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Identification of Mo^{91} and Mo^{91m}*

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The known 65-second activity in Mo^{91} is shown to have an intense 650±15 kev gamma ray. The 65-second activity is therefore assigned to a 650±15 kev isomeric level which decays by a gamma transition 70±10 percent of the time and by positron emission 30±10 percent of the time. There are at least two higher-energy gamma rays with energies 1.22±0.03 Mev and 1.55±0.03 Mev. Existent (γ,n) and $(n,2n)$ data are used to show that 65-sec., 650-kev Mo^{91m} is a $p_{1/2}$ state and that 15.5-min Mo^{91} is a $g_{9/2}$ state. This assignment implies that the neutron binding energy of Mo^{92} is 12.5 Mev.

INTRODUCTION

THE research reported below presents evidence to show that the ground state of Mo^{91} is associated with the known 15.5-minute activity and that the 65-second activity should be assigned to a previously unreported 650-kev isomeric level.

The 15.5-minute activity was first produced[1] by a (γ,n) reaction on molybdenum (Mo). Soon afterwards, this activity was identified as also resulting from the $(n,2n)$ reaction[2,3] on Mo. The assignment of the 15.5-minute activity to Mo^{91} was first inferred from activation experiments[4] and later proved by both the $(n,2n)$ reaction[5] and the (γ,n) reaction[6] on separated Mo^{92}.

The 65-second activity was first reported as resulting from a (γ,n) reaction[7] on Mo and was subsequently assigned to Mo^{91} because it was produced by a (γ,n) reaction[6] on separated Mo^{92}.

EXPERIMENTAL PROCEDURE

Unseparated molybdenum was bombarded with bremsstrahlung gamma rays from the Illinois 22-Mev betatron. The main data were taken at 21 Mev. Check runs made at various energies between 14 Mev and 22 Mev showed that the activities measured were formed at all of these energies. The radiaoctivities were detected using a NaI scintillation crystal which was one inch square and two inches long. The energies of the emitted gamma rays were measured by using a grey-wedge pulse-height analyzer.[8] Absorbers prevented either positrons or x-rays from entering the crystal. The lifetimes were measured by using a single channel pulse height selector to reduce background.

The long-lived activity contained no gamma rays except for the annihilation radiation produced from its positrons. Its half-life was found to be 15.7±0.3 minutes in good agreement with other recent determinations of 15.5±0.5 minutes[6] and 15.5±0.2 minutes.[9]

The half-life of the second activity was measured to be 66±3 seconds; this value is a little lower than the previously reported 75±5 seconds[6] but it is in good agreement with the more recent value of 65.5±2 seconds.[9] The most intense short-lived radiation was a 650±15 kev gamma ray which was about 2.3 times as intense as the positrons implied by the annihilation gamma rays. Both internal conversion and K-capture events would not have been observed but their intensity is probably negligibly small. Since the 650-kev gamma rays are too intense to follow the positrons, these gamma rays must occur in a separate branch of the decay. This interpretation would indicate that a 650-kev isomeric level exists and that 70±10 percent of the decays occur through the 650-kev gamma ray while 30±10 percent occur through positron branches.

Other gamma rays were observed which had higher energies and considerably weaker intensities. Two gamma rays which had half-lives of about 65 seconds had energies of 1.22±0.03 Mev and 1.55±0.03 Mev. In addition, there was some evidence for several other gamma rays in the energy range between 1.8 Mev and 2.9 Mev. These gamma rays had such low intensity that the observed peaks could not be unambiguously associated with either the photoeffect or the Compton effect and the energies were not determined. (The data are so poor that they do not exclude the possibility that these gamma rays were due to bremsstrahlung.) It seems probable that all of the gamma rays with energy above 650 kev follow the positron emission and therefore, that the positron spectrum is complex. The three most intense gamma rays, 650 kev, 1.22 Mev, and 1.55 Mev had been observed by Duffield[10] but neither their precise energy nor their intensity had been measured.

DISCUSSION

The auxiliary experimental data with which the assignments of the activities in Mo^{91} must be consistent include the (γ,n) threshold and yield experiments by

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Katz, Baker, and Montalbetti[9] and the $(n,2n)$ experiments of Brolley, Fowler, and Schlacks[11] and of Brolley.[12] The assignment of the 65-second activity to the 650-kev isomeric level replaces a previously suggested assignment by Katz, Baker, and Montalbetti in which the 65-second activity was associated with the ground state and the 15.5-minute activity was associated with a postulated 150-kev isomeric level.[9] This earlier assignment, which had been based mainly on a measured difference in the (γ,n) threshold energies of 150±50 kev, led to several inconsistencies that are removed by the new decay scheme.

