PHYSICAL REVIEW C VOLUME 19, NUMBER 2 FEBRUARY 1979

Identification of ^{148}Ho and ^{149}Ho

K. S. Toth
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

C. R. Bingham
University of Tennessee, Knoxville, Tennessee 37916

D. R. Zolnowski and S. E. Cala
Cyclotron Institute, Texas A & M University, College Station, Texas 77843

H. K. Carter
UNISOR, Oak Ridge, Tennessee 37830

D. C. Sousa
Eastern Kentucky University, Richmond, Kentucky 40475

(Received 19 June 1978)

The new nuclides, ^{148}Ho and ^{149}Ho, were identified in ^{10}B bombardments of ^{144}Sm. A gas-jet system was used to transport product nuclei to a shielded area suitable for γ-ray measurements. The 21-s isotope, ^{149}Ho, was found to decay primarily to a ^{149}Dy level at 1091 keV and less intensely to the $i_{13/2}$1073-keV state observed in a previous in-beam γ-ray study. This radioactivity, in analogy to neighboring odd-A terbium and holmium isotopes, probably represents the $h_{11/2}$ proton orbital in ^{149}Ho which decays *via* an allowed β transition to the 1091-keV level. The latter, is therefore, proposed to be the $h_{9/2}$ neutron state in ^{149}Dy. The 9-s isotope, ^{148}Ho, was identified mainly through a 1688-keV γ-ray which: (1)was in coincidence with dysprosium K x rays, (2)increased dramatically in intensity when the ^{10}B bombarding energy was raised from 85 to 96 MeV, and (3)remained constant (over the same range) in intensity relative to that of the 620-keV γ ray known to belong to ^{148}Dy decay. On the basis of systematics for low-lying levels in even-even $N = 82$ nuclei, the 1688-keV transition is thought to deexcite the first-excited state in ^{148}Dy.

[RADIOACTIVITY ^{148}Ho, ^{149}Ho, measured $T_{1/2}$, E_γ, I_γ, $\gamma\gamma$ coin; ^{148}Dy, ^{149}Dy deduced levels.]

I. INTRODUCTION

The systematic properties of low-lying states in even-Z $N=83$ isotones are of interest because levels in these nuclei should be describable in terms of microscopic calculations with the assumption of an $N=82$ and $Z=50$ core. Indeed, direct reaction, decay scheme, and in-beam γ-ray studies have traced the excitation energies of single-neutron orbitals beyond 82 neutrons from ^{137}Xe to ^{147}Gd (see, e.g., Refs. 1 and 2). Levels in ^{149}Dy, the next nucleus in the series, have been recently investigated[3,4] in beam by means of the ^{152}Gd (α, 7n) reaction. The first-excited level, the $i_{13/2}$ intrinsic state, was located[3] at 1073 keV and found to deexcite to the $f_{7/2}$ ground state *via* an $E3$ transition. The authors subsequently found[4] an isomeric level which was interpreted in terms of a three-particle configuration built on a $^{146}_{64}$Gd$_{82}$ core. Evidence for a sub-shell at $Z=64$ has long been available from α-decay studies; see Ref. 5, for example.

The motivation for the present study was the identification of ^{149}Ho which would enable one to investigate its decay to ^{149}Dy and thus complement the in-beam results. The projectile-target combination ^{10}B+ ^{144}Sm was selected for this search. In examining the various nuclidic yields ^{148}Ho was identified at the highest bombarding energy used.

II. EXPERIMENTAL METHOD

The ^{10}B ions were accelerated in the Texas A & M University isochronous cyclotron to an energy of 101 MeV. The target consisted of a ^{144}Sm (86% enrichment) oxide layer deposited onto a 6.25 μm aluminum foil. A helium gas-jet chamber was used to thermalize product nuclei recoiling out of the target. They were then pumped through a Teflon capillary to a shielded area where γ-ray measurements could be made. After penetrating the entrance window of the gas-jet apparatus and the target backing, the maximum energy on target of the ^{10}B ions was about 96 MeV. Aluminum foils were used as absorbers to vary the bombarding energy.

