Mass measurement of proton-rich, medium-weight nuclei by the (^{3}He,^{6}He) reaction

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The (^{3}He,^{6}He) reaction at 70 MeV on ^{70}Ge, ^{90}Zr, ^{106}Cd, ^{112}Sn, and ^{144}Sm has been used to study the proton-rich nuclei ^{67}Ge, ^{87}Zr, ^{103}Cd, ^{109}Sn, and ^{141}Sm. The observed ground state mass excesses have been determined to be -62.65 ± 0.03, -79.344 ± 0.009, -80.620 ± 0.018, -82.634 ± 0.011, -75.933 ± 0.016 MeV, respectively. Excited states observed in these reactions are also reported. The cross sections for the (^{3}He, ^{6}He) reaction decrease with increasing A but not as dramatically as has been observed with the (^{3}He,^{7}Be) reaction.

NUCLEAR REACTIONS ^{70}Ge, ^{90}Zr, ^{106}Cd, ^{112}Sn, ^{144}Sm(^{3}He, ^{6}He)^{67}Ge, ^{87}Zr, ^{103}Cd, ^{109}Sn, ^{141}Sm; $E = 70$ MeV; measured reaction Q values, deduced mass excesses, excitation energies.

I. INTRODUCTION

The masses of medium-weight, proton-rich nuclei have been determined mainly by beta decay end-point measurements. For a nucleus far-from-stability the mass excess (M.E.) is obtained by combining successive beta end-point measurements until one reaches either a stable nucleus or a nucleus whose mass excess is known from a Q value determination in a charged particle reaction. The determination of the mass excesses of even a few nuclei far-from-stability via charged particle reactions is highly desirable because accurate determinations can be expected to improve the binding energy information in an entire region surrounding these nuclei.

The (^{3}He,^{6}He) reaction has been a powerful method for studying proton-rich nuclei in the mass region up to zinc. It has not been previously applied to heavier nuclei, due in part to the assumption that the already extremely small cross section would become even smaller, much as had been observed in the (^{3}He,^{7}Be) reaction.[1]

In this paper we report the observation of the (^{3}He,^{6}He) reaction on targets of ^{70}Ge, ^{90}Zr, ^{106}Cd, ^{112}Sn, and ^{144}Sm. The measured Q-values yield new determinations of mass excesses for ^{67}Ge, ^{87}Zr, ^{103}Cd, ^{112}Sn, and ^{141}Sm. In addition, several excited states were identified in each nucleus. We also report the cross sections observed and discuss the global trends of cross-section for the (^{3}He,^{6}He) reaction.

II. EXPERIMENTAL METHOD

The Michigan State University cyclotron provided 70 MeV ^{3}He beams with typical intensities of 1 μA on target. The reaction products were detected in the focal plane of an Enge split-pole magnetic spectrograph using a two-wire charge-division gas proportional counter for position and ΔE information in a manner previously described.[2] Time-of-flight and light output information were provided by a plastic scintillator backing the proportional counters. The ^{6}He reaction products were identified using the resulting ΔE, light output, and TOF information. The data were event recorded using a PDP 11/45 computer for final off-line sorting.

The targets used in this study are listed in Table I. The target thicknesses were measured using α particles of 8.785 MeV energy from sources produced by ^{228}Th decay products. The errors in the measured Q values due to the uncertainties in the target thickness were less than 6 keV except for ^{106}Cd, where the nonuniformity of the target contributed 12 keV. Either the ^{60}Ni(^{3}He,^{6}He)^{57}Ni ($Q = -11.054 \pm 0.004$ MeV) or the ^{62}Ni(^{3}He,^{6}He)^{59}Ni ($Q = -8.255 \pm 0.002$ MeV) reactions were chosen as the calibration reactions because they have almost the same Q value as the reactions of interest. This made it unnecessary to change the magnetic field of the spectrograph, and eliminated a major source of error in the Q value determination.

The data were acquired in a sequence consisting of calibration-measurement-calibration. The requirement that the calibrations before and after the measurement agree insured against errors due to field change, detector malfunction, or other similar problems. Measurements

TABLE I. Targets

Target	% Enrichment	Thickness (μg/cm^2)[a] Target	^{12}C Backing
^{70}Ge	84.62	310	20
^{90}Zr	98.66	245	
^{106}Cd	82.90	1100	
^{112}Sn	80.04	850	
^{144}Sm	95.1	645	25
^{60}Ni	99.79	258	
^{62}Ni	98.83	239	

[a] Unless specified, all targets were self-supporting foils.

were made mainly at 7° and 10° laboratory angles, but some data on specific targets were taken at 5°, 8°, and 13°. The results reported here are the weighted average of at least two separate experimental runs. The acquisition of the data at different angles insures proper kinematic tracking and separate experimental conditions make the two measurements independent. This helps reduce the possibility of systematic errors.

