conditions in C+C but not in O+O, supporting the postulated reaction mechanism. A full report on these measurements, including further information and discussion bearing on the reaction mechanism, will be submitted for publication in the near future.

CONCLUSIONS

At energies below the Coulomb barriers, elastic scattering measurements on the C+C and O+O systems are in accord with the Mott-scattering predictions for identical spin-zero bosons. At higher energies evidence has been obtained for the existence of a quasi-molecular interaction mechanism present in the C+C but absent in the O+O system. It is suggested that this mechanism depends critically upon the characteristics of the component nuclei involved. Further measurements on the corresponding system reaction cross sections are suggested to provide further insight into the mechanism involved.

It is believed that this is the first evidence for such molecular states in nuclear interactions; these states may provide an interesting probe for study of high-spin nuclear states as well as quasi-fission situations of particularly simple configuration. Further study of the binding involved in these states should provide significant information on the nature of the nuclear surfaces involved and on the nucleon interactions in the surfaces which give rise to the bond.

ACKNOWLEDGMENTS

We are indebted to a great many of our colleagues, in many laboratories, for discussions concerning these results; particular thanks are due Dr. E. W. Vogt and Dr. H. McManus. We would also express our appreciation to Dr. J. M. McKenzie for supplying the Au-Si detectors used and to Mr. W. Woytowich for preparing the carbon and silicon monoxide targets. We are indebted to C. E. L. Gingell for his assistance in instrumentation and to P. Ashbaugh and his associates for operation of the tandem accelerator.

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Short-Lived Isomers of Ge^{71}, As^{74}, Br^{78}, and Tc†

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Short-lived isomers have been produced with the pulsed beam of a Van de Graaff generator and observed between pulses with scintillation detectors. The results are summarized in the following table:

Isotope	Half-life	Isomeric transition (kev)	Observed gamma ray (kev)
Ge^{71}	20.3 ± 0.3 msec	23 ($M2$)	175
As^{74}	8.0 ± 0.3 sec	283 ($M3$)	283 ± 5
Br^{78}	118.0 ± 1.5 μsec	149 ($M2$)	149 ± 2, 32 ± 2
Tc	8.15 ± 0.20 μsec		177 ± 4
Tc	15.5 ± 0.8 μsec		43 ± 3

INTRODUCTION

ONE of the notable successes of the nuclear shell model has been the prediction of the islands of isomerism for odd nuclei.[1] The simple application of the predicted sequence of nucleon shells has led to the prediction of isomeric transitions characterized by a spin change of 3 or 4. In some cases the expected spin changes have not been found because of level shifts. The disappearance of a $\Delta I=3$ or 4 isomer may give rise instead to an $M2$ isomer. For the region of 28 to 50 equivalent nucleons, the shell model predicts single-particle levels $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, and also $7/2+$ and $5/2+$ levels formed by coupling of several equivalent $g_{9/2}$ nucleons. The island of isomerism is comprised of $M4$ transitions between $g_{9/2}$ and $p_{1/2}$ levels and low-energy $E3$ transitions between $7/2+$ and $p_{1/2}$ levels. However, $M2$ isomers have been found[2] and the level configurations were $g_{9/2}-f_{5/2}$ (references 3 and 4) or

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[1] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952); M. Goldhaber and A. W. Sunyar, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955). Chap. 16, p. 453.

[2] *Nuclear Level Schemes, A=40−A=92*, compiled by K. Way, R. W. King, C. L. McGinnis, and R. van Lieshout, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955), and *Nuclear Data Sheets*, edited by C. L. McGinnis, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washingron 25, D. C.).

$p_{1/2}-5/2+$ (reference 5); unexpected $E3$ isomers have been found owing to $g_{9/2}-p_{3/2}$ configurations.[4,6]

The spins and parities of levels in odd-odd nuclei have been explained on the basis of single-particle shell-model states for the odd proton and neutron; the angular momenta are then coupled according to certain coupling rules.[7] However, proton-neutron coupling energies can be sufficiently strong to rearrange the single-particle level sequence; thus it has been impossible to predict with confidence the relative position of different levels. Since the occurrence of isomerism and the type of transition responsible for it depend critically on the relative position of the low-lying levels, one finds that isomers of odd-odd nuclei do not fall into well-defined groups. Although isomers exist in Br^{80} and Br^{84} (reference 8), none had been found in Br^{82} or in the even arsenic isotopes. In the present work a search was made for $M2$ transitions in the odd-neutron nuclides Ge^{71} and Se^{75}, as well as for short-lived isomers in the odd-odd arsenic isotopes 74 and 76, further in the bromine isotopes 78 and 82. The single-particle states permit level spins between 0 and 6 or even 9, and thus a possibility exists for the occurrence of short-lived isomers.