The recoils were collected from the gas-jet on a Mylar tape which entered and exited a collection chamber through openings equipped with seals. This arrangment allowed the cyclotron beam to be used continuously since a fresh source could be collected while the previous one was being assayed at the counting station. The drive mechanism for the tape system was automated and cycle times could be varied depending on the half life of the nuclide of most interest. Singles and coincidence measurements were made simultaneously with two large-volume Ge(Li) detectors. Coincidence data were accumulated in a three-word, $\gamma-\gamma-\tau$, list mode using a 4096-channel analog-to-digital converter interfaced to an in-house computer. These list data were then transferred from the memory to magnetic tapes for storage and subsequent analysis. Singles spectra from one of the Ge(Li) detectors were accumulated in another data acquisition system in a spectrum multiscale mode for half-life information.

III. RESULTS AND DISCUSSION

A. ^{149}Ho decay

As with neighboring odd-A holmium and terbium isotopes, ^{149}Ho was anticipated to have a high-spin ($h_{11/2}$) and a low-spin ($d_{5/2}$) isomer with the former, based on previous experience,[6] taking up about 90% of the peak production cross section. The maximum of the ^{144}Sm(^{10}B, 5n) excitation function was expected to be in the neighborhood of 80 MeV. Initial measurements at about that energy revealed a new 21-s activity associated with a 1091-keV γ-ray. Its yield as a function of bombarding energy was found to peak when the number of absorber foils had reduced the beam energy to ~85 MeV. Coincidence and singles measurements were then begun at this incident energy.

Figure 1 shows a portion of the singles γ-ray spectrum measured. It represents the first 15 s of counting accumulated following a large number of 1-min. bombardment and assay cycles. In addition to the new 1091.1 ± 0.1-keV γ ray, the 1073.3 ± 0.1-keV transition seen in beam,[3,4] was also observed. Both were found to decay with a 21 ± 2s half-life. This new radioactivity is assigned to ^{149}Ho on the basis of the following evidence. The intensity of the 1091-keV γ-ray varied with bombarding energy in the same manner as those of the 101- and 106-keV γ-rays known[7] to belong to the decay of ^{149}Dy. The 1073- and 1091-keV transitions were in coincidence with dysprosium K x rays. Further Z identification is provided by the fact that neither transition has been observed in in studies[7,8] of dysprosium nuclides produced in ^{12}C + ^{142}Nd and ^{14}N + ^{141}Pr bombardments. Holmium isotopes cannot be made in these projectile-target combinations.

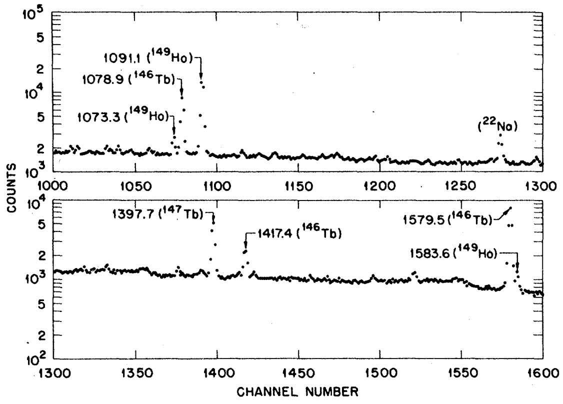

FIG. 1. Portion of a γ-ray spectrum obtained in 85-MeV ^{10}B bombardment of ^{144}Sm. It represents the first 15 s of counting accumulated following numerous 1-min. irradiation and assay cycles. The 1073.3-, 1091.1-, and 1583.6-keV γ rays are assigned to the new isotope, ^{149}Ho.

Only K x rays and annihilation radiation were observed in coincidence with the 1073- and 1091-keV γ rays. The evidence then is that they are ground state transitions and establish ^{149}Dy levels at the same two energies. In the case of the 1073-keV transition this suggestion agrees with the in-beam studies[3,4] which, as noted in the Introduction, propose an $i_{13/2}$ level at 1073 keV. As anticipated, therefore, it would seem that the 21-s activity represents the decay of the $h_{11/2}$ proton state in ^{149}Ho. The decay of the analogous state in ^{147}Tb populates[2] three levels in ^{147}Gd as follows: (1) 1397 keV, $h_{9/2}$ neutron state, 85%; (2) 1798 keV, a fragment of the same orbital, 14%; and (3) 997 keV, $i_{13/2}$ neutron state, 1%. The situation in the present instance is similar. If one uses from systematics[9] 6 MeV for the electron-capture decay energy for ^{149}Ho and assumes that the 1091-keV γ ray encompasses all of the β-decay strength to the 1091-keV level, then a logft value of 4.3 is calculated. This low value clearly indicates an allowed decay, consistent with a beta transition proposed to be $\pi h_{11/2} \rightarrow \nu h_{9/2}$. Thus it appears that the $i_{13/2}$ state located at 997 keV in ^{147}Gd has moved up to 1073 keV while the main $h_{9/2}$ neutron state has dropped sharply from 1397 to 1091 keV. (Figure 2 shows a tracing of single-neutron states in even-Z, $N = 83$ isotones.)

