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Authors
Chasteler, R.M.
Nitschke, J.M.
Firestone, R.B.
et al.

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R.M. Chasteler, J.M. Nitschke, R.B. Firestone,
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Decay of the Neutron-Rich Isotope ^{171}Ho and the Identification of ^{169}Dy

R. M. Chasteler, J. M. Nitschke, R. B. Firestone,
K. S. Vierinen*, and P. A. Wilmarth

Nuclear Science Division
Lawrence Berkeley Laboratory,
1 Cyclotron Road
Berkeley, California 94720, USA

* *present address*
University of Helsinki
Department of Physics
SF-00170, Helsinki 17, Finland

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ABSTRACT: *Neutron-rich rare-earth isotopes were produced in multi-nucleon transfer reactions between ^{170}Er ions and ^{nat}W targets. On-line mass separation was used together with β and γ-ray spectroscopy in these studies. At mass A=169, the heaviest known dysprosium isotope, 39(8) s, ^{169}Dy, was identified. It was observed to β^- decay to the ground state of ^{169}Ho or through a level at 1578 keV. In the A=171 mass chain, a partial decay scheme for 55(3)-s ^{171}Ho was determined.*

Recent successful searches at the OASIS mass-separation facility[1] for new neutron-rich rare-earth isotopes with ^{176}Yb beams on ^{nat}W to produce ^{174}Er and ^{171}Ho,[2] have spurred further experiments using multi-nucleon transfer reactions with neutron-rich rare-earth beams. The SuperHILAC at the Lawrence Berkeley Laboratory provided high intensity beams (50-125 pnA) of 8.5 MeV/u ^{170}Er ions which impinged on a ^{nat}W target inside of the OASIS ion source. The ^{nat}W targets were of sufficient thickness (> 15 mg/cm^2) to degrade the ^{170}Er ions below the Coulomb barrier. Reaction products were ionized, mass analyzed, and the desired mass chain transported ionoptically to a shielded counting area. There, the activities were collected on a fast-cycling tape system and transported to a detector array for β and γ-ray spectroscopy. A β telescope and low-energy (10-400 keV) γ-ray detector, consisting of a 718μm Si detector and a planar hyperpure Ge (HPGe) detector, faced the radioactive layer of the tape. On the opposite side of the tape, a large solid angle (~35%) 1-mm thick plastic scintillator, for electron detection, and 52% Ge detector, for γ-ray detection, were located. A 24% Ge detector was located at 90^o with the respect to the other detectors at a distance of ~4.5 cm from the source. Time resolved multispectrum singles data were acquired with the HPGe and 52% Ge detectors, where the tape cycles were divided into eight equal time intervals for half-life determinations. Coincidence events registered in the various detectors were recorded in an event-by-event mode.

At mass A=169, a search for the new isotope ^{169}Dy was undertaken. The expected Q_β value for this isotope was ~3.2 MeV taking the average of the mass predictions compiled by Haustein.[3] Half-life predictions were 38 s, by Klapdor *et al.*,[4] and 64 s, using the Gross Theory of β decay[5] and the Q_β value above. A tape cycle time of 160 s was therefore chosen to maximize this activity. High-energy β particles [Figure 1(a)] were measured in the β telescope with energies extending beyond the β endpoints (~2.0 MeV for ^{169}Ho) of known A=169 isobars that could be expected to emerge from the ion source of the mass separator. The two-component decay fit of the background-subtracted beta intensity between 2.1 and 3.2 MeV is shown in the inset to Figure 1(a). The 43(11) s half-life obtained for the short-lived activity does not match any of the previously known beta-decaying A=169 isobars. A Fermi-Kurie plot of the high energy β^- particle singles data in the beta telescope and a least-squares linear fit of the plot from 2.1 to 2.9 MeV yielded a beta endpoint of 3.2(3) MeV [Figure 1(b)]. Similar analysis of β^- particles decaying to the 853- and 941-keV levels in ^{169}Ho decay gave beta endpoints of 1.3(1) and 1.2(1) MeV respectively in good agreement with 1.3 and 1.2 MeV found in the literature.[6] Close inspection of the γ-ray singles spectra yielded only one short-lived γ ray at 1578.2(4) keV with a half-life of 35(11) s. No Ho K x rays were observed and all other γ rays were longer lived. The event-by-event data showed the 1578-keV γ ray to be in coincidence with the β^- particle spectrum shown in Figure 2. Statistics were too poor to obtain a beta endpoint using Fermi-Kurie analysis, but visual inspection of the spectrum indicates an endpoint of ~1.5 MeV, which is consistent with the measured decay energy of 3.2(3) MeV. A maximum likelihood decay fit of the time data for the β^- particles in Figure 2 yielded a half-life of $58\binom{+32}{-16}$ s. Based on the agreement between both the experimental decay energy and half-life with the predictions, we assign the observed activity to the new isotope ^{169}Dy with a half-life of 39(8) s as determined from the weighted average of both the gamma and beta half-lives.

