[3]J. Valentin, J. L. Sarrouy, and I. Chavat, Compt. Rend. 255, 887 (1962).
[4]B. Harmatz and T. H. Handley, Nucl. Phys. 81, 481 (1966).
[5]J. Gizon, A. Jourdan, M. Peyrard, and J. Valentin, J. Phys. (Paris) 28, 249 (1967).
[6]J. Treherne, J. Vanhorenbeeck, and J. Valentin, Nucl. Phys. A131, 193 (1969).
[7]R. Arlt, Z. Malek, G. Musiol, G. Pfrepper, and H. Strusny, Joint Institute of Nuclear Research Report No. D-3893, 1968 (unpublished), p. 41.
[8]J. B. Cumming, National Academy of Sciences, National Research Council, Nuclear Science Series No. NAS, NS-3107, 1962 (unpublished).
[9]The enriched ytterbium 170 sample was obtained from Oak Ridge National Laboratory with the following isotopic composition: ^{170}Yb 67.2%, ^{171}Yb 17.4%, ^{172}Yb 7.7%, ^{173}Yb 2.84%, ^{174}Yb 3.89%, and ^{176}Yb 1.02%.
[10]Using the mass table from: G. T. Garvey, W. J. Gerace, R. L. Raffe, I. Talmi, and I. Kelson, Rev. Mod. Phys. 41, S1 (1969).
[11]S. Bjornholm, J. Borggreen, H. J. Frahm, and N. J. Sigurd Hansen, Nucl. Phys. 73, 593 (1965).
[12]B. R. Mottelson and S. G. Nilsson, Kgl. Norske Videnskab. Selskabs, Skrifter 1, No. 8 (1959).
[13]R. S. Hager and E. C. Seltzer, Nucl. Data A4, No. 1 and 2 (1968); and O. Dragoun, H. C. Pauli, and F. Schmutzler, Nucl. Data A6, No. 3 (1968).
[14]P. F. Zweifel, Phys. Rev. 107, 329 (1957); A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, The Netherlands, 1959).
[15]P. A. Seeger, Nucl. Phys. 25, 1 (1965).
[16]R. Arlt, Z. Malek, G. Musiol, G. Pfreffer, and H. Strusny, Izv. Acad. Nauk SSSR Ser. Fiz. 33, 1218 (1969).
[17]The computer program was originally written by R. Gunnink, H. B. Levy, and J. B. Niday, Lawrence Radiation Laboratory Report No. UCID-15140, 1967 (unpublished); and modified by B. R. Erdal.

PHYSICAL REVIEW C VOLUME 2, NUMBER 1 JULY 1970

Evidence for the Missing 2− State in Ag^{110}†

W. R. Kane and G. Scharff-Goldhaber
Brookhaven National Laboratory, Upton, New York 11973
(Received 9 March 1970)

In spite of ingenious investigations of the isomeric decay of 253-day Ag^{110m} by several groups of authors, the missing low-energy first excited (2−) state in Ag^{110} has so far escaped detection. High-precision studies of the γ rays from the $Ag^{109}(n,\gamma)Ag^{110}$ reaction, as well as coincidence studies, now provide conclusive evidence for this level at an energy of 1.28 ± 0.10 keV.

The 253-day isomer of Ag^{110}, although it has been the subject of many investigations, still poses an unresolved problem. Namely, while the spins and parities of the isomeric state and the ground state of Ag^{110} are known to be 6+ and 1+, respectively, the only transition observed in the decay of Ag^{110m} is an $M4$ transition. It is thus necessary to postulate the existence of a "hidden" $E1$ transition from an intermediate 2− level, for which no conclusive evidence has yet been obtained.

