order of the multiple-quantum transitions differs by one unit, the values of the hyperfine interactions and the magnetic moments will be in error by about 10%, but the sign of the moment would not be affected.[5]

It is difficult to justify rigorously the assumption that the multiple-quantum order is the same for the two species. One might expect that, since the spins and hyperfine interactions of all three isotopes are of comparable size, the refocussing conditions and transition probabilities might be similar. Although the theory of the multiple-quantum transitions has been investigated, the multiple resonances observed in the present experiment are not well enough separated to make the theory in its present state readily applicable.[4]

D. DISCUSSION

According to the shell model of the nucleus, the most probable proton-neutron configuration of both of the odd-odd indium isotopes studied is $g_{\frac{9}{2}}$, $s_{\frac{1}{2}}$.[6] In order to estimate the magnetic moment of this configuration, one assumes that the values of the intrinsic magnetic moments of the nucleons in the free state are largely suppressed when the nucleons are bound in the nucleus.[7] It is further taken without proof that the amount of suppression is the same as in nuclei in the same states in neighboring odd-even and even-odd nuclei. The calculation is then carried out in the standard manner.[8]

For the estimation of the magnetic moments of In^{114m} and In^{116m} the intrinsic moment for the $g_{9/2}$ proton hole was calculated from the measured moment of In^{115} The intrinsic moment of the odd neutron ($s_{\frac{1}{2}}$ state) was taken from Sn^{117}. The moment calculated in this manner is $\mu=4.5$ nm for both radioactive nuclides, in good agreement with our experimental values (Tables I and II).

[5] In a concurrent independent determination, P. B. Nutter [Phil. Mag. 1, 587 (1956)] also found $I^{116m}=5\hbar$ and $\mu^{116m}=+4.21 \pm 0.08$ nm.

[6] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, Inc., New York, 1955), pp. 147–148.

[7] F. Bloch, Phys. Rev. **83**, 839 (1951). See also H. Miyazawa, Progr. Theoret. Phys. Japan **6**, 263 (1951) and A. de-Shalit, Helv. Phys. Acta **24**, 296 (1951).

[8] E. H. Bellamy and K. F. Smith, Phil. Mag. **44**, 33 (1953).

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Formation of Cd^{115} Isomers in High-Energy Fission of Bismuth*

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The relative yields and recoil properties of the Cd^{115} isomers independently formed in the 450-Mev proton fission of bismuth have been measured. The 43-day Cd^{115m} isomer has a higher yield and smaller range than the 53-hr Cd^{115}. Cd^{115m} is also formed in a higher deposition energy process than Cd^{115}. These results are explained in terms of the high-spin states of the fission fragments resulting both from the high bombarding energy and from the fission act proper.

I. INTRODUCTION

THE formation of isomeric pairs has been studied in a variety of nuclear reactions over a wide range of bombarding energies.[1–9] The relative yield of the two isomers has been found to depend on the spin of the excited product nucleus prior to the gamma-ray cascade by which the latter de-excites to the observed isomers.[1] The isomer formed predominantly is the one with spin closest to that of the excited product nucleus. The spin of the latter depends in turn on a number of factors such as the spin of the target nucleus, and the spin and orbital angular momentum of the bombarding particle and of any ejected particles. For reactions induced by thermal neutrons, the spin of the target nucleus is the controlling factor in determining the spin of the excited product nucleus.[2] As the bombarding energy is increased, the compound nucleus can be formed in higher angular momentum states and the ensuing evaporation of nucleons can finally lead to a wide range of spin states of the excited product nucleus.[8] This situation is reflected in the large variation in relative yield of isomers that has been observed for different reactions and bombarding energies.[3–8] As the bombarding energy is raised beyond the range of

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† The author acknowledges the aid of a National Science Foundation predoctoral fellowship.
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[8] Meadows, Diamond, and Sharp, Phys. Rev. **102**, 190 (1956).
[9] G. Rudstam, "Spallation of medium weight elements," Uppsala, 1956, Appelbergs, Boktrycheri Ab.

applicability of the compound nucleus model the situation is further complicated by the resulting spread in deposition energy. Rudstam[9] has shown that there is a wide range in angular momentum values for each deposition energy, with the average angular momentum of the residual nucleus increasing with the deposition energy.

The formation of isomeric pairs in fission is in general also governed by the previously mentioned factors. The situation is somewhat more complicated, however, due to the possibility that states of high angular momentum may be favored in the fission act proper,[10] and may in turn lead to excited fission fragments with high spins. The relative yield of isomers formed in fission has been determined in a number of cases. In low-energy fission, the relative yields generally reflect the β^--branching ratio of the parent formed independently with higher yield,[11] and hence give little indication of the independent formation of isomers. The independent yields of isomeric pairs have been studied in a number of cases in high-energy fission.[12–14] In all cases the high-spin state is favored.

