KERNFORSCHUNGSZENTRUM

KARLSRUHE

August 1969 KFK 1092

Institut für Angewandte Kernphysik

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KARLSRUHE

Reprint from

"NEUTRON CAPTURE GAMMA-RAY SPECTROSCOPY"

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1969

GAMMA DECAY OF ^{96}Mo AND ^{98}Mo AFTER THERMAL NEUTRON CAPTURE IN ^{95}Mo AND ^{97}Mo

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Abstract

GAMMA DECAY OF ^{96}Mo AND ^{98}Mo AFTER THERMAL NEUTRON CAPTURE IN ^{95}Mo AND ^{97}Mo. The gamma-ray spectra following neutron capture in the odd-mass molybdenum isotopes have been studied with Ge(Li) and NaI(Tl) detectors. The analysis of measured angular distributions yields detailed information on the structure of some levels. The results are compared with theoretical predictions.

1. EXPERIMENTAL PROCEDURE

The measurements were performed at the FR-2 research reactor in Karlsruhe. The targets consisted of MoO_3 powder (enriched to 96.2% in ^{95}Mo, σ_c = 14.5 b) and metallic molybdenum powder (enriched to 92.8% in ^{97}Mo, σ_c = 2.2 b), enclosed in thin-walled polyethylene capsules. For the energy range up to 2.7 MeV a Ge(Li) diode with anti-Compton shield [1] has been used. Coincidences and angular correlations of some gamma-gamma cascades have been measured with two 4-in. diam. × 5-in. NaI(Tl) crystals in a fast-slow coincidence set-up [2] coupled with the on-line computer system MIDAS [3].

2. RESULTS FROM ^{95}Mo(n, γ)^{96}Mo

The decay scheme known from the radioactive beta decay of ^{96g}Tc, ^{96m}Tc and ^{96}Nb [4] could be extended considerably by the present investigation (Fig. 1). Noteworthy is a new level at 1625.93 keV. Because of the good resolution of the anti-Compton spectrometer [1], it could be established that the known 850-keV gamma-ray [6] de-exciting the 4^+ level at 1628 keV is really a triplet with two intense lines at 847.67 and 849.95 keV and a weak one at 853.03 keV (Fig. 2). Comparing the intensities of the gamma rays observed in the Ge(Li) spectrum with those observed in the NaI(Tl) spectrum coincident with the 778-keV transition, one must conclude that both intense gamma rays at 850 keV are in coincidence with the 778-keV transition. The intensity balance does not allow the strong 847.67-keV line to be fitted between higher energy levels. Another fact confirming this new level is the energy difference of 128 keV between the 7656 and 7528-keV primary transitions, which is too small to fit the energy difference between the known 1498 and 1628-keV levels. The 1625.7-keV line is probably a ground-state transition, in which case the spin of the new level is limited to 1 or 2. From the angular correlation measurement of the unresolved 848 to 778 and 850 to 778-keV cascades,

