 19 (1977) 175.
8. R.G.H. Robertson and B.H. Wildenthal, Phys. Rev. C8 (1973) 241.
9. R.E. Tribble, D.M. Tanner, A.F. Zeller, D.P. May, and C. Jones, BAPS 24 (1979) 847.

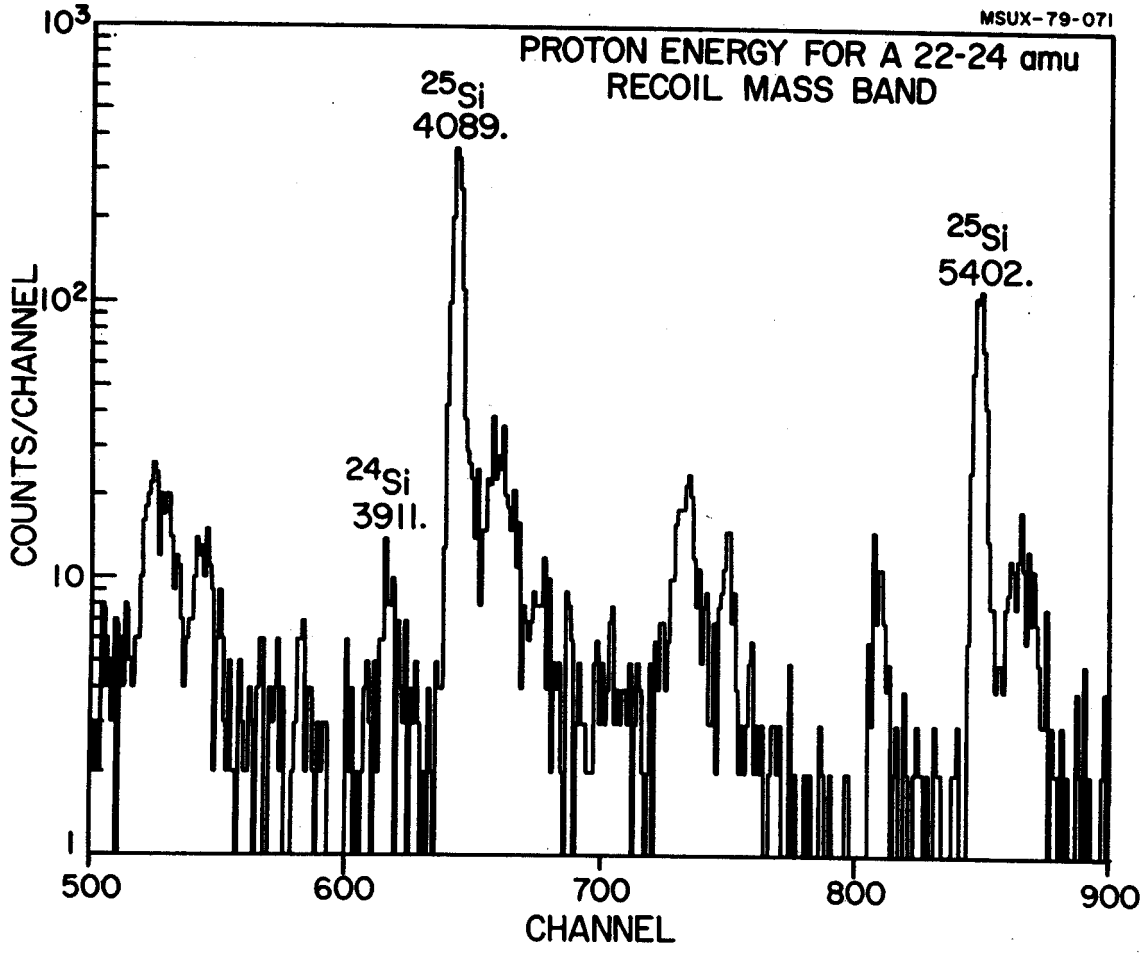


Fig. 3 shows proton energy spectrum obtained in coincidence with the MCP, and with a recoil mass band of 22-24 amu. This data represents a 334 mC bombardment.