EXPERIMENTAL PROCEDURE

The equipment and procedures have been described previously.[9] The activities were produced with the pulsed beam of an electrostatic generator. The target material was mounted at the end of a 2-in. long by $\frac{7}{16}$-in. diam stainless steel tube with a 0.010-in. wall thickness. Ga_2O, Ge, and Se targets were thin, evaporated layers on a 0.010-in. thick gold backing. The Mo target consisted of a piece of metallic foil. Survey work and half-life measurements were made with a $2\frac{1}{2}$-in. diam by $2\frac{7}{8}$-in. long well-type crystal. Energy measurements were made with an $1\frac{1}{2}$-in. diam by 1-in. long crystal, which was calibrated with standard gamma-ray sources.[10] In general, the pulse-height calibration drifted slowly because the air stream which cooled the target affected the crystal temperature. A run was used for an energy determination only if calibrations, taken before and after the recording of the unknown, checked with each other.

Gamma transitions were detected if their energy fell into the range from 30 to several hundred kev; gamma rays from lower energy transitions are highly converted and were not investigated. A measurement of the K x-ray yield from the internal conversion would have revealed the existence of such transitions and could have been used for calculating internal conversion coefficients in those cases where gamma rays were observed. However, these x rays, 10.0 kev for Ge to 17.8 kev for Mo, were absorbed in the steel target tube (20% transmission at 30 kev), and special techniques would have been required for their detection. Where such unobserved transitions were possible, other information about the levels in the nuclide had to be used.

The search for isomers was conducted with both proton and deuteron bombardment at incident energies between 2 and 5.5 Mev. The initial survey, made with a 40% irradiation duty cycle and short-time gates ($\sim$30 μsec) produced all short-lived isomers in comparable amounts, independent of half-life. Subsequently, activities in a given half-life range were brought out[9] with a low duty cycle (1 to 4%). Finally, the half-life and gamma-ray energy of each specific isomer were measured at a duty cycle of about 2%. Isotopic mass assignments were based on bombardment of enriched isotopes and on cross bombardment techniques. The proton-induced reactions included (p,n) above threshold, (p,γ), and (p,p'); the latter process can involve a Coulomb excitation of a higher excited state which in turn de-excites to the isomeric state. The significant reactions under deuteron bombardment were (d,n) and (d,p) processes; at higher bombarding energies the (d,α) cross section can also be significant. Although the (p,γ) reactions have small cross sections, the best ratio of desired activity to background could generally be obtained if the isomer was formed by this reaction.

RESULTS

Odd-Neutron Nuclei

Ge⁷¹

The ground state of Ge^{71} is $p_{1/2}$ and, since there are 39 neutrons, a low-lying $g_{9/2}$ level is to be expected. It was known from the As^{71} decay[2] that the first excited level at 175 kev is $5/2-$ and has a half-life of 0.07 μsec, and, further, that the second excited level at 198 kev is either $7/2+$ or $9/2+$. The possible $M2$ isomer due to a $9/2+$ to $5/2-$ transition was searched for as part of a survey of the short-lived activities that could be induced on a Ge target by proton or deuteron bombardment.

Targets with natural isotopic abundance, as well as targets enriched in a specific Ge isotope,[11] were em-

[3] Alois W. Schardt, Phys. Rev. **108**, 398 (1957).

[4] Albert Goodman and A. W. Schardt, Bull. Am. Phys. Soc. **4**, 56 (1959), and Albert Goodman, thesis, University of New Mexico, 1961 (unpublished).

[5] J. P. Welker, A. W. Schardt, G. Friedlander, and J. J. Howland, Jr., Phys. Rev. **92**, 401 (1953).

[6] J. C. Hubbs, W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee, Phys. Rev. **104**, 757 (1956).

[7] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960); references to other work on this subject are given in this paper.

[8] J. E. Sattizahn, Jr., J. D. Knight, and M. Kahn, J. Inorg. & Nuclear Chem. **12**, 206 (1960), and J. E. Sattizahn, Jr., thesis, University of New Mexico, 1957 (unpublished).