The data were examined to identify the $\frac{9}{2}^-$ level corresponding to 1798-keV state in ^{147}Gd. Only one other previously unassigned γ ray was found to be consistent with a 21-s half life, i.e., 1583.6 ± 0.2 keV (see Fig. 1). The ratio of its intensity to that of the 1091-keV γ ray remained approximately constant as the incident energy was varied. On these bases it is assigned to ^{149}Ho.

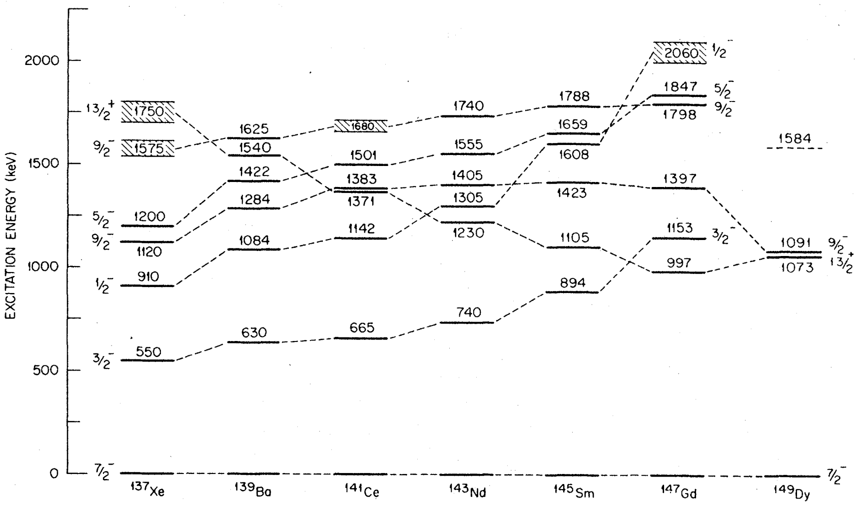

FIG. 2. Excitation energies of single-neutron states for even-Z, $N = 83$ isotones from ^{137}Xe to ^{149}Dy. Cross-hatched areas indicate predicted energies of several so far unreported levels. The dashed level in ^{149}Dy at 1584 keV may correspond to the $\frac{9}{2}^-$ 1798-keV level in ^{147}Gd.

Table I summarizes the energies and relative intensities of the three ^{149}Ho γ rays. As can be noted from table I, $I\gamma_{1091}/I\gamma_{1584}$ is 11, while in ^{147}Tb $I\gamma_{1397}/I\gamma_{1798}$ is 6. The 1584-keV γ ray, therefore could be the deexciting transition from the fragment of the $h_{9/2}$ neutron orbital. If that is the case, the $h_{9/2}$ strength is somewhat more concentrated in one level (1091 keV) in ^{149}Dy than in ^{147}Gd (1397 keV). In Fig. 2 we indicate a tentative level in ^{149}Dy at 1584 keV with no spin assignment.

It should be pointed out that the 1073-keV γ ray on a relative basis is much more intense than the corresponding 997-keV transition in ^{147}Gd. By using the 6-MeV decay energy one calculates a logft value of 5.5 for the beta branch to the 1073 -keV level. This value is somewhat low for a first-forbidden transition. However, the uncertainty on estimated energies is quoted[9] as being 1 MeV. If the decay energy is raised to 7 MeV, the the logft value becomes 5.9; at the same time, the value for the 1091-keV level becomes 4.7, i.e., still well within the range for an allowed transition. Feeding of the $\frac{13}{2}^+$ state from higher-lying levels by weak, unidentified transitions would also increase the logft value. Once again, because the 1091-keV γ ray is so intense, the amount of direct beta decay to the 1091-keV state would not be altered much by weak transitions from levels located at higher excitation energies.