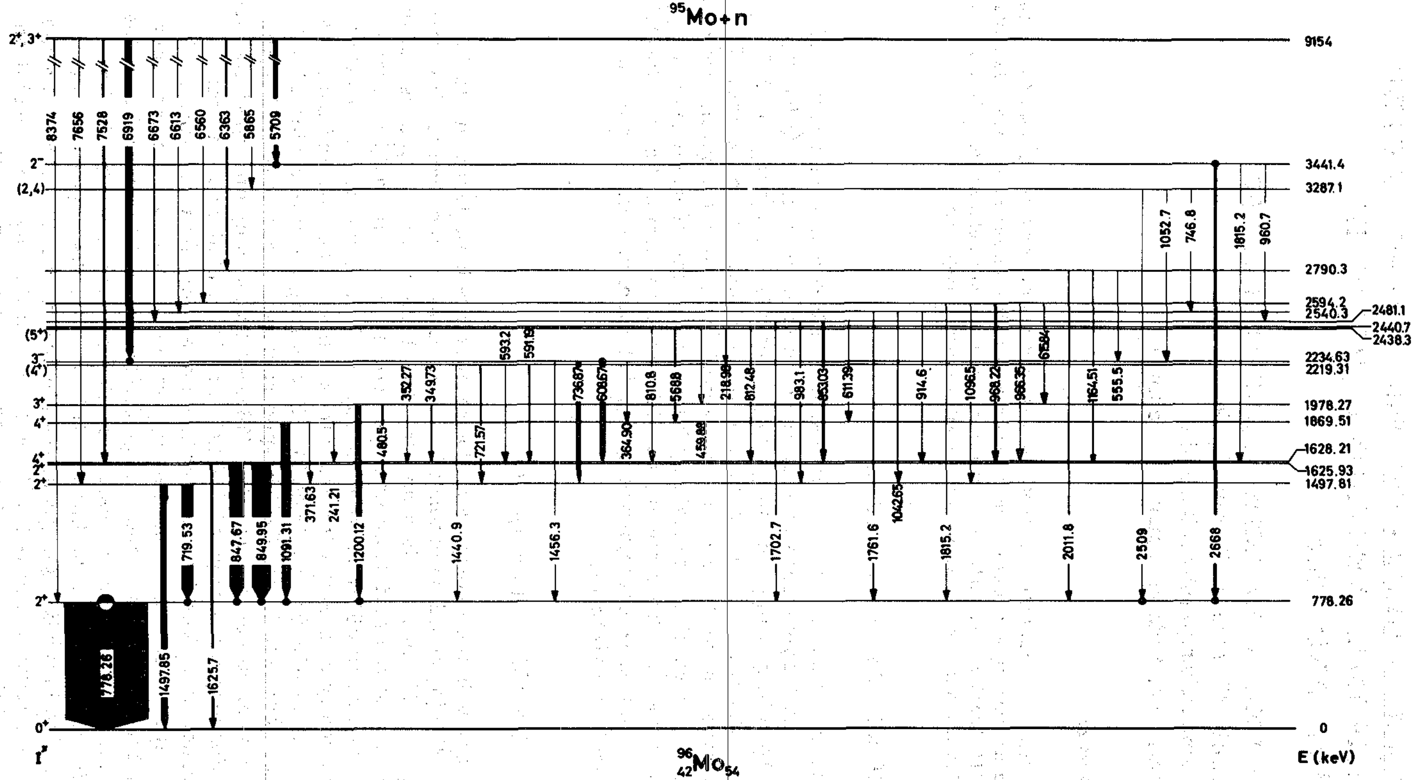

FIG.1. Level scheme of ^{96}Mo observed in the reaction ^{95}Mo(n,γ)^{96}Mo. Levels above 2.6 MeV found only by Ritz's combination principle are not shown.