[9] Alois W. Schardt, Phys. Rev. **122**, 1871 (1961).

[10] The following sources were used: In^{114m} (24.7 and 192 kev), Am^{241} (59.7 kev), Be^{207} (76.7 and 570 kev), Ce^{139} (166 kev), and Na^{24} (511 kev).

[11] The enriched stable isotopes were obtained from The Isotope Division, U. S. Atomic Energy Commission, Oak Ridge, Tennessee. The desired isotopes constituted the following percentages of the Ge content: Ge^{70} 94.2%; Ge^{72} 89.2%; Ge^{73} 78.04%; Ge^{74} 97.7%; and Ge^{76} 98.6%.

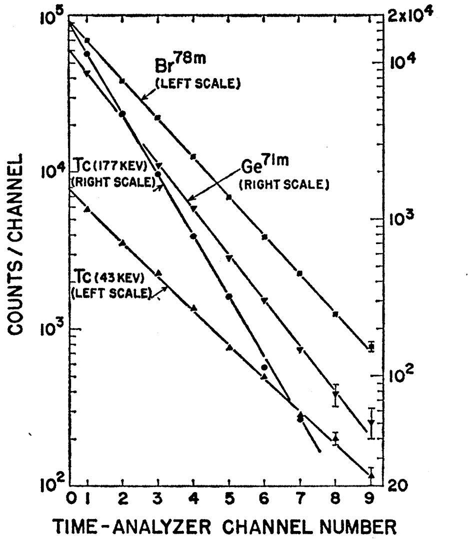

FIG. 1. Decay curves taken with the time-delay analyzer; the background counting rates have been subtracted from the raw data. The 20.3-msec Ge^{71} data were taken with 19.93-msec wide channels; the background was 77 counts/channel. The corresponding numbers for the other isomers were as follows: 118-μsec Br^{78}, 99.5 μsec, 2520 counts/channel; 8.15-μsec Tc (177 kev), 10.5 μsec, 231 counts/channel; 15.5-μsec Tc (43 kev), 10.5 μsec, 130 counts/channel. The 15.5-μsec Tc decay curve is not straight due to a small contribution from the 8.15-μsec isomer.

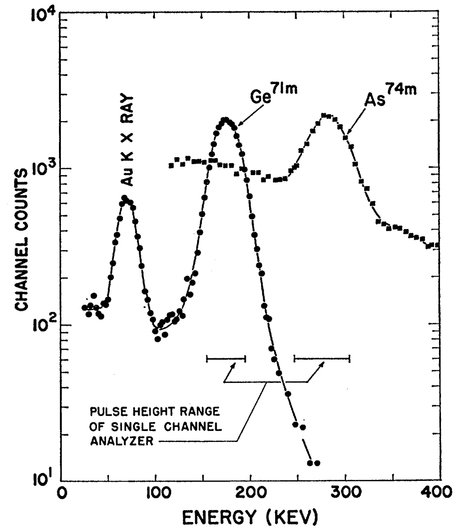

FIG. 2. Gamma spectra of Ge^{71m} and As^{74m} taken with the source at the center of a $2\frac{1}{2}$-in. diam well-type NaI(Tl) crystal. The As^{74m} gamma-ray rides on a spectrum from annihilation quanta.

ployed. In addition to the known isomers, 0.5-sec Ge^{73m}, 6-μsec As^{73m}, 16.8-msec As^{75m}, and 116-msec As^{77m}, two new isomers were observed. One of these activities had a half-life of 20.3±0.3 msec (Fig. 1), decayed by a 175-kev gamma ray (Fig. 2), and was produced in a Ge^{70} target by 4-Mev deuteron irradiation but not by proton irradiation. The assignment of this activity to Ge^{71} was confirmed by proton irradiation (1.315–2.17 Mev) of natural Ga; the reaction involved was $Ga^{71}(p,n)Ge^{71m}$. No (p,n) threshold could be found; however, the lowest proton energy at which the yield above background was significant places the isomeric level below 270-kev excitation in Ge^{71}.