Our proposed partial decay scheme for ^{169}Dy is shown in Figure 3. The intensity of the ground state beta branch was estimated by fitting the 2.1 to 2.9 MeV interval of a calculated "ideal" beta particle spectrum, with a 3.2 MeV beta endpoint, to the measured beta spectrum to determine the total integral of beta particles in the spectrum. The fit of the calculated to the measured β spectra is shown in Figure 4. The beta telescope efficiency was calculated in a seperate experiment using the above procedure on beta particles with ~2.0 MeV endpoints from ^{168}Ho decay,[7] gated on γ rays detected in the 52% Ge detector. A ground state to excited state (1578 keV) beta branching ratio of 3.5 was determined with an estimated uncertainty of ~20% due to possible errors in the calculated spectrum fit and to take into account that the beta telescope efficiency may change with beta particle energy. The decay scheme is consistent with the lack of Ho K x rays since there should be little internal conversion.

For ^{169}Dy and ^{169}Ho, the assignments of the 103^{rd} neutron and 67^{th} proton orbitals, 5/2-[512] and 7/2-[523] respectively, are well established for this region.[7] Our measured log *ft* = 5.4 for the ground state branch is consistent with a log *ft* = 5.8 for the 7/2-[523] proton to 5/2-[512] neutron transition reported in the decay of ^{167}Ho, but it is lower than the log *ft* = 6.4 for the 5/2-[512] neutron to 7/2-[523] proton transition previously measured in ^{171}Er decay.[7] The log *ft* = 4.8 for the β^- feeding to the level at 1578 keV is faster than any known β transtion involving the 5/2-[512] neutron level. A three quasiparticle state could be a possible assignment of the 1578-keV level composed of 7/2-[523] proton and 5/2-[512] neutron particle states and a 5/2-[523] neutron hole state. This assignment would have a resulting 7/2- spin and parity which permits Gamow-Teller allowed beta feeding and strong ground state γ feeding. The assignment of the 5/2-[512] neutron level to the 39-s ^{169}Dy parent and the 7/2-[523] proton orbital to the measured ^{169}Ho ground state are tentatively proposed in agreement with nuclear level predictions of Nilsson *et al.*[8] using the nuclear deformations of Möller and Nix.[9] The 1578-keV level has been left unassigned.

In a similar experiment at the A=171 mass chain, a 128-s tape cycle time was used to determine the half-life and the decay scheme of ^{171}Ho. Rykaczewski *et al.*,[10] first identified this isotope by measuring 47(5) s Er K x rays in coincidence with electrons in plastic scintillators. We were able to confirm their findings by measuring Er K x-ray coincident β^- particles with energies up to ~2.5 MeV.[2] In this experiment, short-lived, high-energy β^- particles (1.0 - 3.0 MeV), which extended beyond the β endpoints of the known A=171 isobars, were seen in the beta telescope and found to decay with a half-life of 56(4) s. Figure 5 shows the β^- spectra and the background-subtracted single-component decay curve for the β intensity between 1.0 and 3.0 MeV. A Fermi-Kurie analysis was performed on these β's, but no unambiguous β^- endpoint could be deduced. Table I lists the Er K x rays and fifteen γ rays assigned to the decay of ^{171}Ho with their measured relative intensities and γ-ray coincidences. These transitions were all short-lived with an average half-life of 54(3) s and were in coincidence with β^- particles in the beta telescope. The identification of the 199- and 279-keV γ rays presented difficulties due to interfering radiations induced at these energies by the neutron background. Analysis of the 358-keV γ ray was complicated by a sum peak from the 308-keV γ ray and the Tm K_α x rays in ^{171}Er decay.[11] The 61.2-keV γ ray could not be resolved in the singles spectra due to Lu K_β x rays at this energy, however the 61.2-keV transition was detected in β-gated coincidence data where its intensity was determined relative to the 79-keV transition. The 61.2-keV transition was determined to be M1 from its measured K conversion coefficient. Six of the γ rays reported in Table I have been observed previously in the adopted level scheme for ^{171}Er.[12] Based on the past studies, coincidence and intensity information, we propose the partial ^{171}Ho decay scheme in Figure 6. The decay scheme is consistent with the absence of a unique beta endpoint due to the many different beta branches shown. The 199-keV level had a measured life-time of 200(30) ns in good agreement with the previous result of 210(10) ns.[12] The placement of the 841-keV level is uncertain because of the possible reversal of the order of the 61- and 642-keV γ cascade and could alternatively be placed at