The existing experimental evidence is as follows: A spin 6 for the 253-day isomer has been determined in an atomic-beam experiment.[1] Even parity for this level is inferred from its allowed β decay to an even-parity level in Cd^{110}.[2] The 1+ spin and parity of the ground state of Ag^{110} are inferred from its allowed β decay to 0+ and 2+ levels in Cd^{110}.[2] These assignments are in accordance with the shell-model configurations $[(g_{9/2}^{-3})_{7/2,p}(d_{5/2}^{-1})_n]_{1,6}$ expected for this nucleus. The nuclear magnetic moments for both states, computed on the j-j coupling model, also support this assumption.[3] The $M4$ multipole order of the 116.41-keV isomeric transition has been determined unambiguously by Geiger[4] in measurements of its K/L and $L_I/L_{II}/L_{III}$ internal-conversion coefficient ratios. Searches for the dipole transition have been carried out by several groups. Katoh and Yoshizawa[2] were able to deduce an upper limit of 25 keV from the absence of conversion-electron lines in the singles spectrum. Pasternak and Nardi[5] searched in vain for γ rays coincident with Ag K x rays from the internal conversion of the isomeric transition and thus reduced the upper limit to 5 keV, unless $\tau_{1/2} > 2$ μsec. Thus a low-energy $E1$ transition with a typical hindrance factor might have escaped detection. Hamilton, Jansen, Goudsmit, and Sattler[6] searched for low-energy conversion lines from Ag^{110m} with an iron-free double-focusing spectrometer. They did not find any conversion lines of a transition with $E \geq 4$ keV. Recently, positive evidence for a low-energy transition in the decay of Ag^{110m} has been reported by Rivier and Gizon[7]: Since a 3.18 ± 0.15-keV level had been deduced from neutron capture γ-ray studies by Elze *et al.*,[8] Rivier and Gizon searched for conversion electrons, also with an iron-free double-focusing spectrometer, and reported that they had observed an internal-conversion-electron peak corresponding to the *M*-shell conversion of a 3.7-keV transition in Ag^{110}. However, the peak is superimposed on a β background ~3 times higher, and the statistical uncertainties are large; thus this evidence seems unconvincing. Finally, unpublished results[9] on preaccelerated conversion electrons in coincidence with the *K*-conversion line of the 116-keV transition, studied with a double-lens Gerholm spectrometer, led to a lower limit of $\tau = 10^{-7}$ sec for a transition with $E \geq 0.9$ keV.

Thus the $2- \to 1+$ transition appears to elude detection. An alternative method of determining the 2− level in Ag^{110} may be based on the study of the γ-ray spectrum from the $Ag^{109}(n,\gamma)Ag^{110}$ reaction. The capturing state in Ag^{110} is known to be either 0− or 1−.[10] The Ag^{110} level scheme arrived at from previous studies of the $Ag^{109}(n,\gamma)Ag^{110}$ reaction[8,11-13] is quite complex, as is typical for odd-odd product nuclei in the medium-mass region.[10] In such a nucleus a substantial number of cascades would be expected to populate a 2− first excited state. One attempt to identify a low-lying state with the 2− level was mentioned above.[8] A more