TABLE I. Transition energies and photon intensities for 21-s ^{149}Ho.

E_γ (keV)	I_γ[a]
1073.3 ± 0.1	13 ± 1
1091.1 ± 0.1	100
1583.6 ± 0.2	9 ± 2

[a] Relative intensities based on a value of 100 for the 1091-keV transition.

We would now like to discuss the information shown in Fig. 2. In Ref. 1 the decay of ^{145}Eu to ^{145}Sm was reported, and as in Fig. 2 the excitation energies of single-neutron states were traced from ^{137}Xe to ^{145}Sm. As the proton number increased the excitation energies increased for all but one of the levels. This level (originally thought to be $\frac{9}{2}^-$ but shown[10] recently to be $\frac{13}{2}^+$) dropped markedly in energy (see Fig. 2). On the basis of this systematic behavior, it was possible to predict the locations in ^{147}Gd of the two $\frac{9}{2}^-$ states as well as the $f_{5/2}$ and $p_{1/2}$ levels; the $i_{13/2}$, 997-keV and the $p_{3/2}$, 1153-keV levels in ^{147}Gd had already been found in earlier investigations.[11,12] In the subsequent study[2] of ^{147}Tb decay the $\frac{9}{2}^-$ and $\frac{5}{2}^-$ levels in ^{147}Gd were found at the predicted[1] energies. The present study and Ref. 3, however, indicate that this smooth behavior, at least for the $i_{13/2}$ and $h_{9/2}$ states, has been disrupted at ^{149}Dy.

This disruption may be due to the closure at $Z = 64$ where the $g_{7/2}$ and $d_{5/2}$ proton orbitals are filled so that ^{149}Dy (its last two protons are in $h_{11/2}$ orbitals) is the first $N = 82$ nucleus to occupy the new subshell. A proton subshell at 64 was first suggested[13] when a discontinuity in the progression of α-decay energies for $N = 84$ nuclides was noted at $Z = 64$. To obtain a theoretical understanding of this closure BCS calculations were made[14] for the proton system of 82-neutron nuclei. By assuming a sufficient spacing between the $d_{5/2}$ and $h_{11/2}$ proton orbitals these calculations did produce a discontinuity in binding energies at $Z = 64$. Shell-model calculations for nuclei in this region have also been made[15] with the assumption of an ($N = 82$

$+Z=50$) core. Because of the complexities involved, the $h_{11/2}$ proton orbital was not considered. It certainly should be included for nuclei at $Z \gtrsim 64$ since occupation of that orbital becomes an important consideration at this atomic number. Further and more complete theoretical studies are now clearly needed. With the available experimental evidence perhaps such calculations could utilize an ($N=82+Z=64$) core to explore the structure of nuclei with $Z \geqslant 66$.

B. Decay of ^{148}Ho

At 96 MeV the intensity of a 1688-keV γ ray was observed to increase dramatically *vis-à-vis* its intensity at 85 MeV. This transition energy parallels those of transitions deexciting first-excited states in even-even $N=82$ nuclei which increase gradually from ^{136}Xe to ^{144}Sm (1660 keV). Although in ^{146}Gd the first-excited level drops to 1580 keV (see Refs. 2 and 16), the 1668-keV γ-ray is still a good candidate for the first-excited to ground-state transition in ^{148}Dy.

Because of its shorter half life, coincidence and singles measurements were made at 96 MeV with a counting and collection cycle of 28 s. Figure 3 shows in part (A) the spectrum observed at 85 MeV and in part (B) the one at 96 MeV. The marked increase in intensity of the γ ray in question can be noted by comparing the two spectra. The energy and half life of this transition were 1688.3 ± 0.2 keV and 9 ± 1 s, respectively.

The identification of this new activity with ^{148}Ho is based on the following evidence: (1) while a complete excitation function could not be obtained (because of an insufficient amount of bombarding energy) its intensity relative to that of the 620-keV ^{148}Dy γ ray[7] remained constant from 85 to 96 MeV; (2) it was in coincidence with dysprosium K x rays; and, (3) it had not been observed in the earlier studies[7,8] of the decay of dysprosium nuclides.