259.8 keV. There is no indication of direct β^- feeding to this level. The beta intensities and log *ft* limits listed in Figure 6 were calculated assuming no ground-state feeding. Since β transitions have been measurted between the 7/2-[523] proton and the 5/2-[512] neutron states,[7] ground state β feeding is expected in ^{171}Ho decay, but could not be determined. The spin and parity for the ^{171}Er levels listed in the decay scheme are from the adopted level scheme.[12] The assignment of the ^{171}Ho parent state (the 67th proton) as 7/2-[523] was discussed above in the ^{169}Dy decay. The upper-limit, assuming no ground state feeding, for β feeding to the 199-keV level is ≤2%, but because decay to this level would be second-forbidden (unique), no beta feeding to this level is proposed. The average predicted Q_β value for the decay of ^{171}Ho is ~3.2 MeV.[6] A Fermi-Kurie analysis of β^- particles feeding the 903- and 907-keV levels yielded an endpoint of 2.3(6) MeV, consistent with the predicted Q value. A half-life of 55(3) s, calculated as the weighted average of all the gamma and beta decay information, is adopted for this isotope.

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Table I. Gamma-ray energies E_γ, intensities I_γ(rel.), and γ-ray coincidences measured in the decay of ^{171}Ho.

E_γ (keV)	I_γ (rel.)[a]	Coincident γ rays (X=Er K x rays)
48.2 Er $K_{\alpha 2}$	51(8)	X, (61), 199, 279, (454), (642), (708), (903), (907), (1687)
49.1 Er $K_{\alpha 1}$	106(7)	b
55.7 Er $K_{\beta 1}$	34(3)	X, 199, 279, (358), (454), (824)
61.2(5)	4(2)	X, 199, 642
79.1(1)	25(2)	X, 279, (454), (824), (1687)
198.6(1)	88(23)	X, 61, 642, 705, (708)
279.2(4)	60(9)	X, 79
358.3(3)	49(33)	X
453.8(3)	13(4)	X, 79
532.2(1)	58(4)	X
642.5(2)	39(5)	X, (61), 199
704.7(3)	27(5)	X, 199
708.5(1)	34(19)	X, 199
727.6(1)	44(5)	X
823.9(5)	30(6)	X, 79
903.3(4)	100(6)	c
907.2(2)	57(6)	(X)
1687.1(10)	25(8)	X, (79)

a Intensities are relative to 100 for the 903.3-keV gamma transition.

b "Clean" coincidence gate could not be set due to interferences of Tm $K_{\alpha 2}$ x rays.

c No coincidences were observed.

Figure Captions:

Figure 1. Beta decay data for the A=169 mass chain; (a) β particle spectrum measured in the β telescope and (b) Fermi-Kurie plot and least-squares linear fit from 2.1 to 2.9 MeV resulting in a β^- endpoint of 3.2(3) MeV. The inset in (a) shows the two-component background-subtracted decay of the β^- intensity between 2.1 and 3.2 MeV (shaded portion of the spectrum).