It is thus apparent that angular momentum is an important parameter in the formation of isomeric pairs in fission, and may also account for differences between low- and high-energy fission in general.[13] In order to obtain more information on the role of angular momentum states in fission we have examined some of the properties of one isomeric pair formed in high-energy fission. In this study we report the results of recoil studies on the Cd^{115} isomers formed in the 450-Mev proton induced fission of bismuth. The ranges, angular distributions, kinetic energies, and average deposition energies for the direct formation of the two isomers, as well as their relative yield, were determined. A correction was made for the contribution to the Cd^{115} activities from the decay of 21-min Ag^{115} and from the decay of the short-lived Ag^{115m} isomer previously postulated by Wahl and Bonner.[15] The choice of bismuth as the target element was dictated by the desire to obtain substantial independent yields of the Cd^{115} isomers as well as adequate counting rates.

II. EXPERIMENTAL

The experimental procedure followed was similar to that previously reported by Porile and Sugarman.[16] The target assembly consisted of a bismuth foil surrounded on either side by aluminum recoil catcher foils, all foils being of thickness greater than the range of the fragments. Extra aluminum foils were included for determination of the activity level from impurity activation in the aluminum. The foils were the same as those described earlier.[16] The irradiations were performed in the internal circulating beam of the University of Chicago synchrocyclotron at a radius of 76 inches corresponding to a nominal proton energy of 450 Mev. The targets were irradiated for either four hours or twenty minutes, depending on whether the properties of the Cd^{115} isomers formed cumulatively or of Ag^{115} were under investigation. The target assembly was positioned in either of two ways relative to the beam depending on whether recoils projected in the beam direction or perpendicular to it were collected. A total of thirteen irradiations was performed in the course of this study. In some experiments two separate target assemblies were irradiated simultaneously.

After the bombardment, the target and catcher foils were separated and dissolved in the appropriate acids for chemical analysis. The chemical procedure followed for the isolation of cadmium was based on previous work.[17] It consisted of several cycles of palladium and antimony sulfide scavengings from $2N$ HCl, precipitation of CdS from $0.3N$ HCl, precipitation of $Cd(OH)_2$ with $6N$ NaOH in the presence of Zn holdback carrier, and $Fe(OH)_3$, $In(OH)_3$, and $BaCO_3$ scavengings with conc. NH_4OH and Na_2CO_3. The final precipitate was $CdNH_4PO_4 \cdot H_2O$. Analysis of duplicate samples of the same solution in general gave agreement to within 0.5%. In the experiments designed to distinguish between the contribution of independently formed Cd^{115} and that formed from decay of Ag^{115}, the foils were dissolved in the presence of both Ag and Cd carrier. In the case of the aluminum foils, the solution was made $8N$ in HCl in order to keep the silver in solution. AgCl was precipitated from the various solutions as simultaneously as possible and the precipitates were weighed to determine the chemical yield. The separation of silver from cadmium for four samples was usually completed about 15 minutes after the end of the irradiation. The silver samples were allowed to decay for two and one-half hours and were then dissolved in conc. NH_4OH, cadmium carrier was added, and the cadmium samples were separated as before. The measured activity was corrected for the decay of Ag^{115} during bombardment and separation.

The activity measurements were made on the same end-window methane flow proportional counters used in an earlier work.[16] All samples from a given run were counted on the several counters used in rotating fashion in order to minimize the effect of small variations in the counting efficiency of the counters. An empirically determined self-absorption correction was applied to the various samples isolated in each experiment. When determining the relative yield of the two isomers, the contribution of In^{115m} to the observed counting rate was

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determined from the observed growth. The counting efficiencies of Cd^{115} and Cd^{115m} were taken from the compilation by Russell[18] for the same counters and geometry. In the determination of the recoil properties of the isomers, the various samples were counted through 30 mg/cm^2 aluminum absorber in order to minimize the contribution of the weak radiations of In^{115m}.

The identification of the radioactive species present in the isolated samples was made by analysis of the decay curves and comparison of the half-lives of the analyzed components with reported values.[19] All samples consisted of 53-hr Cd^{115} and 43-day Cd^{115m}. At the initial time of counting, 1.5 days after the bombardment, no Cd^{117m} was detectable. The counting rates varied from about 100 000 cpm for cumulatively formed Cd^{115} isolated from the target foil to about 200 cpm for cumulatively formed Cd^{115m} isolated from the recoil catcher foils. The activation correction for impurities in the aluminum foils was about 0.2%.