Consideration of the known levels in Ge^{71} at 198 and 175 kev suggests that the 23-kev transition between these levels is responsible for the observed half-life of the 175-kev gamma ray. An $M2$ transition of this energy would be expected to have roughly a 20-msec half-life (a 25-kev $M2$ transition in As^{75} has a partial half-life of 20.8 msec). Since the isomeric transition itself was not actually observed, it is conceivable, though not probable, that the 9/2+ level is just below 198 kev and that the 198-kev level populated in the As^{71} decay has a spin and parity of 7/2+.

Se^{75}

The low levels for 43 neutrons are $p_{1/2}$, $g_{9/2}$, and 5/2+ in Ge^{75}, and the levels should also occur in Se^{75}. Since the ground state of Se^{75} is 5/2+ (reference 2), the existence of an $M2$ isomer was expected. Levels in Se^{75} were populated by the $As^{75}(p,n)$ reaction with both 2.6- and 3-Mev protons, but no delayed gamma rays were found in the half-life range of 10 μsec to 1 sec. Since the spin change required in the (p,n) reaction is only 1, the expected 1/2− level should have been formed. The negative result implies probably that a 5/2− or 3/2− level occurs below the $p_{1/2}$ level. An alternate explanation is that the $p_{1/2}$ level occurs in Se^{75} at such a low excitation energy that the isomeric transition was not detected.

Odd-Odd Nuclei

As^{74}

A 283±5-kev gamma activity with a half-life of 8.0±0.3 sec was produced by proton irradiation of Ge^{73} (3.2–4 Mev) and of Ge^{74} for proton energies above 4.2 Mev. The only isotope that can be produced on both targets is As^{74}. The threshold of the $Ge^{74}(p,n)As^{74}$ reaction to a 283-kev level is 3.66 Mev.[12] That the isomer could not be observed above background near the (p,n) threshold is not surprising, since a spin change of 5 is involved in the reaction. The pulse-height spectrum obtained with a Ge^{73} target is shown in Fig. 2. The 283-kev gamma ray is superimposed on a large background, and any low-energy transition accompanying the 283-kev gamma ray would have been missed. The background was due to a longer-lived positron activity, which was produced on all Ge targets and was probably due to an impurity in the targets. The half-life agreed with that of Ga^{68} which would have been produced by a $Zn^{68}(p,n)$ reaction. Traces of zinc could have been present in the target, because the backing was silver-soldered to the stainless steel target tube.

[12] F. Everling, L. A. Koenig, J. H. E. Mattauch, and A. H. Wapstra, Nuclear Phys. 18, 529 (1960).

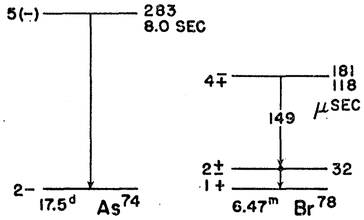

FIG. 3. Proposed level schemes for As^{74} and Br^{78}. The level excitation energies are given in kev.

The isomeric half-life classified the 283-kev transition in As^{74} as $\Delta I=3$. After a correction for internal conversion,[13] the ratio of the experimental to the single-particle gamma transition probability[14] is 9×10^{-3} for an $M3$ and 8×10^{-4} for an $E3$ assignment. A tentative assignment of $M3$ has been made on the basis of the available shell model levels and because a known $M3$ transition in Br^{80} has almost the same transition probability ratio, 17×10^{-3}. The ground state of As^{74} is 2− (Fig. 3) and, unless a low-energy transition was missed, the isomer has a spin of 5. The single-particle levels occurring below 100 kev are 3/2− and 5/2− (As^{73}) for the odd protons and 9/2+, 5/2+, 1/2− (Ge^{73}) for the odd neutron. Regardless of the proton-neutron coupling scheme, a 5+ level cannot be formed from these configurations. According to the coupling rules of Brennan and Bernstein,[7] a large number of low levels can be predicted from these configurations. The 5− level can be accounted for by the coupling between a hole in the $p_{3/2}$ proton shell and a $g_{9/2}$ neutron (coupling rule 3, reference 7).

*As*⁷⁶

No short-lived isomer was found in this nucleus (10 μsec to 10 min). Irradiation of a Ge^{76} target[11] with 3.2-Mev protons yielded no short-lived activity. Since the proton energy was significantly above 1.78 Mev, the (p,n) threshold,[12] any low isomeric level should have been populated. In view of the many proton-neutron configurations available for states in As^{76}, it is not surprising that the condition for isomerism does not exist.