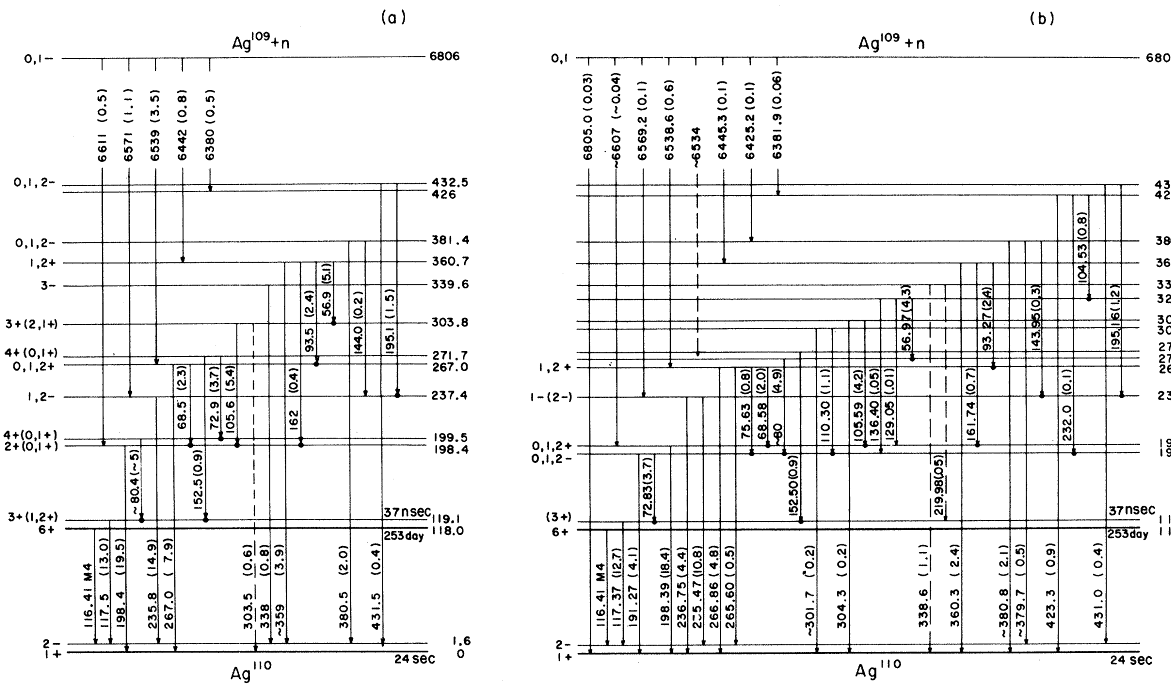

FIG. 1. Partial level schemes of Ag^{110} showing evidence for the 2 − first excited state of Ag^{110} obtained in studies of the $Ag^{109}(n,\gamma)Ag^{110}$ reaction. (a) Evidence presented in Ref. 12. (b) Evidence obtained in the present work. Relative intensities of transitions in thermal-neutron capture are shown in parentheses. Because of the large number of available levels, the primary transitions shown represent only a small fraction of the total transition intensity. A large black dot indicates a coincidence relationship. For clarity the splittings of close level multiplets are not to scale. The energies for levels populated by primary transitions now agree with energies obtained from low-energy singles and coincidence measurements on the average within 0.5 keV. Discrepancies nowhere exceed 1 keV. The situation with respect to the first excited state is now as follows: (1) The positions of the 118.65- and 236.75-keV levels are now fixed by the new transition energies and coincidence relationships, so that the 117.37- and 235.47-keV transitions must terminate at the first excited state. (2) There is no evidence for the placement of the 338.6-keV transition as terminating at the first excited state. If this transition is assigned as a ground-state transition, an observed 219.98-keV transition may be placed between the 338.6- and the 118.65-keV level. (3) The placement of an ~359-keV transition terminating at the first excited state is in error; a 360.3-keV transition actually proceeds to the ground state. (4) The 380.5-keV transition , assigned earlier as terminating at the first excited state, is actually a doublet, with a splitting agreeing approximately with the 1.28-keV energy of the first excited state. (5) The 431.0-keV transition fits in energy between the 432.0-keV level and the first excited state. No coincidence results were obtained in support of this assignment. Further support for the placement of the first excited state at 1.28 keV in Ag^{110} is obtained from three additional transitions, with energies 484.1, 613.7, and 748.2 keV [not shown in Fig. 1(b)], which fit in energy between the 1.28-keV state and well-established levels at 485.2, 614.7, and 749.4 keV, respectively. Other modifications of the level scheme are self-evident.

recent attempt, based on extensive additional measurements, is that of Freund,[12] who found a number of inconsistencies in the "energy-sum" balance given in the previous work. Freund placed a level at 1.6 ± 1.0 keV and assigned it 1− or 2− spin and parity. The part of his level scheme which is relevant for the placement of the 1.6-keV state is shown in Fig. 1(a). It includes all six levels from which he thought this 1.6-keV state to be populated. The author assumed that this is the state at which the 116.41-keV *M*4 transition terminates. While Freund's arguments suggested the existence of the 1.6 ± 1.0-keV 2− level, they had to be investigated further on the following grounds:

(1) Three transitions, with energies of 359, 380.5, and 431.5 keV are placed only on the basis of the energy combination principle. In view of the number of transitions observed, and the uncertainties in level and transition energies, it is possible that these transitions actually arise elsewhere in the level scheme.