III. RESULTS

Figures 1 and 2 show examples of typical spectra obtained. The resolution was approximately 60 keV FWHM except when limited by the thickness of the targets employed.

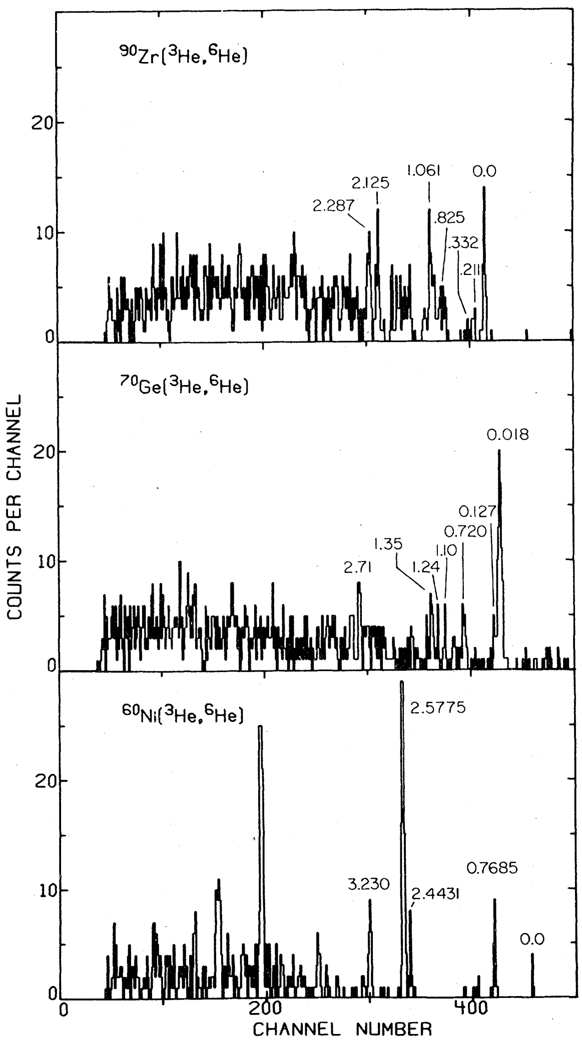

Fig. 1. Spectra of ^{6}He particles observed from various targets in the (^{3}He,^{6}He) reaction. All spectra were taken at $\theta_L = 7°$ and $E_{^3He} \simeq 70$ MeV. The states labeled by their excitation energy in the ^{60}Ni(^{3}He,^{6}He) spectrum served as calibration points for the other reactions.

The results of the Q value measurements and the deduced mass excesses are summarized in Table II. The present best values of the mass excesses are included for comparison. The previously accepted mass excesses are based on measurements of the beta decay end-point energies as tabulated by Wapstra and Bos.[3] The measure-