*Br*⁷⁸

Duffield and Vegors[15] reported a (127±5)-μsec activity with a (149±6)-kev gamma ray which was produced by a (γ,n) reaction on a natural Br target. They assigned this activity to an isomer in either Br^{78} or Br^{80}. This isomer was produced in the present work by proton bombardment of Se^{77} at 2.6 Mev and of Se^{78} above the (p,n) threshold; thus the isomeric state is in Br^{78}. It was further shown that the isomer decays by two gamma rays (Fig. 5) 149±2 and 32±2 kev; that they are in cascade was demonstrated by a coincidence experiment. The 32-kev gamma-ray intensity is about 50% of the 149-kev intensity. Since the highest multiplicity one can assign to the 149-kev transition is $M2$, it follows that the conversion coefficient of the 32-kev transition is about 1.5; this value is consistent[13] only with an $E1$ ($\alpha=2.2$) or $M1$ ($\alpha=2.9$) assignment to the 32-kev transition, because the next value for α ($E2$) would be 50. The isomeric half-life was remeasured and found to be 118.0±1.5 μsec (Fig. 1). Since the 32-kev gamma ray is $\Delta I=1$, it is prompt, and the half-life has to be due to the 149-kev transition. Indeed, an $M2$ assignment gives a ratio of experimental to theoretical[14] gamma transition probability of 0.0028, in good agreement with the general trend of $M2$ transitions.

When this work was started, it was believed[2] that Br^{78} had a 6.4-min isomer at 157 kev and that the half-life of the ground state was shorter than 6 min. In order to measure the half-life of the ground state, an activation was made by the $Se^{78}(p,n)Br^{78}$ reaction below the threshold for the (p,n) reaction of the supposed isomer. The ground-state threshold was first measured with a Se^{78} target[11,16] by detecting the positron activity (Fig. 4). Below the 4.43-Mev threshold[17] the induced activity was primarily 18-min Br^{80}; above this energy the observed half-life was primarily due to a 6.5-min activity. A good determination of the half-life, made from data taken 70 kev above threshold,[18] gave a value of 6.47±0.1 min. A proton energy of 5 Mev was used in an attempt to activate the supposed 157-kev isomer, but no indication of its existence was found.

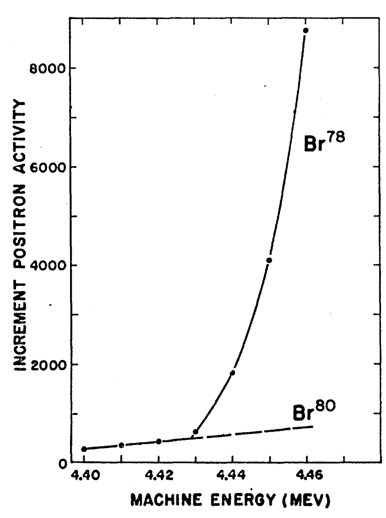

FIG. 4. Excitation function for the production of Br^{78} positron activity near the $Se^{78}(p,n)$ threshold.

[13] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958).

[14] S. A. Moszkowski, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. 13, p. 373.

[15] R. B. Duffield and S. H. Vegors, Jr., Phys. Rev. **112**, 1958 (1958).

[16] The isotopic composition of the target was as follows: 0.66% Se^{74}, 0.88% Se^{76}, 1.26% Se^{77}, 90.24% Se^{78}, 6.75% Se^{80}, and 0.82% Se^{82}.

[17] Although these threshold measurements are generally accurate to ±0.01 Mev, this value does not agree with the value 4.35±0.01 Mev recently reported by R. Rikmenspoel and D. M. Van Patter, Bull. Am. Phys. Soc. **5**, 338 (1960).

[18] The energy above threshold at which this measurement was made is not affected by a possible error (reference 17) in the absolute value of the threshold energy.

Independent of this work, Pierson and Coryell[19] showed that a 6.4-min, 157-kev isomer does not exist and measured the ground-state half-life to be 6.25 ± 0.2 min.

On the basis of the above results a new level scheme can be proposed for Br^{78} (Fig. 3). The isomeric level is at 181 kev, has a half-life of 118 μsec and a spin of 4. The first excited state is at 32 kev with a spin of 2. On the basis of its half-life the isomeric transition is $M2$; therefore, the first and second excited states have opposite parity. If the isomeric level has negative parity, it may be due to a $g_{9/2}$-$p_{1/2}$ proton-neutron configuration (rule 1, reference 11). The first excited 2+ level would in that case be due to a hole in the $f_{5/2}$ proton shell coupled to the $p_{1/2}$ neutron configuration (rule 3, reference 11). Levels with the opposite set of parities can also be accounted for, but a 4+ level would require a violation of rule 2, reference 11.