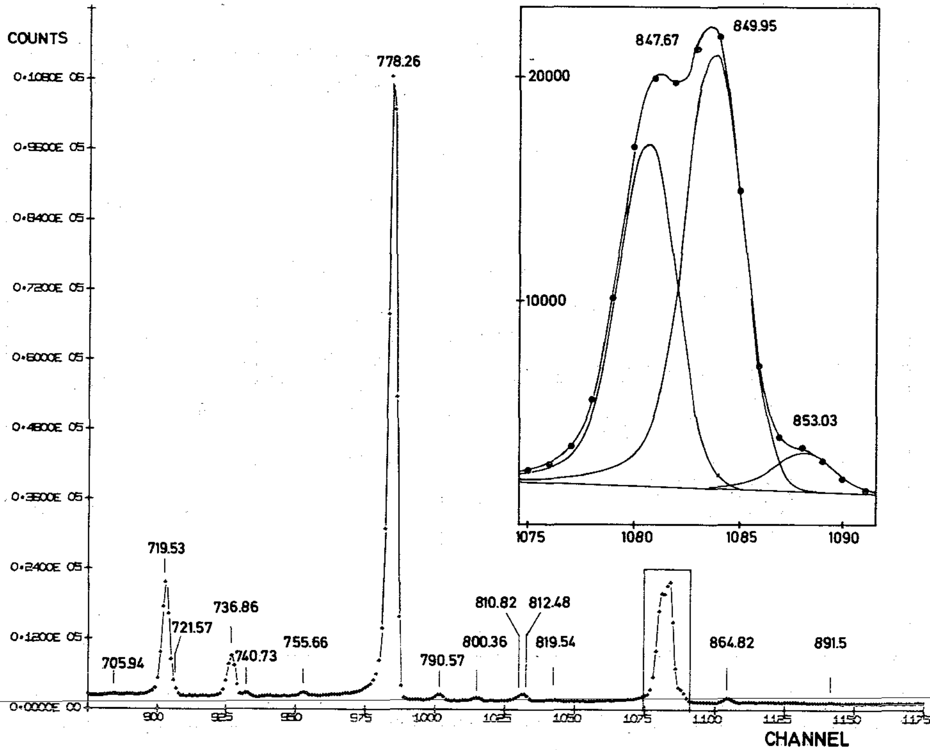

FIG.2. Portion of the ^{96}Mo spectrum, measured with a Ge(Li) detector in the anti-Compton spectrometer [1]. The inset shows the triplet at 850 keV with computer fit analysis (solid line).

the spin 1 for the 1626-keV level is ruled out (Fig. 3). Assuming that the 850-keV transition de-exciting the 4^+ level is a pure quadrupole radiation, the mixing parameter of the 848-keV line is near 1. This value implies a positive parity for the 1626-keV level and should be compared with the quadrupole admixture of only 15% ($\delta \approx 0.45$) found for the 720-keV transition from the 1498-keV level. This shows that the new level has much more collective character than the second 2^+ state. The spin/parity values of 4^+ and 3^+ for the levels at 1869.51 and 1978.27 keV, respectively, found in beta decay [4, 5], could be confirmed by angular correlation measurements of the 1091 to 778 and 1200 to 778-keV gamma cascades. An additional transition of 352.27 keV from the 3^+ level to the 1626-keV level could be assigned. Probably this transition is identical with the 351.9-keV line observed in the decay of ^{96}Nb and ^{96m}Tc, but placed in a different position [4]. The energy of the 2234.63-keV level corresponds with the energy value of the 3^- octupole vibrational state at 2.25 MeV found in (d, d') measurements [7]. The negative parity of this level is confirmed by the assumption of multipolarity E1 for the strong primary 6919-keV transition feeding this level from the positive parity capture state. Between 2.6 and 3.6 MeV a large number of levels can easily be obtained by applying Ritz's combination principle. Only three levels,