The interpretation of the (γ,n) threshold experiments which led to the postulate of a 150-kev isomeric level implied that both isomers of Mo^{91} were being formed directly at energies only slightly above threshold. However, it is shown below that direct formation of both isomers would be inconsistent with either the shell model or with neutron emission rates. (This inconsistency motivated the present investigation.)

According to the successful spin-orbit coupling shell model, an isomeric pair in Mo^{91} should have the single particle configurations of $g_{9/2}$ and $p_{1/2}$.[13] Since a spin 1 state is usually excited when zero spin Mo^{92} absorbs a gamma ray, only a neutron which carried away three units of orbital angular momentum (i.e., an $l=3$ neutron) could produce a direct transition to the $g_{9/2}$ level in Mo^{91}. Both theoretical consideration of neutron transmission through a centrifugal barrier,[14] and experimental verification[15] in the analogous case of photoneutron reactions in Zr^{90}, show that $l=3$ neutrons would not be observable within 1 Mev of threshold.

The reported (γ,n) studies of Katz, Baker, and Montalbetti[9] on Mo^{92} can be reinterpreted consistently if the 650-kev isomeric level is taken into account and assigned a $p_{1/2}$ single particle configuration. If, as expected, the $g_{9/2}$, 15.5-minute ground state is not formed directly at energies within 1 Mev of threshold, an attempted measurement of the 15.5-minute threshold would give only the threshold of its 65-second isomeric parent. On this basis, the apparent 150±50 kev threshold difference must be attributed to experimental error. (We have made preliminary measurements of this apparent threshold difference and found it to be −30 ±60 kev rather than 150±50 kev.)

It is also possible to reinterpret the apparent ratio of the cross section for the formation of the 65-second activity to that of the 15.5-minute activity as measured by Katz, Baker, and Montalbetti. If the 15.5-minute isomer is not formed directly at low energy, the measured[9] ratio of 0.3 indicates that the 15.5 minute activity that grows from the isomeric level has 3.3 times as many positrons as does the 65-second activity. According to our interpretation this would imply an isomeric branching of about 77 percent, as compared with our value of 70±10 percent. The fall of the measured[9] ratio to 0.2 at higher energies could be interpreted as evidence for direct formation of the ground state. The implied direct formation would then be 50 percent of the indirect formation of the ground state. (We have done preliminary experiments which also show that the direct formation of the ground state at high energies is about 50 percent of the indirect formation.)

The most recent $(n,2n)$ experiments[12] gave a threshold of 12.48±0.1 Mev for the 15.5-minute activity and only a trace of 65-second activity even at 18 Mev. These results are different from those obtained from (γ,n) reactions but this difference can be explained in terms of the spins of the excited states reached. Whereas gamma-ray absorption results in a spin change of only 1, the predominantly high-angular momentum associated with high-energy incident neutrons should accentuate high-spin states. Thus, the $(n,2n)$ experiment would be expected to lead predominantly to the $g_{9/2}$ state in Mo^{91}. The emphasis of the 15.5-minute activity in the $(n,2n)$ experiments is inconsistent with the previously suggested assignment of $p_{1/2}$ to the 15.5-minute level. Similarly, the 12.48 Mev threshold cannot be explained if the isomeric levels were only 150 kev apart. If, however, both the thresholds given by Katz *et al.*,[9] are regarded as being the same threshold energy for excitation of the 650-kev excited state in Mo^{91}, then the value of 13.15 Mev for the measured threshold also implies that the true, but unobservable, threshold for (γ,n) excitation of the ground state of Mo^{91} is 12.50 Mev. The $(n,2n)$ data thus support the assignment made in this paper of the 15.5-minute activity to the $g_{9/2}$ ground state of Mo^{91}.

The final evidence supporting the proposed assignments to Mo^{91} and Mo^{91m} is shown in Table I which illustrates the similarity between Mo^{91m} and neighboring isomers. The two characteristics of the Mo^{91m} isomeric state that fit into the systematics are the energy and the lifetime. The energy of the Mo^{91m} fits well into the pattern of the energy separation between the $g_{9/2}$ ground state and the $p_{1/2}$ excited state for nuclei which have 49 neutrons; as the even number of protons increases, the $g_{9/2}$ level moves down with respect to the $p_{1/2}$ level. Although the variation in level spacing is not predictable quantitatively, it seems reasonable that the

TABLE I. Characteristics of isomeric state of Mo^{91} and neighboring isomers.