III. RESULTS

A. Relative Yields

The relative yields of the Cd^{115} isomers formed both independently and from ancestor decay, as well as the relative occurrence of these two modes of formation are given in Table I. These results represent an average of three determinations with an agreement to within 2%. Errors in the estimation of counting efficiencies may amount to 10%. The relative yields of the isomers for both cumulative formation and for formation from decay of 21-min Ag^{115} were determined directly from the decay curves and application of the usual correction factors. The ratio of 10.2 obtained for the yields of the isomers from the decay of 21-min Ag^{115} is in agreement with the result of Wahl and Bonner.[15] The yield of 21-min Ag^{115} relative to the yield of $Cd^{115,115m}$ plus the yield of Ag^{115m} was determined from experiments in which both cadmium and silver were isolated.

The results for independently formed $Cd^{115,115m}$ obtained in this fashion include the contribution from the short-lived Ag^{115m} isomer, which decays by β^- emission to Cd^{115} prior to the separation of silver from cadmium. The existence of Ag^{115m} was postulated by Wahl and Bonner[15] to explain the anomalously high independent yield of Cd^{115} in slow neutron fission of uranium. The relative yield of Ag^{115m} in high-energy fission may be estimated as follows. The relative yield of Cd^{115} with respect to Cd^{115m} in the 450-Mev proton fission of tantalum and rhenium is 0.36.[14] This represents an independent yield ratio since for these low Z targets such neutron excessive species as Ag^{115} are no longer formed in appreciable yield. If we assume that the ratio of 0.36 also holds for the independent formation of the Cd^{115} isomers in the fission of bismuth, it is then possible to estimate the contribution of Ag^{115m} by using the fact that this isomer does not appear to decay to Cd^{115m}.[15] The resulting value of 0.03 for the fractional contribution of Ag^{115m} to the total yield of the Cd^{115} isomers may well be in error by a factor of two, but should be small in any case. It is gratifying in this connection to see that the value of 0.61 obtained in this study for the ratio of cumulative yields of Cd^{115} and Cd^{115m} agrees exactly with the value determined by Kruger and Sugarman.[14] This agreement lends some confidence in our use of their value of 0.36 for the independent yield of the isomers.

TABLE I. Relative yield of Cd^{115} isomers.

Mode of formation	Total yield of isomers, %	Relative yield: 53-hr Cd^{115}/ 43-day Cd^{115m}
Cumulative	100	0.61
Decay of Ag^{115}	14.5	10.2
Independent plus decay of Ag^{115m}	85.5	0.41
Decay of Ag^{115m}	3.0	Very large[a]
Independent	82.5	0.36[b]

[a] Wahl and Bonner, reference 15.
[b] Kruger and Sugarman, reference 14.

It is seen that the direct formation of the Cd^{115} isomers accounts for 82.5% of their total yield. This contrasts with the situation in low-energy fission, where the $Cd^{115,115m}$ yield comes practically entirely from ancestor decay,[15] reflecting the increase in most probable charge which is associated both with increase in bombarding energy and decrease in charge and mass of the target nucleus. The spins of Cd^{115m} and of Cd^{115} are 11/2 and 1/2, respectively,[19] and it is seen that the formation of the high-spin state is favored.

It is possible to make some deductions on the branching ratio of Ag^{115m} to give Cd^{115} or Ag^{115} from the data given. Table I shows that the ratio of yields of Ag^{115m} and Ag^{115}, assuming that Ag^{115m} decays exclusively to Cd^{115}, is 0.21. If we assume that the spins of Ag^{115m} and Ag^{115} are 7/2 and 1/2, respectively, in agreement with the spins of other even-odd isomeric pairs of silver,[19] it would follow that Ag^{115m} should have the higher independent yield in high-energy fission. The principal decay mode of Ag^{115m} would, under these conditions, be isomeric transition and the value of 14.5% quoted for the relative yield of Ag^{115} would, under these conditions, include a substantial fraction of the yield of Ag^{115m}. If the reverse spin assignment is correct, then the direct β^- decay of Ag^{115m} will be the principal decay mode of this isomer.

B. Recoil Properties

The experimentally measured quantities in recoil experiments are the recoil activity of a given nuclide collected in the forward and backward recoil catchers, ReF and ReB, or in the perpendicular recoil catchers, the activity remaining in the target foil, and the thick-

[18] I. J. Russell, Ph.D. thesis, University of Chicago, 1956 (unpublished).
[19] Hollander, Perlman, and Seaborg, Revs. Modern Phys. 25, 469 (1953).