The 1688-keV transition was also found to be in coincidence with 661.5 ± 0.2 keV and 504.3 ± 0.3-keV γ rays. The half life of the 662-keV γ ray was 8.5 ± 1.0 s, in agreement with the value determined for the 1688-keV transition. It too was in coincidence with the 504-keV γ ray and dysprosium K x rays. An accurate half life was difficult to deduce for the 504-keV γ ray because of its proximity to the annihilation radiation peak; however, it was consistent with a value of ~9 s. Table II summarizes the photon energies and intensities of the three transitions assigned to the decay of ^{148}Ho.

The intensities establish the following cascade

TABLE II. Transition energies and photon intensities for 9-s ^{148}Ho.

E_γ (keV)	I_γ[a]
504.3 ± 0.3	17 ± 3
661.5 ± 0.2	69 ± 7
1688.3 ± 0.2	100

[a] Relative intensities based on a value of 100 for the 1688-keV transition.

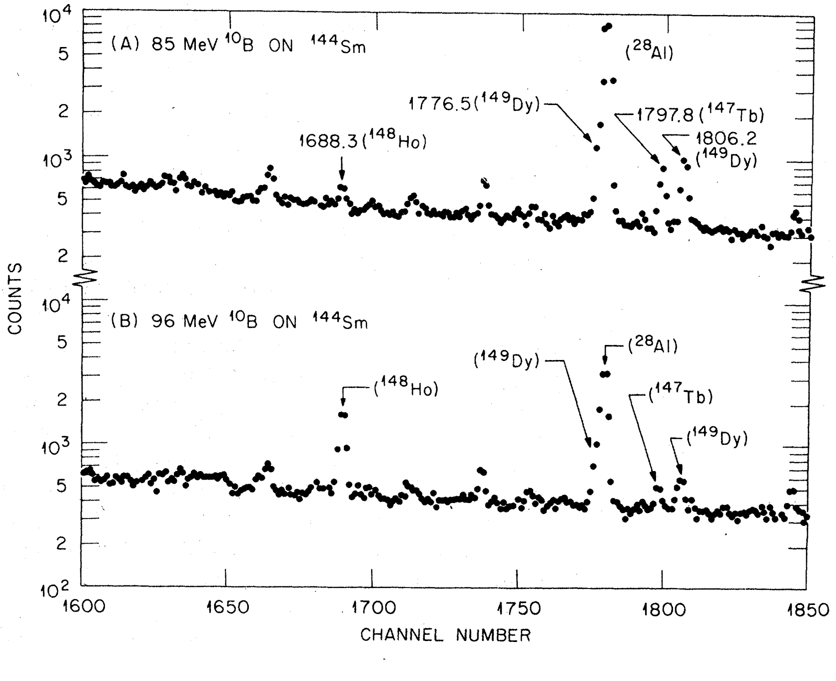

FIG. 3. Part (A) is a portion of a spectrum obtained in 85-MeV ^{10}B bombardment of ^{144}Sm, while part (B) is a spectrum covering the same energy range but obtained at 96 MeV. The spectra (A) and (B) represent the first 15 and 7 s of counting, respectively, accumulated following numerous irradiation and counting cycles. The 1688.3-keV γ ray, whose intensity increases dramatically at 96 MeV, is assigned to the new isotope, ^{148}Ho.

(and sequence of levels in keV): 504 (2854) → 662 (2350) → 1688 (1688) → ^{148}Dy ground state. This situation resembles the one found[2] in the decay of the isotone ^{146}Tb, i.e., 441 (3099) → 1078 (2658) → 1580) → ^{146}Gd ground state. In ^{146}Gd the spins of the first two excited levels were assumed to be $4^+ \to 2^+ \to 0^+$, as systematics[16] for even-even nuclei with $N = 82$ indicated. Recent data,[17] however, show that the first-excited state in ^{146}Gd is 3^-, so that the sequence is, instead, $5^- \to 3^- \to 0^+$. The fact that in ^{148}Dy as in ^{144}Sm the energy of the first-excited state has once again increased relative to its value in ^{146}Gd raises the question whether it is 2^+ or 3^- in character. From the intensities of the 662- and 1688-keV γ rays it is apparent that both the 2350- and 1688-keV levels are fed directly by the decay of ^{148}Ho. The spin of the parent is, therefore, 3 or 4 depending on the spins of the two levels in ^{148}Dy.