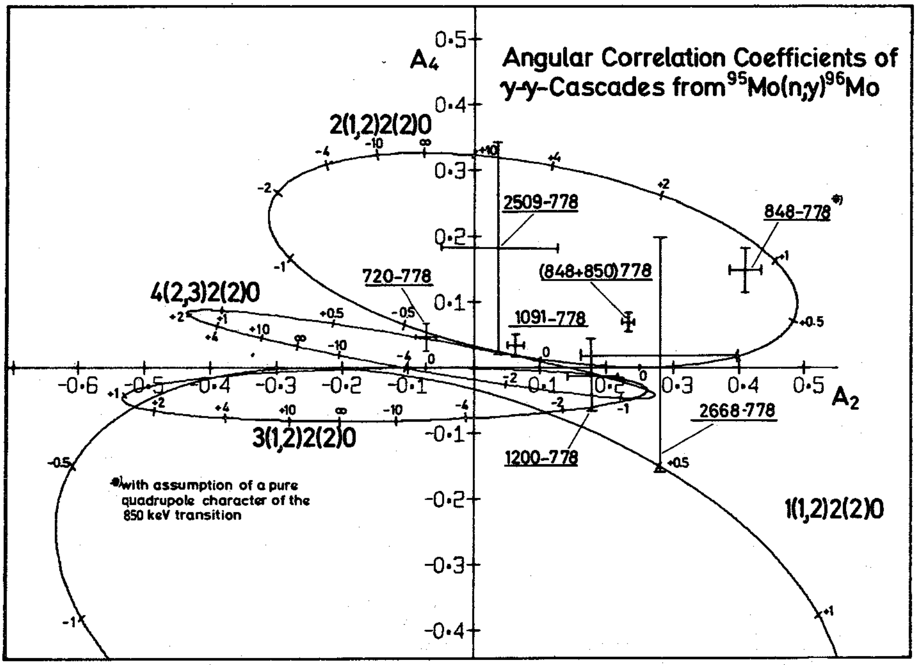

FIG. 3. Angular correlation measurements on ^{96}Mo cascades with the 2-0 transition 778 keV. The crosses show positions of the measured A_2, A_4 coefficients with errors in the A_2, A_4 plane; solid lines are theoretical values as functions of the mixing parameters δ.

namely those at 2790.3, 3287.1 and 3441.4 keV, have been taken over in the level scheme, whose existence was confirmed either by coincidence measurements or by the feeding with intense primary gamma rays. The spin determinations of the levels at 2790.3 and 3287.1 keV are not unique. For the latter, with the 2509 to 778-keV cascade, spin 2 seems very probable, but spin 4 may also be possible, as shown in Fig. 3. The 2668-keV transition is supposed to be a pure E1 transition because of its high intensity. This will give us spin and parity 1^-, 2^- or 3^- for the 3441.4-keV level. Because M2 admixtures to an E1 radiation are usually very weak, one would expect a δ-value near 0 for the 2668-keV radiation. With this assumption one can extract from the angular correlation measurement, despite the great errors, a spin sequence of 2-2-0 for the 2668 to 778-keV cascade. Further coincidence measurements with two Ge(Li) detectors are in progress and should be useful in adding to and confirming this level scheme.

3. RESULTS FROM ^{97}Mo(n, γ) ^{98}Mo

In the ^{98}Mo level scheme (Fig. 4) the first excited level at 734.77 keV has the spin/parity 0^+ [8]. The existence of this remarkable level is assured by the weak primary 7909.6-keV transition (the binding energy of