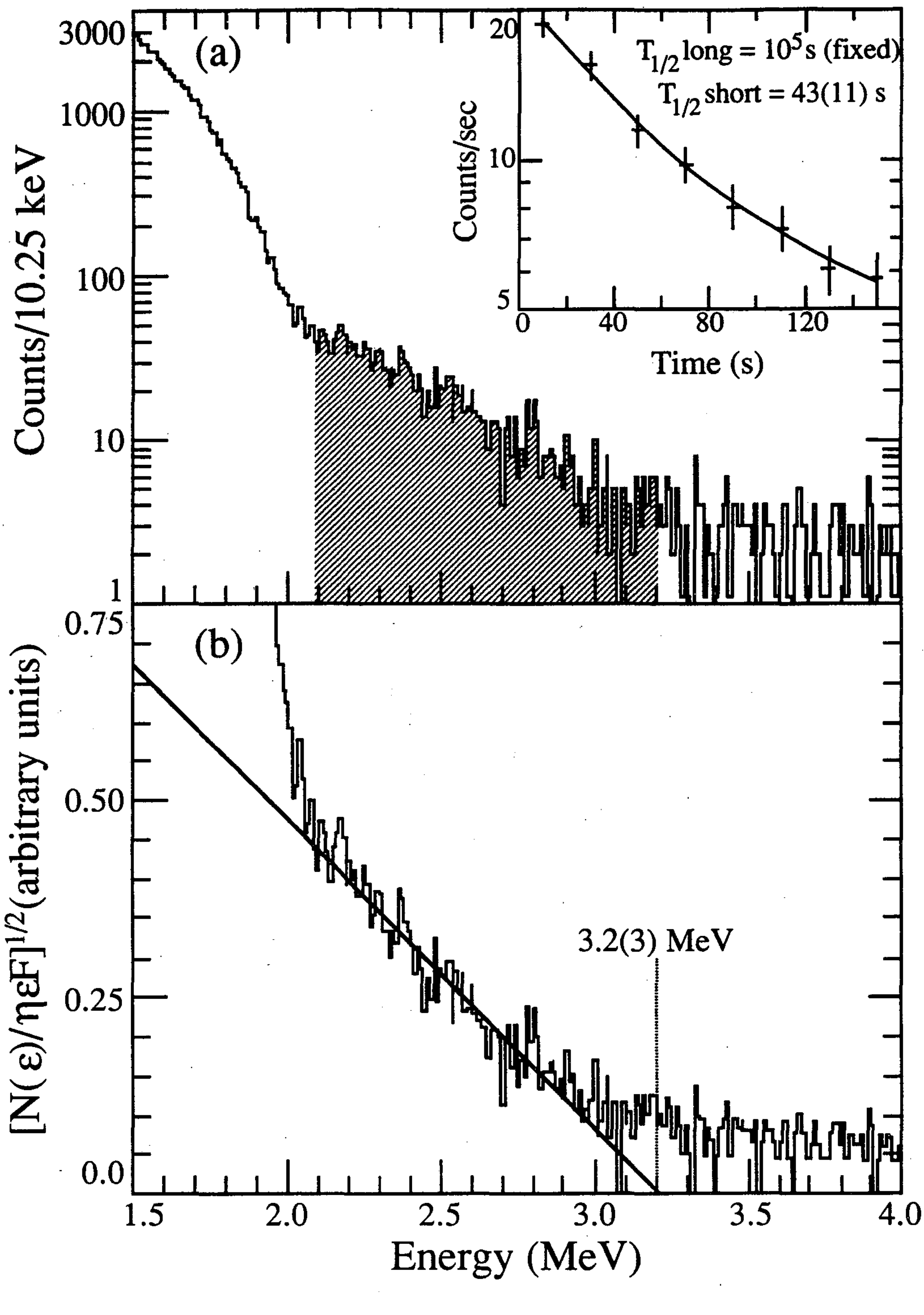
Figure 2. Beta particle spectrum measured in coincidence with 1578-keV γ rays in the A=169 mass chain.

Figure 3. Partial decay scheme proposed for ^{169}Dy. Energies are in MeV. The Q_β value was determined in the experiment. Log *ft*'s are in italics.

Figure 4. Fit of the measured A=169 β spectrum with the calculated β^- spectrum using a 3.2 MeV endpoint, normalized to the 2.1 to 2.9 MeV interval; (a) entire spectrum and (b) the 2.0 to 3.5 MeV region of the spectrum.

Figure 5. Beta particle spectrum measured with the β telescope for the A=171 mass chain. The inset shows the single-component background-subtracted decay of the β^- intensity between 1.0 and 3.0 MeV (shaded portion of the spectrum).

Figure 6. Proposed decay scheme for ^{171}Ho. Energies are in MeV. The Q_β value is from this experiment. Beta branches and log ft limits were calculated assuming no ground-state beta branch.