Nucleus	Protons	Neutrons	Ground state	Isomer	Energy (kev)	Exp. half-life / Theor. half-life
Kr^{85}	36	49	9/2	1/2	305	1.04
Sr^{87}	38	49	9/2	1/2	390	1.22
Zr^{89}	40	49	9/2	1/2	588	1.05
Mo^{91}	42	49	9/2	1/2	650	1.02

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last pair of protons in Mo^{91} (which is probably a $g_{9/2}$ pair) would continue the trend of making the $g_{9/2}$ neutron state more stable.

Table I also shows the agreement between the relative lifetimes of isomeric transitions. The experimentally observed lifetimes, corrected for branching ratio and statistical weight, are compared with the theoretical lifetimes given by Blatt and Weisskopf.[16] The significant part of the comparison is that the ratio of experimental to theoretical value is almost the same for all four examples. If the ground state of Mo^{91} were assumed to have a spin of $\frac{1}{2}$, the Mo^{91m} lifetime would disagree essentially by the statistical weight factor of 5. The absolute agreement between experimental and theoretical values is probably fortuitous. The theory is only an approximate one which is, as yet, only useful for determining dependences of the lifetime on the energy and on the nuclear size. For example, an alternative theoretical formula given by Moszkowski[17] predicts a lifetime which is shorter by a constant factor of 10.7.

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Level Scheme of In^{115}†

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The disintegration of the 2.3-day Cd^{115} and its isomer, the 43-day Cd^{115}, have been studied with thallium-activated sodium iodide counters, anthracene counters, and coincidence methods. The levels of In^{115} have been shown to have excitation energies of 0.335 ($T_{\frac{1}{2}}=4.5$ hr), 0.595, 0.825, 0.858, 0.935, 1.30, and 1.42 Mev, the first four levels being excited in the decay of the 2.3-day period alone and the latter three in decay of the 43-day activity only. The gamma transitions from the 1.3-Mev level proceed directly to the ground state of In^{115} while all the transitions from the 1.42-Mev level terminate at the 0.935-Mev level. The gamma transitions from the 0.595, 0.825, and 0.858-Mev levels lead to the metastable state at 0.335 Mev. About three percent of the transitions from the 0.858-Mev level terminate at the 0.825-Mev level which in turn de-excites by way of a 0.230 Mev–0.260 Mev gamma-ray cascade or by emission of a 0.490-Mev quantum in the crossover transition. The angular correlation function for the 0.485 Mev–0.935 Mev cascade in the decay of the 43-day Cd^{115} is found to be essentially isotropic. A level scheme for In^{115} has been established by these measurements.

INTRODUCTION

THE radiations of the 43-day activity have been previously studied by several groups of investigators.[1–4] It has been suggested[4] that In^{115*} de-excite with the emission of a 0.950-Mev gamma ray or by the emission of a 0.45 Mev–0.50 Mev cascade. Other measurements[3] showed that the 43-day activity emits a complex beta spectrum such that de-excitation of In^{115*} occurs with the emission of a 0.94-Mev gamma ray or a 1.30-Mev gamma ray or a 0.48 Mev–0.94 Mev cascade.

The 2.3-day activity has also been investigated[5–7] and shown to emit a complex beta spectrum and gamma rays at 0.335 Mev and 0.52 Mev. Hayward[4] has reported gamma rays of quantum energies 0.335, 0.360, 0.500, and 0.525 Mev, the 0.360- and 0.500-gamma rays being in cascade. He has also suggested that a 0.500-Mev level in In^{115} is excited in the decay of both activities.

Since the above quoted results are not in good agreement, it was decided to investigate further the radiation characteristics of the cadmium activities. NaI(Tl) and anthracene spectrometers were employed in coincidence as was a thin-lens magnetic spectrometer.

To obtain sources of the 2.3-day activity, elemental metallic cadmium was irradiated by slow neutrons for 72 hours in the Brookhaven pile. Chemical separations were performed for removal of Sb, Sn, and other impurities. It was noted that the relative intensities of the several gamma rays present remained unchanged by the purifications. The source of 43-day cadmium was first processed at Oak Ridge National Laboratory and later additionally purified at Bartol for removal of Sb^{124}.

In the course of studying the 2.3-day activity, the

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