(2) The 338-keV transition is placed solely on the basis of the existence of a level at ~341 keV established in studies of the $Ag^{109}(d,p)Ag^{110}$ reaction.[14] Since the error in the level energy is several keV, this assignment is also questionable.

(3) While intensity considerations and coincidence results require that the strong 117.5- and 235.8-keV transitions populate either the ground state or first excited state, the evidence in Fig. 1(a) is not sufficient, in either case, to distinguish between these two possibilities. However, Freund reasoned that since a 234-keV level is populated by the $Ag^{109}(d,p)Ag^{110}$ reaction,[14] which is expected to populate only odd-parity levels, and the 235.8-keV transition is thought to have *M*1 multipole order,[8] the 235.8-keV transition must populate a low-lying odd-parity level, almost certainly the "hidden" first excited state. However, this argument, while plausible, is too indirect to give definite proof for the existence of the 2− level.

In order to verify the existence and determine the energy of the 2− level we have carried out new measurements on the $Ag^{109}(n,\gamma)Ag^{110}$ reaction. This work was performed in two principal stages. First, precision measurements of both high- and low-energy γ rays,[15] and coincidence measurements employing two Ge(Li) detectors were carried out. The γ-ray energy measurements were performed both with a thermal-neutron beam and

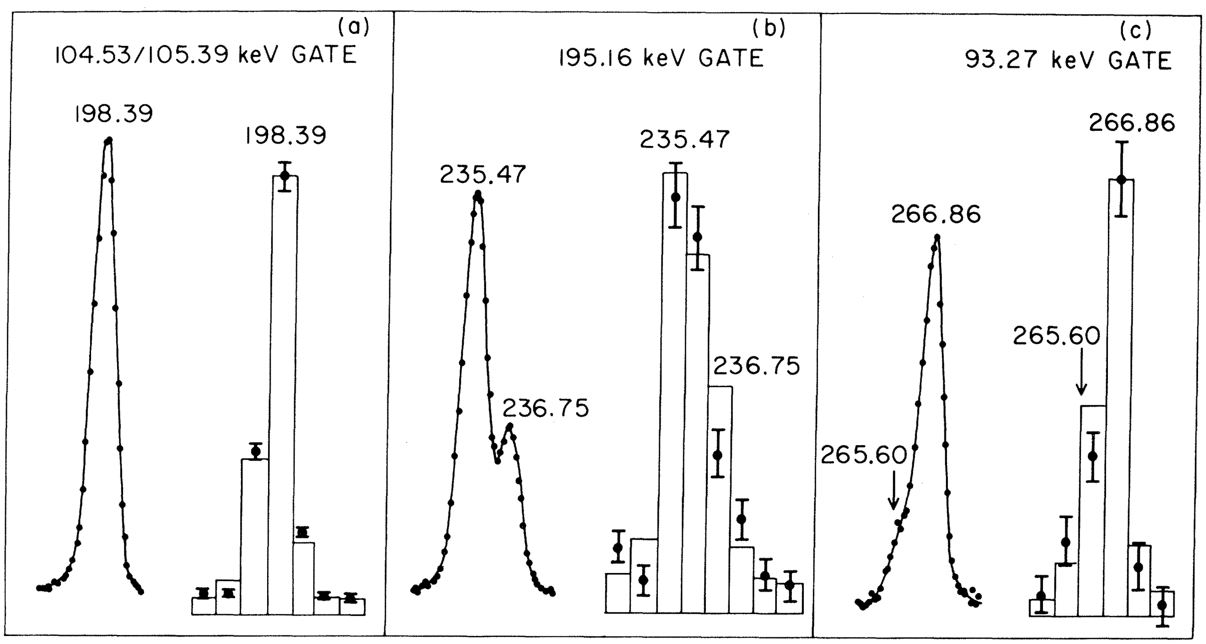

FIG. 2. Singles and coincidence results showing the structure of the 235.47–236.75 and 265.50–266.86-keV transition doublets [(b) and (c)]. For comparison, corresponding results for the 198.39-keV transition (a single peak) (a) are shown. Since one channel in the coincidence results corresponds to eight channels in the singles spectra, histograms have been constructed by summing over eight-channel segments of the singles peaks to indicate the coincidence results expected from the structure of the singles peaks. The transition used as a coincidence gate is indicated. The individual sections are not drawn to a common scale. In part (b) the structure of the 235.47–236.75-keV doublet is seen to appear clearly in the coincidence results. In part (c) because of the limited statistical accuracy of the coincidence results and the low intensity of the 265.60-keV satellite peak, the results are consistent with the presence of either one or two peaks in coincidence with the 93.27-keV transition.

on the 5.19-eV resonance of Ag^{109}, with the use of a crystal diffraction neutron monochromator,[16] since some transitions which were weak in the thermal spectrum had higher intensities in the resonance spectrum and their energies could thus be determined more accurately. By this means a reliable and detailed level scheme was established in which transitions to the first excited state could be identified with confidence [see Fig. 1(b)]. Then, in order to demonstrate conclusively the existence of the first excited state, a resolved 235.47–236.75-keV γ-ray doublet observed in a high-resolution spectrum and believed to correspond to transitions from the 236.75-keV initial state to the first excited state and ground state was shown to be indeed in coincidence with a 195.16-keV transition known to populate the 236.75-keV initial state [Fig. 2(b)]. This doublet (not previously thought to originate from the same state) already existed in the conversion-electron data.