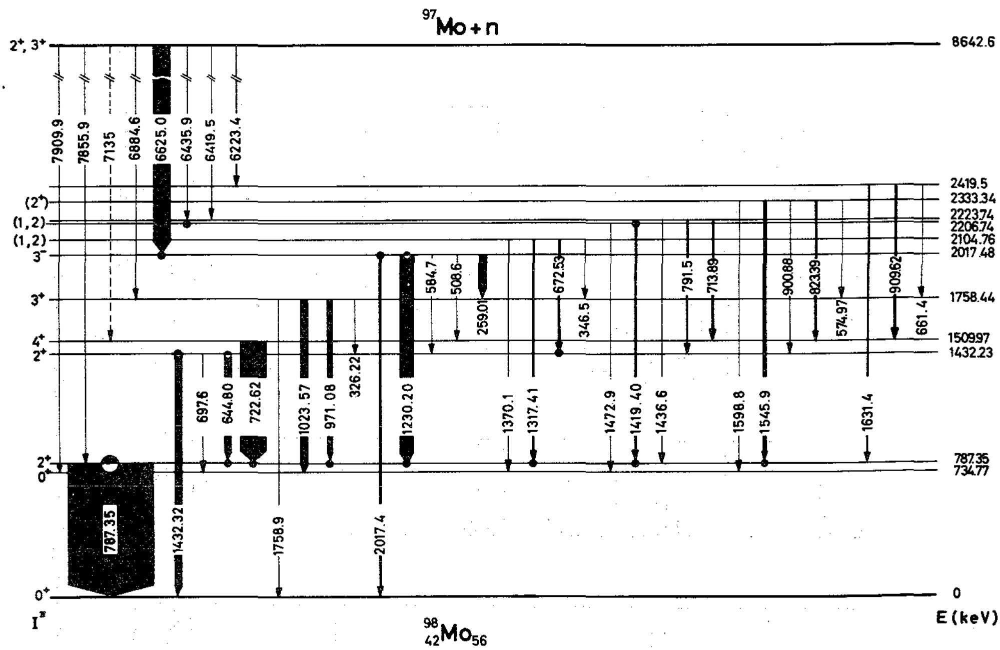

FIG.4. ^{98}Mo level scheme observed in the reaction ^{97}Mo(n,γ)^{98}Mo. Levels above 2.5 MeV found only by Riz's combination principle are not shown.

the last neutron is 8642.5 keV). The following levels (spin and parity in parentheses) 787.35 keV (2^+), 1432.21 keV (2^+) and 1509.97 keV (4^+) are well known [9] and look like the usual one and two-phonon vibrational states, respectively. The beta decay studies of ^{98}Nb (2.8 sec) give two alternative spin and parity assignments (1^+ and 2^+) for the 1758.44-keV level [9]. This discrepancy has been removed by angular correlation measurements on the 971 to 787-keV cascade. From this measurement the 1758.44-keV level is unambiguously assigned a spin of 2. Interesting is the strong E2 admixture of $82 \pm 2\%$ to the 971.08-keV transition. The very strong primary 6624.8-keV transition must be an E1 transition from the positive-parity capture state. With a negative parity for the 2017.48-keV state the analysis of the angular correlation measurement of the 1230 to 787-keV gamma cascade permits only a spin of 3 for this level. Indeed Kim and Cohen [7] have found the collective 3^- octupole state near 2.04 MeV via the (d, d') reaction. Noteworthy is the strong 2017.4-keV ground-state transition, which must be a pure E3 radiation. A similar transition to the 0^+ level at 734.77 keV was not found. The spin assignments of the levels above the 3^- state are only tentative and not confirmed by angular correlation measurements. The presence of transitions to the 734.77-keV 0^+ level limits the possible spin values for the 2104.76 and 2206.74-keV levels to 1 or 2. For the 2333.34-keV level the assignment of 2^+ will be the only one permitted because of the presence of transitions to the 0^+ level at 734.77 keV as well as to the 4^+ level at 1509.97 keV.