(a)
(b)
Counts/10.25 keV
3000
1000
100
10
1
$T_{1/2}$ long = 10^5 s (fixed)
$T_{1/2}$ short = 43(11) s
Counts/sec
20
10
5
0
40
80
120
Time (s)
$[N(\varepsilon)/\eta\varepsilon F]^{1/2}$(arbitrary units)
0.75
0.50
0.25
0.0
3.2(3) MeV
1.5
2.0
2.5
3.0
3.5
4.0
Energy (MeV)

Figure 1

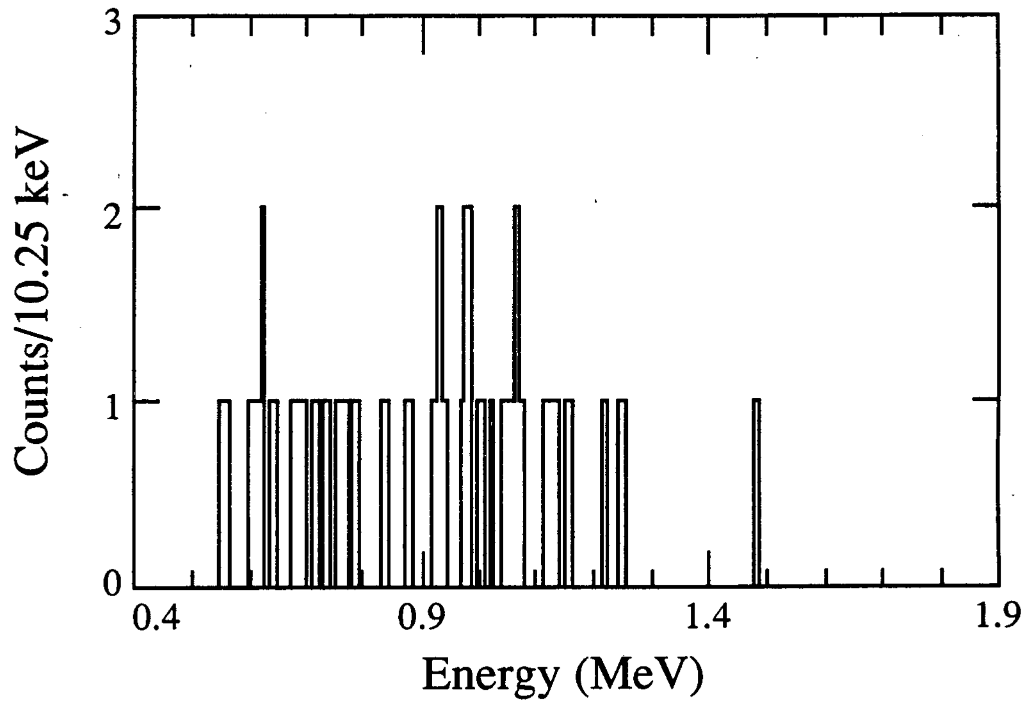


Figure 2

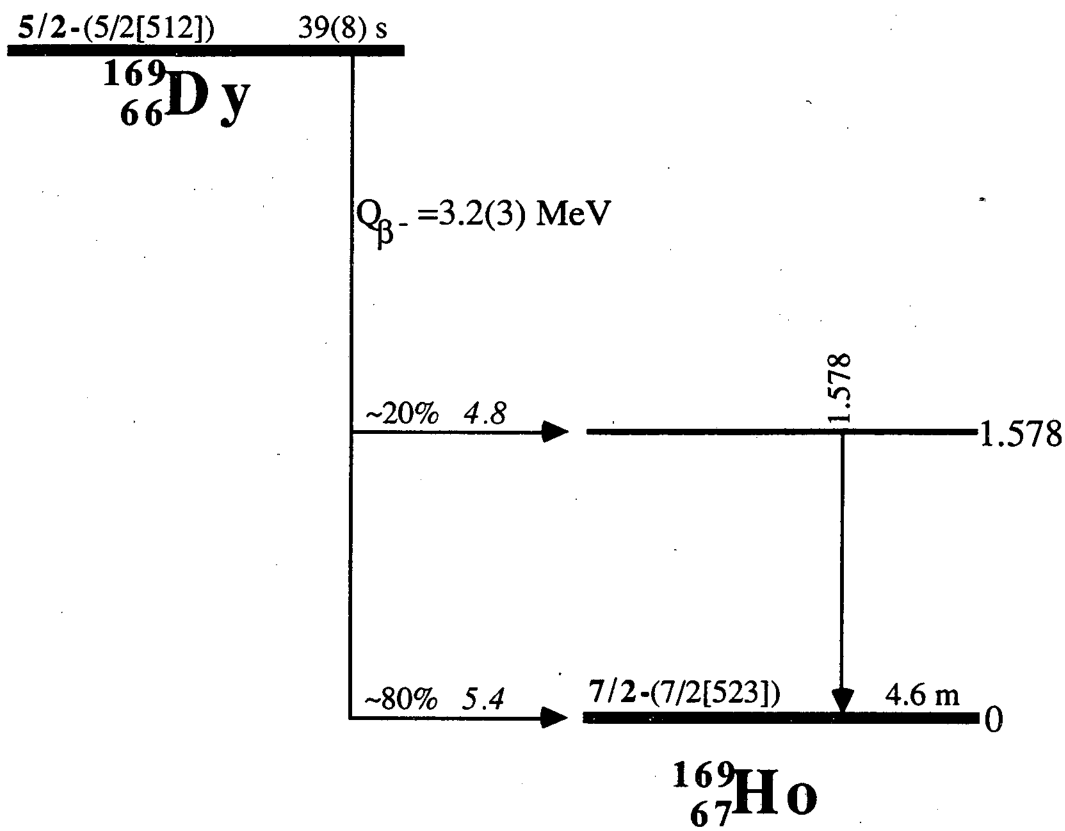

5/2-(5/2[512])
39(8) s
169 66 Dy
Qβ- =3.2(3) MeV
~20% 4.8
1.578
1.578
~80% 5.4
7/2-(7/2[523])
4.6 m
0
169 67 Ho