[8] An additional doublet at 265.60–266.86 keV [Fig. 2(c)] was found, and coincidences with the 93.27-keV transition measured. In this case, since the 265.60-keV transition is weak, it was only possible to show that the coincidence results are consistent with the assumption that also the weaker line coincides with the 93.27-keV γ ray. In Fig. 2, these two doublets are shown, both in the singles spectra and in the coincidence results, along with the 198.39-keV line, a single peak, for comparison. Histograms of the singles spectra are superimposed upon the coincidence results to indicate the expected peak shapes. Further, a third previously unresolved doublet of ~379.7– ~380.8 keV was found. No strong low-energy transitions populate its initial state.

The most accurate value for the energy of the first excited state, obtained from the splitting of the 235.47–236.75-keV doublet, is 1.28 ± 0.10 keV, in fairly satisfactory agreement with the internal-conversion results of Elze *et al.*,[8] which give a separation of 1.14 keV between these two transitions.

The arguments for the odd parity of the 1.28-keV level are based on the multipole order assignments for the 235.47-, 236.47-, and 266.86-keV transitions (Table I, last column) deduced from the conversion coefficients. (No internal-conversion peak for the 265.60-keV member of the second doublet was observed.) Since the odd proton in Ag^{109} is in a $p_{1/2}$ orbital and there are no low-lying odd-parity neutron orbitals, the population of the 236.75-keV level in the (d,p) reaction requires that it have odd parity; the $M1$ multipole order assignment to the 235.47-keV transition from this level to the 1.28-keV level therefore leads to an odd-parity assignment for the latter. *Hence it appears beyond doubt that the* 1.28-keV *state is indeed the missing* 2− *state.* (The 266.86-keV level is not populated by the (d,p) reaction (Ref. 14) and may therefore be expected to have even parity, in agreement with the $M1$ assignment to the ground-state transition.)

The energy of the 253-day isomeric state is then 117.69 keV. Since β-spectrum end-point measurements previously indicated an energy of ~135 keV for the isomeric state, the cumulative error of these measurements must be ~20 keV, somewhat greater than the estimated errors.[2]

It is of interest to estimate the probable half-life of the 1.28-keV level. The Weisskopf estimate for the half-life of a 1.28-keV $E1$ transition in Ag^{110}, using the estimated total-internal-conversion coefficient 770,[17–19] is $\sim 2\times 10^{-10}$ sec. Assuming a hindrance factor[20] ranging from 10^3 to 10^7, a probable half-life in the range 10^{-7} to 10^{-3} sec follows.