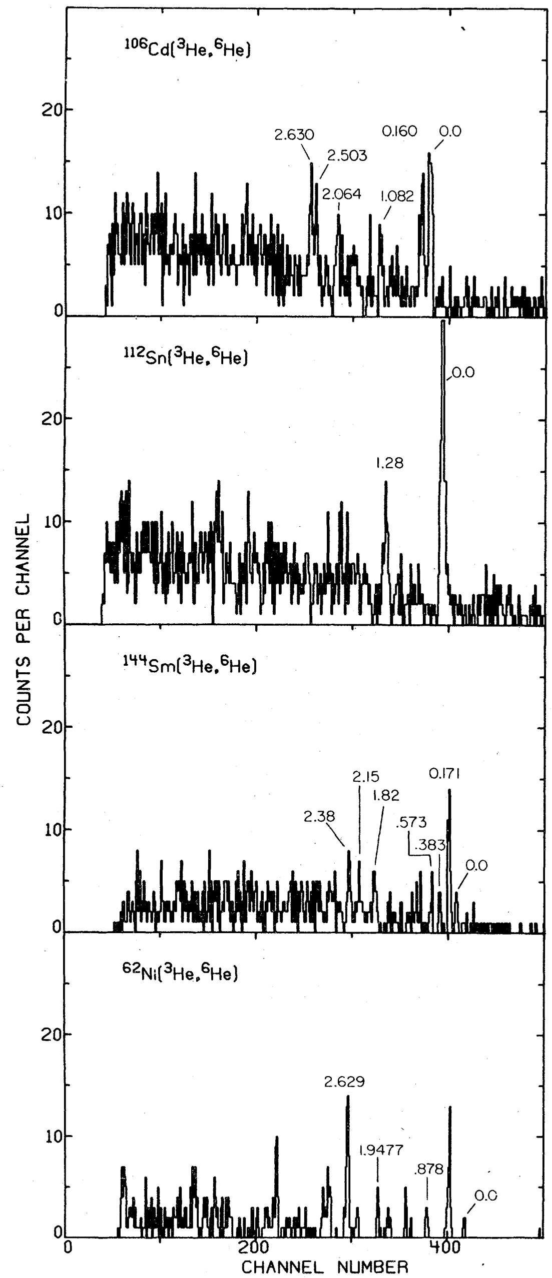

Fig. 2. Spectra of ^{6}He particles observed from additional targets in the (^{3}He,^{6}He) reaction. All spectra were taken at $\theta_L = 7°$ and $E_{^3He} \simeq 70$ MeV. The states labeled by their excitation energy in the ^{62}Ni(^{3}He,^{6}He) spectrum served as calibration points for the other reactions.

TABLE II. Mass Excesses and Q-values.

Nucleus	Number of Measurements	Measured Q-value (MeV)	Inferred Mass Excess (MeV)	Previous Mass Excess Ref. 2 (MeV)	$\frac{d\sigma}{d\Omega}$ (nb/sr)
^{67}Ge a)	2	-10.572±0.03	-62.65 ±0.03	-62.450±0.050	270
^{87}Zr	6	-12.083±0.008	-79.344±0.009	-79.430±0.080	100
^{103}Cd	3	-9.173±0.017	-80.620±0.018	-80.600±0.140	170
^{109}Sn	4	-8.686±0.009	-82.634±0.011		70
^{141}Sm	5	-8.693±0.012	-75.933±0.016	-75.910±0.060	90

a) Lowest energy state observed is assumed to be 18 keV state. See text.

ment reported here for the mass excess of ^{109}Sn is compared to various mass formula predictions in Table III since no previous measurement has been accepted by Wapstra and Bos.

The errors shown for the mass excesses obtained in this study correspond to the standard deviation of the mean of the various determinations. These internal errors were compared to a careful analysis of various sources of random error. In general, agreement between the observed uncertainty and the expected random error is good. Occasionally the expected random error was greater than that observed. The larger of the two results has been used in all cases.

The observed differential cross section for population of the ground state in each reaction is included in Table II. The value quoted is the average over all angles. The variations observed between angles were generally within the statistical accuracy of the individual measurements in the small angular range covered.

Table IV lists the excited states observed in these studies. The criterion for identification of excited states was that they be observed in at least two independent runs. In general, only a small number of individual excited states were observed. Much of the strength of the (^{3}He,^{6}He) reaction on these heavier nuclei is observed to be spread among a large number of unresolved excited states. Angular distributions were not obtained in this study since the reaction mechanism for (^{3}He,^{6}He) is still poorly understood, and not enough information was available to allow any simple shape comparisons to be made.

TABLE III. Comparison of ^{109}Sn mass excess to predictions. (See Reference 22).

	Mass Excess (MeV)
Experimental	-82.634±0.011
Groote, Hilf, Takahashi	-83.65
Seeger and Howard	-82.52
Liran and Zeldes	-82.52
Bauer	-84.38
Beiner, Lombard, and Mas	-81.9
Janecke, Garvey, and Kelson	-82.92
Comay and Kelson	-82.9
Janecke and Cynou	-82.87
Wapstra and Bos	-82.620

IV. DISCUSSION

The results of our mass determinations show varying degrees of agreement with previous measurements. In the case of the mass excess of ^{109}Sn, our measurement is the first accurate determination although a measurement by β^+ end-point methods is in the literature. The examination of each case, which follows, should help in understanding the results.

A. ^{67}Ge

Until recently, the two existing mass excess determinations for ^{67}Ge differed by five standard deviations from each other. Stelson and McGowan[5] determined the mass excess of ^{67}Ge to be -62.446 ± 0.046 MeV by a ^{64}Zn(α,n)^{67}Ge threshold measurement, but the beta end-point determination of Vasil'ev et al. yielded a mass excess of -62.720 ± 0.050 MeV. Recently Murphy et al.[7] found the threshold of the ^{64}Zn(α,nγ)^{67}Ge reaction to be -62.666 ± 0.012 MeV. In addition, their study of the level scheme of ^{67}Ge resulted in the identification of excited states at excitation energies of 18.2 and 122.7 keV.