Figure 3

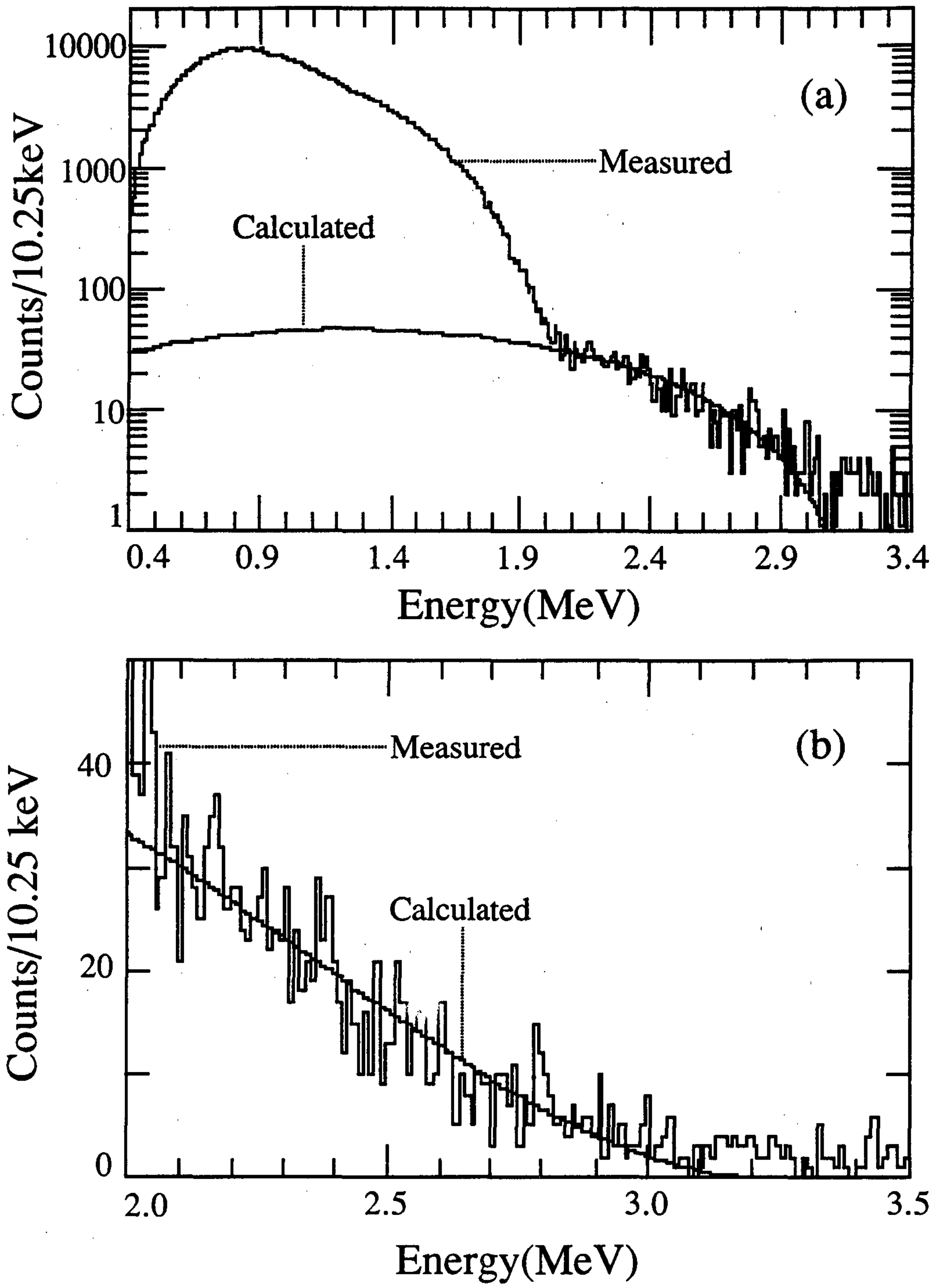
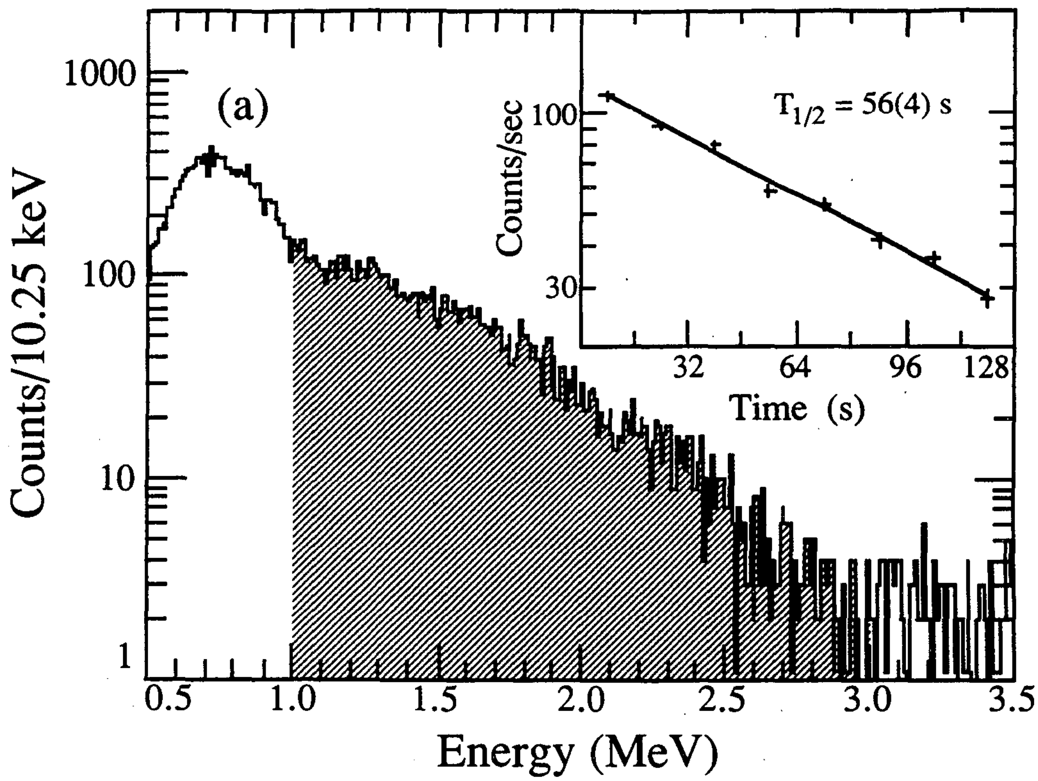

(a)
Measured
Calculated
10000
1000
100
10
1
Counts/10.25keV
0.4
0.9
1.4
1.9
2.4
2.9
3.4
Energy(MeV)
(b)
Measured
Calculated
40
20
0
Counts/10.25 keV
2.0
2.5
3.0
3.5
Energy(MeV)

Figure 4



(a)
Counts/10.25 keV
1000
100
10
1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Energy (MeV)
Counts/sec
100
30
$T_{1/2}$ = 56(4) s
32
64
96
128
Time (s)