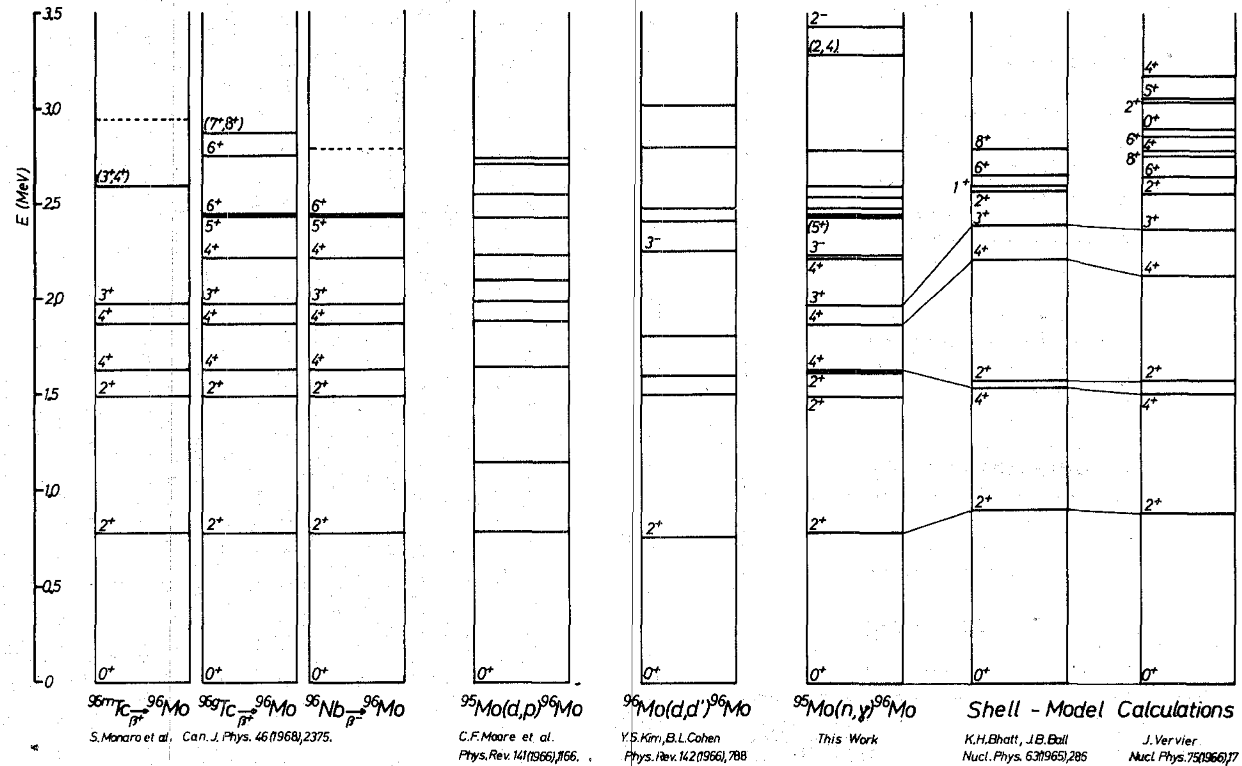

FIG. 5. ^{96}Mo level schemes found by different reactions [4, 7, 12] compared with shell-model calculations from Refs [10, 11].

4. COMPARISON WITH THEORETICAL CALCULATIONS

When looking at the level schemes of ^{96}Mo and ^{98}Mo one finds levels which cannot be explained by vibrational models, such as one of the two 2^+ states around 1.5 MeV in ^{96}Mo and the low-lying 0^+ state at 735 keV in ^{98}Mo. As these two nuclei are not too far off the closed neutron shell N = 50 and the semi-closed proton shell Z = 40, one would expect that the level scheme will be reproduced by the shell-model. Bhatt and Ball [10] and Vervier [11] have performed shell-model calculations, based on the $^{90}_{40}Zr_{50}$ core. For nucleons outside this core they use residual interactions empirically determined from the known level schemes of $^{92}_{42}Mo_{50}$, $^{92}_{41}Nb_{51}$, and $^{92}_{40}Zr_{52}$ for the protons and neutrons in the $\pi 1g_{9/2}$ and $\nu 2d_{5/2}$ orbits, respectively. For ^{96}Mo the results of these calculations are shown in Fig. 5, together with the level schemes observed in different reactions [4, 7, 12]. The agreement is not very good. Again there is only one 2^+ level in the region of 1.5 MeV. The second 4^+ and the 3^+ levels observed between 1.8 and 2.0 MeV are reproduced with too high energies. This disagreement is very likely due to the increasing number of neutrons outside the closed shell. For ^{98}Mo with the closed subshell $\nu 2d_{5/2}$ the theory expects a simple level scheme with a spin sequence 0^+ (ground state), 2^+, 4^+, 6^+, 8^+, according to a pure proton excitation to higher orbits. This is in complete contradiction to the experimental results and shows that the influence of the subshell closure cannot be very significant.

5. FINAL REMARKS

Further investigations of the (n, γ) reaction with the odd-mass molybdenum isotopes are in progress and will give reliable information of higher levels. In addition, attempts should be made to extend shell-model calculations by involving admixtures of further nucleon configurations to improve the reproduction of experimentally found levels.

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