TABLE II. Recoil properties of Cd^{115} isomers and Ag^{115}.

Nuclide and mode of formation	ReF/ReB	η	R_{FB} (mg/cm² Bi)	R_P (mg/cm² Bi)	R (mg/cm² Bi)	b/a $(a+b\cos^2\theta)$
Cd^{115}-cumulative	1.246±0.004	0.0555±0.0010	8.18±0.04	8.09±0.01	···	···
Cd^{115m}-cumulative	1.290±0.005	0.0637±0.0013	7.66±0.05	7.67±0.04	···	···
Ag^{115}-cumulative	1.210±0.020	0.0476±0.0050	7.90±0.15	7.90[a]	7.90±0.15	small
Cd^{115}-independent	1.253±0.007	0.0562±0.0018	8.23±0.06	8.13±0.02	8.16±0.04	0.050±0.030
Cd^{115m}-independent	1.290±0.005	0.0637±0.0013	7.66±0.05	7.67±0.04	7.66±0.03	0±0.035

[a] Single determination.

ness of the target foil. These quantities may be used to obtain the range of the fragments as given by forward-backward experiments, R_{FB}, the range of the fragments as given by perpendicular experiments, R_P, and the true range, R. These three ranges will in general differ from each other because of the anisotropic emission of the fragments in the center-of-mass system. Assuming that the angular distribution of the fragments is of the form "$a+b\cos^2\theta$,"[20] it is possible to obtain the value of b/a from recoil experiments. We also obtain for each fragment the value of η, which is defined as the ratio of the forward component of velocity of the struck target nucleus to the velocity of the fragment in the system of the moving target nucleus. The method by which these quantities are obtained from the experimental data, as well as the assumptions underlying the treatment, is discussed in an earlier paper.[16]

The recoil properties of the Cd^{115} isomers are given in Table II. The results for the cumulative formation of the isomers and for Ag^{115} were determined experimentally. The results for the independent formation of the isomers were obtained from the above results and the respective relative yields. It was assumed for this purpose that Ag^{115m} had the recoil properties observed for Ag^{115}, in view of the small contribution of Ag^{115m} and the possibility that a fraction of the observed Ag^{115} actually was formed as Ag^{115m}. The listed values are the average of four determinations, except when specified otherwise. The quoted errors are the standard deviations from the mean. The errors quoted for Ag^{115} are considerably larger than those for the cumulatively formed isomers. This reflects the additional errors for Ag^{115} due to small departures from simultaneity in the isolation of silver from all samples, as well as from the fact that two chemical yield determinations had to be made for each sample.

The results in Table II show that the fragments are emitted essentially isotropically in the center-of-mass system. The results for Cd^{115} do show a slight preference for emission in a direction parallel to the incoming proton, but, on the basis of the data, there is no substantial difference in the magnitude of b/a for the two isomers, assuming that they are both emitted according to an "$a+b\cos^2\theta$" distribution in the center-of-mass system. These results are not inconsistent with the results of Wolke and Gutmann,[20] who find a value of 0.09 for b/a for $Cd^{115,117}$. A comparison of the ranges of the independently formed Cd^{115} isomers shows that there is a 6% difference between them, with the high-spin isomer having the smaller range. This difference is definitely outside the limits of error.

The kinetic energies of the fragments may be obtained from the measured ranges by use of the range-velocity proportionality constant given earlier.[16] The resulting values are listed in Table III. The average forward component of momentum of the struck nucleus leading to each fragment, $\bar{P}_A$, may be obtained from the velocity of each fragment and the corresponding η, assuming that the mass of the struck nucleus after the initial cascade is 207.[16] The average energy deposited in the struck nucleus as excitation energy, $\bar{E}_A^*$, may be obtained from the listed values of $\bar{P}_A$, by use of a momentum-deposition energy relation given earlier[16] and is listed for each nuclide in Table III. It is seen that Cd^{115m} comes from a slightly higher deposition energy process than Cd^{115}. The deposition energy values, as well as the kinetic energy values, are similar to the corresponding values previously obtained for a number of other nuclides.[16]

IV. DISCUSSION

Two differences in the properties of the independently formed Cd^{115} isomers have been found: (1) the high-spin Cd^{115m} isomer is formed in a slightly higher deposition energy process than Cd^{115}, and (2) the kinetic energy of Cd^{115m} is appreciably lower than that of Cd^{115}. The difference in average deposition energy is perhaps associated with the fact that the average angular momentum left in the residual nucleus after the cascade increases with the average deposition energy.[9] Since this initial angular momentum will tend to be preserved in the ensuing de-excitation process and may eventually appear as the high spin of the de-excited residual nucleus, it seems reasonable that Cd^{115m} should result

TABLE III. Kinetic and deposition energies of Cd^{115} isomers and Ag^{115}.