Figure 5

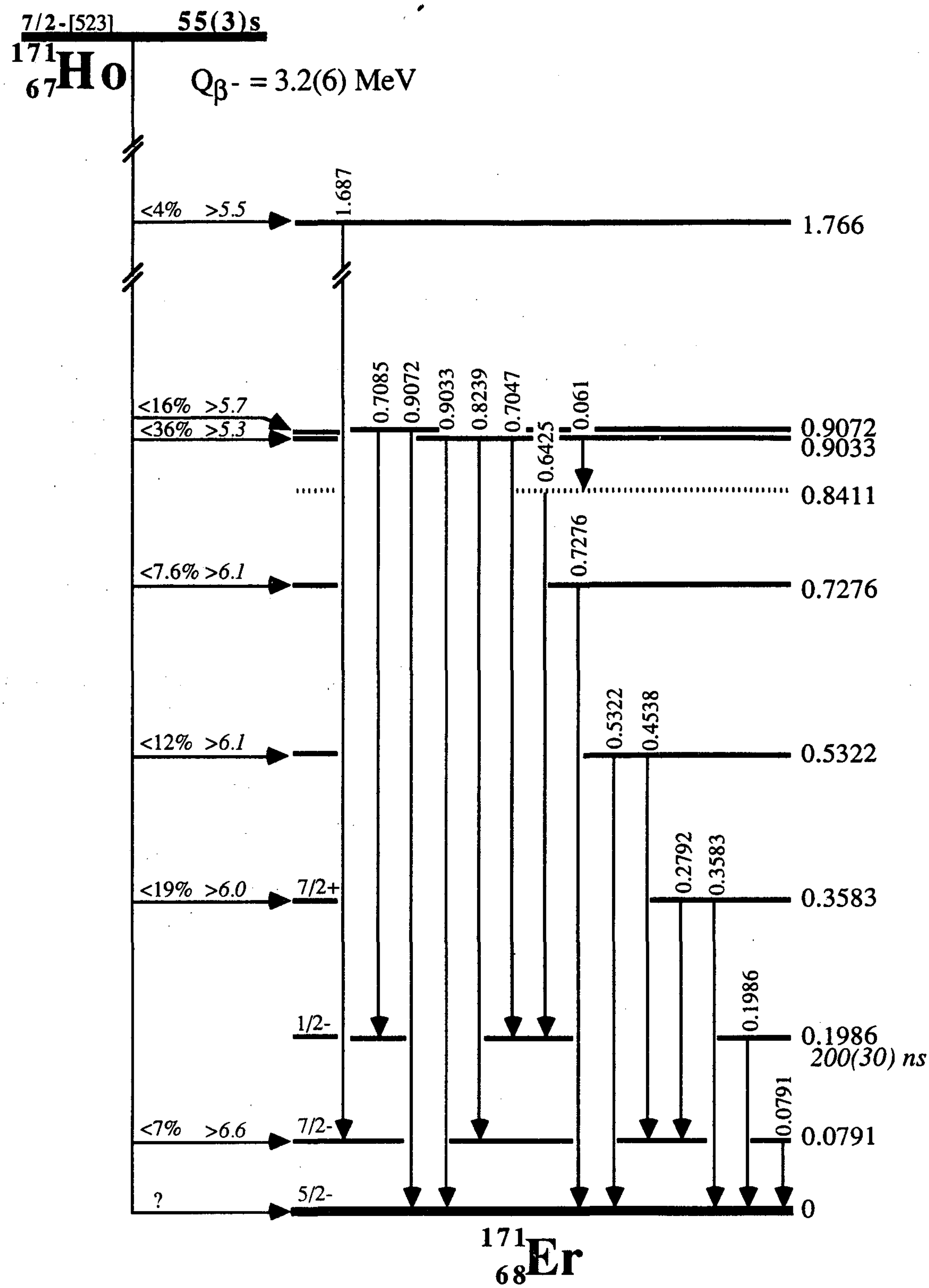

7/2-[523]
55(3)s
$^{171}_{67}$Ho
Q_{β^-} = 3.2(6) MeV
<4% >5.5
1.687
1.766
<16% >5.7
<36% >5.3
0.7085
0.9072
0.9033
0.8239
0.7047
0.6425
0.061
0.9072
0.9033
0.8411
<7.6% >6.1
0.7276
0.7276
<12% >6.1
0.5322
0.4538
0.5322
<19% >6.0
7/2+
0.2792
0.3583
0.3583
1/2-
0.1986
0.1986
200(30) ns
<7% >6.6
7/2-
0.0791
0.0791
?
5/2-
0
$^{171}_{68}$Er

Figure 6

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INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720