Figure 3 compares the information on the energy levels of Ag^{110} resulting from this work with the present knowledge of the low-lying states in other odd-odd Ag isotopes.[21–25] In particular, the position of the 2− and 6+ states relative to the 1+ state as a function of neutron number is of interest.

The detailed Ag^{110} level scheme results will be reported elsewhere by one of us (W. R. K.).

TABLE I. Parity of 1.28-keV level.

			Internal-conversion coefficients					
					α_K(Theory)			
E_γ	I_γ	I_e	α_K(exp)	$E1$	$M1$	$E2$	$M2$	Assignment
117.37	11.6	1.02	(0.088 ± 0.010)[a]	(0.088)	0.233	0.640	⋯	($E1$)
235.47	10.5	0.293	0.028 ± 0.004	0.0124	0.035	0.059	⋯	$M1$
236.75	4.3	0.091	0.020 ± 0.004	0.0123	0.035	0.058	0.173	$E1$ (+$M2$?)
266.86	4.7	0.130	0.028 ± 0.005	0.0088	0.026	0.039	⋯	$M1$

[a]No absolute measurements of the internal-conversion coefficients have been made. The γ-ray intensities are ours, while the conversion-electron line intensities are those of Elze *et al.* (Ref. 8). The 117.37-keV transition, which to make the multipole order assignments consistent must be $E1$, was chosen for normalization.