IV. CONCLUSION

We conclude that the $h_{11/2}$ proton state in ^{149}Ho has been identified through its decay properties. These data have revealed a significant break in the systematic behavior of the $i_{13/2}$ and $h_{11/2}$ neutron orbitals at $Z = 66$. More data are needed to find the $d_{5/2}$ state. This will require more beam time or more sensitive measurements because of the expected[6] low cross section for its formation. However, its identification and study is of interest to see if the regular behavior of the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ neutron states (see Fig. 2) has also been disrupted at $Z = 66$.

The decay of the new isotope ^{148}Ho has been observed; a three-γ-ray cascade has been established, ending with a 1688-keV transition to the ^{148}Dy ground state. It would be extremely interesting to determine whether the 1688-keV level in ^{148}Dy is 3^- or 2^+.

This research was sponsored in part by the U. S. Department of Energy. Oak Ridge National Laboratory is operated by Union Carbide Corporation for the Department of Energy, Division of Basic Energy Sciences, under Contract No. W-7405-eng-26. UNISOR is a consortium of 14 institutions and is partially supported by them and by the U. S. Department of Energy under Contract No. EY-76-C-05-0033 with Oak Ridge Associated Universities. Two of us (C.R.B. and K.S.T.) would like to express thanks to the staff of the Cyclotron Institute at Texas A & M University for their hospitality and to T. T. Sugihara, the Director of the Institute, for his help and encouragement.

---

[1] E. Newman, K. S. Toth, and I. R. Williams, Phys. Rev. C 7, 290 (1973).

[2] E. Newman, K. S. Toth, D. C. Hensley, and W.-D. Schmidt-Ott, Phys. Rev. C 9, 674 (1974); 12, 346 (1975).

[3] A. M. Stefanini, P. J. Daly, P. Kleinheinz, M. R. Maier, and R. Wagner, Nucl. Phys. A258, 34 (1976).

[4] A. M. Stefanini, P. Kleinheinz, and M. R. Maier, Phys. Lett. 62B, 405 (1976).

[5] W.-D. Schmidt-Ott and K. S. Toth, Phys. Rev. C 13, 2574 (1976).

[6] W.-D. Schmidt-Ott, K. S. Toth, E. Newman, and C. R. Bingham, Phys. Rev. C 10, 296 (1974).

[7] K. S. Toth, E. Newman, C. R. Bingham, A. E. Rainis, and W.-D. Schmidt-Ott, Phys. Rev. C 11, 1370 (1975).

[8] K. S. Toth, A. E. Rainis, C. R. Bingham, E. Newman, H. K. Carter, and W.-D. Schmidt-Ott, Phys. Lett. 56B, 29 (1975).

[9] A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 175 (1977).

[10] P. Kleinheinz, M. R. Maier, R. M. Diamond, F. S. Stephens, and R. K. Sheline, Phys. Lett. 53B, 442 (1975).

[11] J. Kownacki, H. Ryde, V. O. Sergejev, and Z. Sujkowski, Phys. Scr. 5, 66 (1972).

[12] V. P. Afanasiev, I. I. Gromova, G. I. Iskhakov, V. V. Kuznetsov, M. Ya. Kuznetsova, and N. A. Lebedev, Izv. Akad. Nauk SSSR Ser. Fiz. 35, 719 (1971) [Bull. Acad. Sci. USSR Phys. Ser. 35, 659 (1971)].

[13] J. O. Rasmussen, S. G. Thompson, and A. Ghiorso, Phys. Rev. 89, 33 (1953).

[14] R. D. Macfarlane, J. O. Rasmussen, and M. Rho, Phys. Rev. 134, B1196 (1964).

[15] B. H. Wildenthal, Phys. Rev. Lett. 22, 1118 (1969); B. H. Wildenthal, E. Newman, and R. L. Auble, Phys. Rev. C 3, 1199 (1971).

[16] J. Kownacki, H. Ryde, V. O. Sergejev, and Z. Sujkowski, Nucl. Phys. A196, 498 (1972).

[17] P. Kleinheinz, S. Lunardi, M. Ogawa, and M. R. Maier, Z. Phys. A 284, 351 (1978).