Br^{82}

No isomer was found in the half-life range from 10 μsec to 5 min. As with As^{76}, the proton energy was well above the $Se^{72}(p,n)$ threshold. Since the ground state of Br^{82} is 5−, the selection rules of the (p,n) reaction would have favored the production of a lower spin isomer. These results together with those of Sattizahn *et al.*[8] demonstrate that, contrary to expectation,[7] there is no isomeric level in Br^{82}.

Tc Isomers

Irradiation of natural Mo foil with 2.4- to 3.2-Mev protons produced two new isomeric activities: a (177 ± 4)-kev gamma activity with an 8.15 ± 0.20 μsec half-life and a (43 ± 3)-kev gamma activity with a 15.5 ± 0.8 μsec half-life (Figs. 1 and 5). Although the 177-kev gamma activity was produced over the whole proton energy range, the activation of the 32-kev gamma activity had a threshold at 2.6 Mev. In addition to these activities, 16-sec Tc^{100} was also seen, but the 190-kev 910-μsec isomer in Tc^{101} (reference 2) was not observed. Presumably the $Mo^{100}(p,\gamma)$ cross section is very small because of competition with the $Mo^{100}(p,n)$ reaction, which has a threshold at 1.2 Mev.

The new isomers were assigned to Tc because a previous search for Mo isomers in this half-life range had been unsuccessful,[15,20] and because gamma rays of these energies are not seen in the Coulomb excitation spectrum[21] of Mo. Furthermore, the short half-life of these

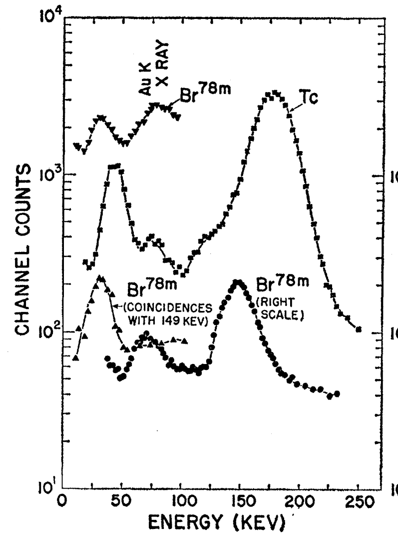

FIG. 5. Gamma spectra of the Br^{78} and Tc isomers. The 15- to 100-kev region of the Br^{78m} spectra, plotted with the symbols ▲ and ▼, was observed with an 0.2-cm thick NaI(Tl) crystal.

isomeric states indicates a spin difference of at most 2, and such levels at 177 or 43 kev above the ground state in Mo should have been observed previously. No threshold was found for the activation of the 177-kev isomer; therefore, it could be due to any one of the following Tc isotopes: mass numbers 93 or 95 to 100, inclusive. The 43-kev isomer occurs probably in either Tc^{95} or Tc^{98}. The 2.6-Mev production threshold of this activity is close to the Mo^{95} or $Mo^{98}(p,n)$ thresholds for a 43-kev level in the final nucleus (2.5 ± 0.2 and 2.6 ± 0.8 Mev).[12] Either of these Tc isotopes could also have been produced by the Mo^{94} or $Mo^{97}(p,\gamma)$ reaction, but it is possible that the (p,γ) cross section was too small to observe the activity below the $Mo^{95,98}(p,n)$ threshold. It is hardly worthwhile to speculate about the nature of these isomers until definite isotopic assignments have been made and until it has been established whether the observed gamma transitions are accompanied by unobserved low-energy transitions.

ACKNOWLEDGMENTS

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[19] W. R. Pierson and C. D. Coryell, Phys. Rev. **119**, 755 (1960).
[20] S. H. Vegors, Jr., and P. Axel, Phys. Rev. **101**, 1067 (1956).
[21] F. K. McGowan and P. H. Stelson, Phys. Rev. **109**, 901 (1958); P. H. Stelson and F. K. McGowan, *ibid.* **110**, 489 (1958).