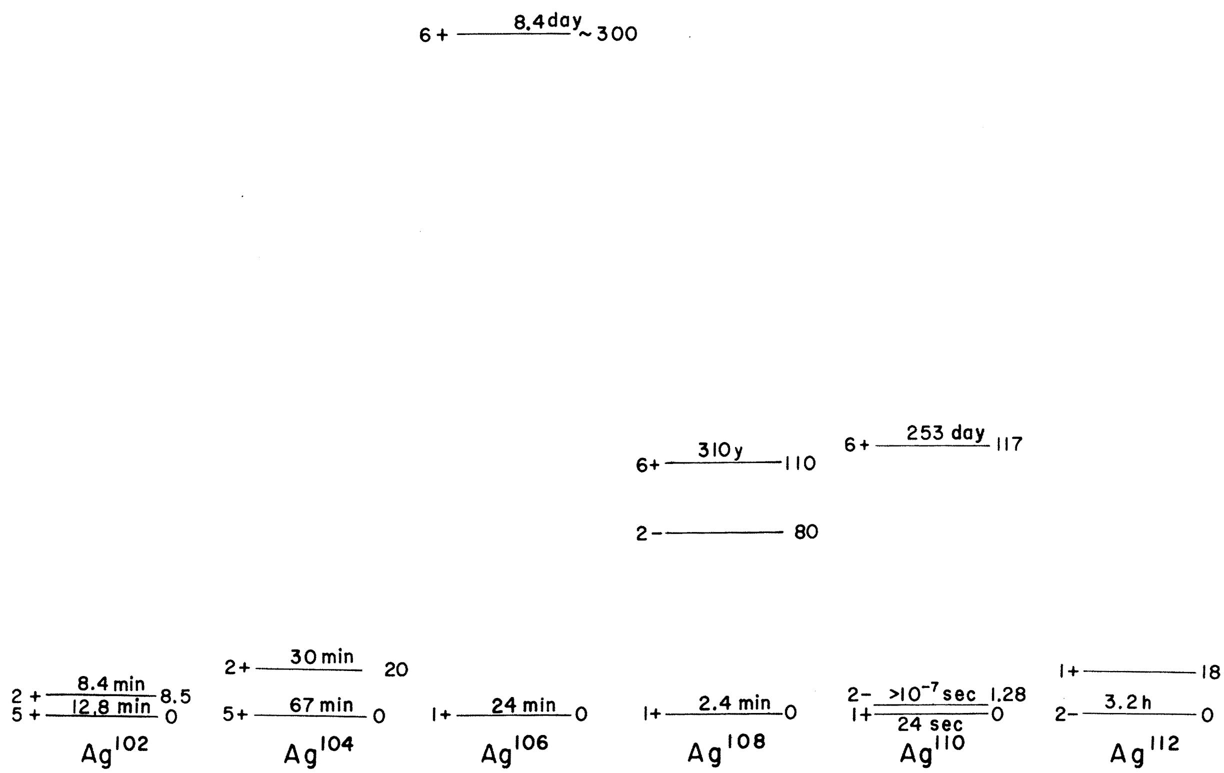

FIG. 3. Present knowledge on low-lying states in odd-odd Ag isotopes. Level energies are indicated in keV. No 6+ state has as yet been observed in Ag^{112}. The configuration of the 1+ and 6+ states is probably $p(1g_{9/2})^{-3}{}_{7/2}n(2d_{5/2})^{-1}$, and that for the 2− states $p(2p_{1/2})^{-1}n(2d_{5/2})^{-1}$.

The high-performance Ge(Li) detectors employed in this work were made at Brookhaven under the direction of H. Kraner. We would like to acknowledge this essential contribution to our experiment and to express our thanks for valuable aid and advice in their utilization.

---

†Work performed under the auspices of U. S. Atomic Energy Commission.

[1]W. B. Ewbank, W. A. Nierenberg, H. A. Shugart, and H. B. Silsbee, Phys. Rev. 110, 595 (1958).

[2]T. Katoh and Y. Yoshizawa, Nucl. Phys. 32, 5 (1962).

[3]H. Ackermann, D. Dubbers, J. Mertens, A. Winnacker, and P. von Blankenhagen, Z. Physik 228, 329 (1969).

[4]J. S. Geiger, Nucl. Phys. 61, 264 (1965).

[5]M. Pasternak and E. Nardi, Nucl. Phys. 55, 669 (1964).

[6]J. H. Hamilton, J. F. W. Jansen, P. F. A. Goudsmit, and A. R. Sattler, Nucl. Phys. 61, 257 (1965).

[7]J. Rivier and A. Gizon, J. Phys. 30, 615 (1969).

[8]T. W. Elze, T. v. Egidy, H. U. Freund, B. C. Dutta, and W. Kaiser, Z. Physik 209, 497 (1968).

[9]K. Takahashi, M. McKeown, and G. Scharff-Goldhaber (unpublished). The low-energy conversion electrons were preaccelerated by applying a 5-kV electric field between the source holder and the case of the magnetic lens. The calibration method is described in an article on Re^{188m} by K. Takahashi, M. McKeown, and G. Scharff-Goldhaber, Phys. Rev. 136, B18 (1964).

[10]L. V. Groshev, A. M. Demidov, V. I. Pelekhov, L. L. Sokolovskii, G. A. Bartholomew, A. Doveika, K. M. Eastwood, and S. Monaro, Nucl. Data A5, 26 (1968).

[11]H. H. Bolotin and A. I. Namenson, Phys. Rev. 157, 1131 (1967).

[12]H. U. Freund, Ph.D. thesis, Technische Hochschule, Munich, 1968 (unpublished).

[13]I. V. Estulin, I. N. Rozantsev, P. T. Prokofiev, and V. A. Bondarenko, Yadern. Fiz. 5, 1149 (1967) [transl.: Soviet J. Nucl. Phys. 5, 819 (1967)].

[14]A. Sperduto, M. Mazari, and W. W. Buechner, Bull. Am. Phys. Soc. 4, 287 (1959).

[15]As a calibration line the 7724.2 ± 0.5-keV Al line was used (R. C. Greenwood, private communication to K. T. Faler, R. R. Spencer, and R. A. Harlan) Nucl. Phys. A123, 616 (1969).

[16]W. R. Kane, D. Gardner, T. Brown, A. Kevey, E. der Mateosian, G. T. Emery, W. Gelletly, M. A. J. M[illegible]scotti, and I. Schröder, Bull. Am. Phys. Soc. 14, 514

[17]The total-internal-conversion coefficient was arrived at in the following way: The *M*-subshell coefficients were obtained by extrapolation of the calculated values of Hager and Seltzer (Ref. 18). *N*- and *O*-subshell coefficients were estimated by taking the products of the individual *M*-subshell coefficients with the ratios of the probability densities of the respective *N*- and *O*-shell electrons to those of the *M*-shell electrons (Ref. 19). The total *M*-shell conversion coefficient is 680, *N*-shell – 88, and *O*-shell – < 1. We are indeed indebted to G. T. Emery for suggesting this method of estimating the *N*- and *O*-shell conversion coefficients.