Nuclide and mode of formation	Kinetic energy (Mev)	$\bar{P}_A$ (931 Mev/c)	$\bar{E}_A^*$ (Mev)
Cd^{115}-independent	55.9±0.5	0.376±0.012	114±4
Cd^{115m}-independent	49.2±0.4	0.401±0.008	123±2
Ag^{115}-cumulative	52.3±1.3	0.309±0.033	94±10

[20] R. L. Wolke and J. R. Gutmann, Phys. Rev. **107**, 850 (1957).

from a higher deposition energy process than Cd^{115}. This tendency towards large deposition energy differences between isomeric pairs with widely different spins is counteracted by the fact that nuclides with the same n/p (neutron/proton) ratio appear to be formed in processes with about the same deposition energy, particularly when these nuclides do not differ by much in mass.[16] The number of neutrons evaporated from a struck target nucleus increases with the deposition energy, leading to fission fragments of decreasing n/p ratio. The direct formation of a fragment of given n/p ratio is thus restricted to a fairly narrow deposition energy interval,[21] thus accounting for the small observed difference in average deposition energy for formation of the Cd^{115} isomers. The results for Ag^{115} are in agreement with this view, as witnessed by the higher n/p ratio, and lower average deposition energy for formation of this nuclide.

The observed difference in kinetic energy of the Cd^{115} isomers is undoubtedly due to a number of factors. The lower average deposition energy for formation of Cd^{115} leads to a somewhat heavier average "fissioning nucleus" for this process. Cd^{115} is therefore on the average formed with a heavier partner than Cd^{115m} and so receives a larger share of the total kinetic energy release. Further, the total kinetic energy released in processes leading to Cd^{115} is likely to be somewhat larger, because the mass ratio for Cd^{115} and its partner is lower than for Cd^{115m} and its corresponding partner. It has previously been shown[16] that the total kinetic energy released in the high-energy fission of bismuth increases with decreasing mass ratio. Since the difference in average "fissioning nuclei" for the two isomers is only about one mass unit, this deposition energy effect is quite small and can at most lead to a difference in observed kinetic energy of one Mev.

The deposition energies of the Cd^{115} isomers were obtained on the assumption that the average residual nucleus after the cascade was the same in each case. This may not be the case if, for the same forward component of momentum of the struck nucleus, there is a difference in the average angular momentum of the residual nucleus for different numbers of cascade nucleons. If, in addition to this, there is a difference in the average deposition energy corresponding to a given forward component of momentum of the struck nucleus for different residual nuclei, then the difference in deposition energy for the Cd^{115} isomers may be larger than indicated. Examination of a number of cascades from the recent Monte Carlo calculations,[22] indicates that the $\bar{E}_A^*$ corresponding to a given $\bar{P}_A$ may actually increase with the number of emitted cascade nucleons. Unfortunately the statistics were too poor to draw any definite conclusions on this point. If this effect is real, then Cd^{115m} may be formed with a higher deposition energy than indicated and, hence, with a low kinetic energy. This effect, however, is probably not substantial enough to account for the observed difference in kinetic energies, since a difference in average deposition energy of some 60 Mev would be required to account for the observed difference.

It is thus possible that the difference in observed kinetic energies may be partially associated with the fission act proper. If, for a given total energy release, the observed kinetic energy is smaller in one case, then the corresponding excitation energy resulting from deformation of the fragments must be larger. If there should be a correlation between high-spin states and large deformation, the low kinetic energy of Cd^{115m} would be explained. There may be a correlation between deformation energy and orbital angular momentum of the fragments since, for a given fissioning nucleus, an increase in deformation energy corresponds to a larger maximum radius of the saddle-point configuration.[23] A rotational motion during the fission act should probably be more effective in forming states of high orbital angular momentum for a larger maximum radius and hence for a larger deformation energy. If a fraction of this orbital angular momentum should be available for the formation of high-spin states then one would have the desired correlation.

The formation of high-spin states in the fission act seems reasonable in view of recent determinations of the relative yield of the independently formed Te^{131} isomers in low-energy fission.[24] It was found in this study that the high-spin isomer is favored, in agreement with the trend previously noted for high-energy fission. The measurement of the ranges of independently formed isomeric pairs in low-energy fission would then be of value since it would yield unambiguous information on the connection between spin and deformation energy, if any. Before taking the previous generalizations very seriously, it would be wise to measure the ranges of some other independently formed isomeric pairs in high-energy fission, particularly in cases where the decay scheme of the parent nuclide is well established.

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