In our study we observed a level at 108 keV excitation energy above the presumed ground state of ^{67}Ge. If we assume that the lowest energy state observed in the ^{70}Ge(^{3}He,^{6}He) reaction was not predominantly the ground state of ^{67}Ge but was instead the 18.2-keV first excited state, then the 108-keV level is identified as a 127-keV level, which we associate with the 122.7-keV level seen by Murphy et al. The mass excess quoted in this paper is based on this identification. Even so, it is impossible to estimate the relative contribution of the ground state and the 18.2-keV level to the lowest excitation energy peak in our spectrum. The errors quoted for the mass excess of ^{67}Ge reflect this uncertainty.

TABLE IV. Excited States observed.

^{67}Ge E_x (MeV)	^{87}Zr E_x (MeV)	^{103}Cd E_x (MeV)	^{109}Sn E_x (MeV)	^{141}Sm E_x (MeV)
0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
0.119 (33)	0.211 (10)	0.180 (12)	1.277 (15)	0.171 (16)
0.702 (33)	0.332 (10)	1.082 (12)		0.383 (16)
0.905 (33)	0.825 (13)	2.064 (22)		0.573 (17)
1.084 (33)	1.061 (15)	2.503 (18)		1.820 (22)
1.223 (33)	2.125 (15)	2.630 (18)		2.150 (22)
1.328 (33)	2.287 (15)			2.380 (22)
2.694 (33)				

B. ^{87}Zr

The presently accepted value for the mass excess of ^{87}Zr is based on two discordant β^+ end-point measurements by Hyde and O'Kelly[9] and Arlt et al.[10] of 2100 ± 20 keV (M.E. = −79.503 ±.020 MeV) and 2260 ± 40 keV (M.E. = −79.344 ± .040 MeV) respectively. Our result is in excellent agreement with the result of Arlt et al.

The levels of ^{87}Zr populated by the β^+ decay of ^{87}Nb and ^{87m}Nb have been studied by Turcotte et al.[11] They find the first excited state in ^{87}Zr at an excitation energy of 0.201 MeV with an inferred $J^\pi = 7/2^+$. The $1/2^-$ state is identified at an excitation energy of 0.336 MeV. This scheme is completely analogous to the structure observed for the other N = 47 nuclei such as ^{85}Sr and ^{83}Kr. The excited states observed in this work at an excitation energy of 0.211±0.010 MeV and 0.332±0.010 MeV are identified as the first two excited states observed by Turcotte et al. The observation of these two states in the ^{90}Zr(^{3}He,^{6}He) reaction confirms our identification of the ^{87}Zr ground state and the systematics of the N = 47 nuclei indicate that there should be no other states near the ground state.

C. ^{109}Sn

No previous measurement of the mass of ^{109}Sn has been accepted by Wapstra and Bos.[3] A β^+ decay end-point determination by Shastry et al.[4] implies a mass excess of −82.40 MeV, 230 keV more positive than reported in this paper. This discrepancy has the wrong sign to be explained by the identification of an excited state as the ^{109}Sn ground state in the (^{3}He,^{6}He) reaction.

A possible explanation of the discrepancy lies in the β^+-decay end-point determination method, in which the β^+ spectrum coincident with the 511-keV annihilation radiation was used. This technique, although accounting for the location of one of the 511 keV γ rays, does not eliminate the possibility of coincident summing of the other 511-keV γ ray or other coincident γ rays. The effects of coincident summing require careful analysis, preferably by comparison to a β^+ decay spectrum of known endpoint energy.

No information exists on levels in ^{109}Sn. A survey of the trends for the N = 59 nuclei indicates that the first excited state should be well separated ($\gtrsim$ 200 keV) from the ground state. Therefore, no problems with low-lying excited states are to be expected in determining the mass excess of ^{109}Sn.

D. ^{103}Cd

The mass excess for ^{103}Cd calculated from the measurements presented in this paper agrees with the presently accepted value,[3] which is the result of a β^+ end-point measurement.[12] The accuracy of the present measurement is more than a factor of ten better than the previous value.