[18]R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).
[19]F. Herman and S. Skillman, *Atomic Structure Calculations* (Prentice Hall, Inc., Englewood Cliffs, N.J., 1963).
[20]C. Perdrisat, Rev. Mod. Phys. 38, 41 (1966).
[21]Ag^{102}: D. J. Hnatowich, E. Hagebø, A. Kjelberg, N. Mohr, and P. Patzelt, to be published.
[22]Ag^{104}: A. Nutley and J. B. Gerhart, Phys. Rev. 120, 1815 (1960).
[23]Ag^{104}, Ag^{106}, Ag^{108}, Ag^{112}: C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.
[24]Ag^{106}: C. H. Johnson and A. Galonsky, Bull. Am. Phys. Soc. 5, 443 (1960).
[25]Ag^{108}: M. Vonach, M. Hille, and P. Hille, Z. Physik 227, 381 (1969).

PHYSICAL REVIEW C VOLUME 2, NUMBER 1 JULY 1970

Comments and Addenda

The Comments and Addenda section is for short communications which are not of such urgency as to justify publication in **Physical Review Letters** *and are not appropriate for regular Articles. It includes only the following types of communications: (1) comments on papers previously published in* **The Physical Review** *or* **Physical Review Letters**; *(2) addenda to papers previously published in* **The Physical Review** *or* **Physical Review Letters**, *in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section may be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts will follow the same publication schedule as articles in this journal, and gallevs will be sent to authors.*

Fast-Neutron Spectroscopy of the Reaction $^9Be(p, n)^9B$ at 20 MeV†

J. D. Anderson, C. Wong, B. A. Pohl, and J. W. McClure
Lawrence Radiation Laboratory, University of California, Livermore, California 94550
(Received 6 October 1969)

Recently a high-resolution proton recoil spectrometer was used to measure the neutron spectrum from 20-MeV proton bombardment of ^9Be. Evidence for levels in ^9B at 1.4- and 3.2-MeV excitation was presented. Using time-of-flight techniques, we have remeasured the neutron spectrum and find no evidence for these levels.

A proton-recoil-neutron spectrometer has recently been developed by Slobodrian *et al.*[1] with an energy resolution of about 1%. This detector has been used to measure the neutron spectrum from the $^9Be(p,n)^9B$ reaction for 20-MeV protons at three angles (9, 12, and 17°). In addition to the ground state and 2.33-MeV level, they report evidence for broad levels at 1.4 and 1.7 MeV, a definite resolved level at 3.16 ± 0.07 MeV, and their spectra shows evidence for at least one more well-defined level at 5.25 MeV. They also interpret our previous measurements[2] as supporting their identification of a level at 3.16 MeV.

Using standard time-of-flight techniques,[3] we have measured the neutron spectrum from the $^9Be\ (p,n)^9B$ reaction at 20 MeV at a lab angle of 15°. Although it was possible to obtain 1% energy resolution at the maximum available flight path (25 m), at that distance γ rays from the target and a collimator (from the next beam pulse) overlapped the neutron energy region of primary interest. With a flight path of 21.4 m and a beam width of 2.4 nsec (full width at half maximum), our spectrometer resolution was 1.3% (240 keV) for 18-MeV neutrons. The target thickness (10 mg/cm^2) and cyclotron beam energy spread were each about 200 keV in width. This yielded a total width (at 18 MeV) of 400 keV. A measured time spectrum is shown in Fig. 1(a).

After background subtraction, correcting for the energy dependence of the detector efficiency, and transforming to the center-of-mass system we obtain the relative energy spectrum shown in Fig. 1(b). To verify the accuracy of our energy scale