The problem of proper identification of the ground state in ^{103}Cd may be considered by observing the systematic trends in the N = 55 nuclei. The lighter N = 55 nuclei have a $5/2^+$ ground state followed by either a $7/2^+$ or $3/2^+$ first excited state. Both the $7/2^+$ and $3/2^+$ levels are observed to be approaching the ground state $5/2^+$ level as the proton number increases. This is consistent with our observation of an excited state at an excitation energy of 177 keV. Since a second low-lying excited state was not observed, the possibility of a ground state doublet cannot be ruled out in this work.

E. ^{141}Sm

Previous studies by Eppley et al.[13] and Kennedy et al.[14] have focussed on the beta decay of ^{141}Sm. These results confirm the existence of an isomeric state in ^{141}Sm and elucidate the detailed decay of both ^{141m}Sm and ^{141g}Sm. The study by Kennedy et al. included β^+ decay end-point determinations and resulted in a mass excess of −75.920 ± 0.060 MeV. These end-point measurements fixed ^{141m}Sm at an excitation energy of 140 ± 70 keV. A recent study of the decay of ^{141}Eu by Deslauriers et al.[15] identified a number of states in ^{141}Sm. Their results placed ^{141m}Sm at an excitation energy of 175.8 ±.3 keV. They also inferred the first excited state of ^{141}Sm to be at 1.58 keV in excitation energy.

The mass excess of ^{141}Sm, determined to be −75.933 ± 0.016 MeV in this work, is in excellent agreement with the results of Kennedy et al. The isomer of ^{141}Sm was observed as the most strongly populated state in the (^{3}He,^{6}He) reaction, and its excitation energy was determined to be 0.171 ±0.016 MeV. In addition, the level seen by Deslauriers et al. at 384.5 keV is identified as the 383 keV level observed in this work. The ambiguity in the ground state mass introduced by the 1.58-keV first-excited state is included linearly in the quoted uncertainty.

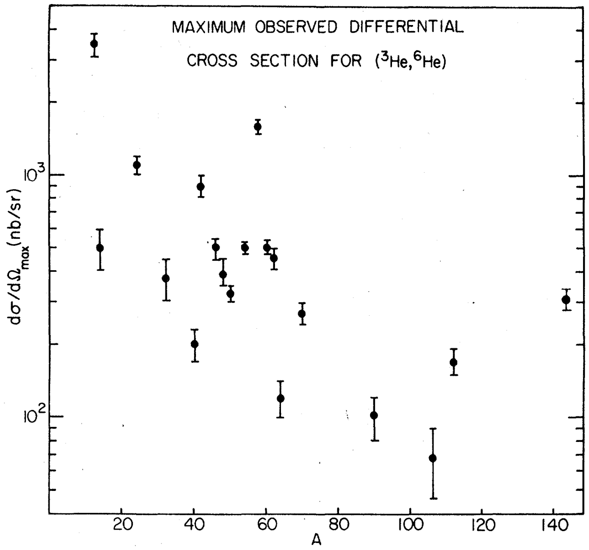

Fig. 3. The maximum differential cross section for the most strongly excited state observed at any angle in the (^{3}He,^{6}He) reaction ($E(^3He)_{lab} \simeq 70$ MeV) plotted as a function of target atomic mass number.

F. Cross section trends

The reaction mechanism involved in the (^{3}He,^{6}He) reaction is still not well understood. Kashy et al.[16] were not able to obtain acceptable fits to the data from the ^{13}C(^{3}He,^{6}He)^{10}C reaction, but calculations by Delic and Kurath[17] show that it is possible to argue that the reaction proceeds by a direct cluster transfer. This direct reaction hypothesis is qualitatively supported by the observation of structure in the angular distributions on a number of nuclei.

In an effort to map the general trends of the (^{3}He,^{6}He) reaction we have plotted the largest cross section observed at any angle as a function of atomic mass number (A) in Figure 3. The data in this figure come from References 16 and 18–22 as well as the results of this study. As one can see, there is a correlation of the maximum observed cross section to a specific state with A. This is similar to the A dependence observed for the (^{3}He,^{7}Be) reaction in Reference 1, though the decrease in cross section is not as large. Attempts to identify other parameters which influence this cross section have not been fruitful.

This dependence on A is in contrast to the excitation-energy-integrated cross section observed in the first 6 MeV in the residual nucleus. Here one finds that the observed excitation-energy-integrated cross section is essentially independent of A. (This crude parametrization assumes that all angular distributions are the same.) These observations would be consistent with the expectation that 3-neutron hole-state strengths (relative to the target nucleus) are concentrated in a relatively few lower energy states for lighter A nuclei.

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