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THE NUCLEUS ^{168}Er STUDIED WITH THE (d,p) REACTION

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The reaction ^{167}Er(d,p)^{168}Er was measured with 22 MeV deuterons at the angles 15°, 30° and 40°. Up to 2.8 MeV, a total of 78 levels were identified. Measured differential cross–sections are given. The results are compared with previous data, especially from the (n,γ) reaction.

1. Introduction

The even–even deformed nucleus ^{168}Er is a very good example for an axially symmetric rotor with SU(3) symmetry in the interacting boson model (IBM). Experimental results and the corresponding theory of this nucleus were discussed in detail in Bohr and Mottelson's textbook [1]. This nucleus was frequently used as a test case for the IBM, for the geometrical model, for the quasiparticle phonon model and other theoretical approaches. Consequently, a wealth of experimental and theoretical papers were published. The newest nuclear data compilation was published in 1994 [2]. The National Nuclear Data Center gave in February 1996 a total of 716 references on ^{168}Er. ^{168}Er was investigated using the (n,γ) reaction

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by Groshev et al. [3], Koch [4], Michaelis et al. [5], Davidson et al. [6], Davidson and Dixon [7], Börner et al. [8], Petkov et al. [9] and Jungclaus et al. [10]. Various transfer reactions were investigated by Burke et al. [11–13]. From the large amount of theoretical publications which discuss ^{168}Er, we would like to quote only Warner et al. [14], Bohr and Mottelson [15], Soloviev and Shirikova [16], Soloviev [17,18], Soloviev et al. [19] and Piepenbring and Jammari [20,21]. Very recently the question was discussed whether two–phonon vibrational excitations exist in ^{168}Er [16,20,21] and experimental evidence for them was observed [8,22].

The (d,p) reaction has been measured by Burke et al. [11] with 12 MeV deuterons at 15 angles between 6° and 90°. The resolution ranged from 8 to 10 keV. However, the energies have only a precission of about 3 keV for the stronger lines. Consequently, we felt that it is necessary to repeat the (d,p) measurement with better resolution, higher energy precision and at deuteron energy of 22 MeV. Our new (d,p) experiment is described in more detail in Ref. 23.

2. *Experimental details and results*

The experiments were performed at the Tandem Accelerator of the University and Technical University of Munich with the Q3D spectrograph [24]. The deuteron beam had an energy of 22 MeV and an intensity of about 1.5 μA. The target consisted of 40 μg/cm^2 enriched ^{167}Er (area 1 mm × 4 mm) on 4 μg/cm^2 carbon. The protons were detected in the focal plane with a multiwire proportional counter (576 wires with 0.5 mm wire distance) [25] at three angles, 15°, 30° and 40°. The energy resolution was 6 keV FWHM. Spectra were measured up to 2.7 MeV. Figure 1 shows an example of the observed spectra. A special monitor detector was used to measure elastically scattered deuterons for absolute intensity calibration in order to obtain differential cross–sections. The angular momentum transfer $\Delta\ell$ can be estimated by comparison of the angular distribution with DWBA calculations [26]. For the purpose, calculated DWBA cross–section are given in Table 1.

The energies of the (d,p) peaks were determined in the following way. The peaks in the spectra were fitted and as many as possible were identified with known levels of ^{168}Er. The energies of the levels below 2 MeV are very precisely known from (n, γ) measurements [2,6,7] and the identification was not difficult in this energy region. In each measured spectrum the parameters of a quadratic calibration polynomial were determined with a least squares fit. These parameters were used to calculate the energies of all peaks. The energies of the level determined in different spectra were averaged. A comparison of these average level energies below 2 MeV with the ones from the (n, γ) reactions showed that a systematic error of 0.33 keV has to be added in quadrature to the errors from the fit. This systematic error is caused by various instabilities and uncertainties of the whole system. This procedure becomes more and more difficult above 2 MeV due to the increasing level density, the less complete (n, γ) level scheme and the problem to identify the (d, p) levels with (n, γ) levels. It was also tried to determine by Ritz combination the γ–decay of the new (d, p) levels and to obtain in this way new calibration energies (see Ref. 23).

Consequently, the systematic error is about 1 keV above 2 MeV and might even increase above 2.5 MeV. However, this deviation has to be a smooth function of the energy. The experimental results are given in Table 2. Interferences due to other Er isotopes were checked.

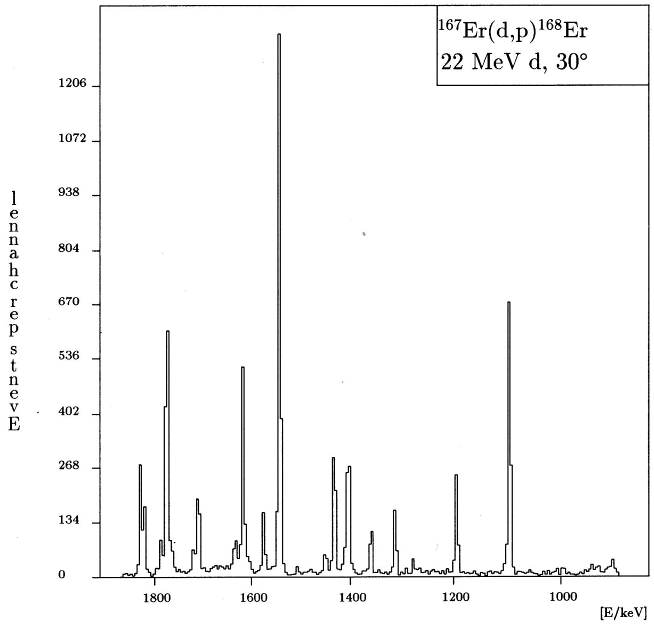

Fig. 1. Measured spectrum of the ^{167}Er(d,p)^{168}Er *reaction. The energy resolution is* 6 keV *FWHM.*

TABLE 1.
Calculated differential cross–sections using a DWBA code.
The values are given in mb.

$\Delta\ell$	$(\mathrm{d}\sigma/\mathrm{d}\Omega)_{DWBA}$ 15°	30°	40°
0	0.068	0.073	0.068
1	0.27	0.22	0.082
2	0.30	0.12	0.086
3	0.31	0.15	0.16
4	0.054	0.073	0.032
5	0.029	0.060	0.035
6	0.012	0.031	0.037
7	0.017	0.016	0.023

TABLE 2.
Level energies and differential cross–sections measured in the ^{167}Er(d,p)^{168}Er *reaction. The energy errors include only fit errors. For total energy errors a systematic error of* 0.33 keV *has to be added in quadrature below* 2 MeV *of* 1 keV *above* 2 MeV.

E (ΔE)* [keV]	$(d\sigma/d\Omega)_{15^\circ}$ [μb]		$(d\sigma/d\Omega)_{30^\circ}$ [μb]		$(d\sigma/d\Omega)_{40^\circ}$ [μb]	
1093.84(14)	160	±14%	100	±14%	88	±14%
1193.45(14)	66	±15%	34	±15%	36	±15%
1276.3(4)	—	—	5	±22%	—	—
1311.49(14)	27	±16%	22	±16%	20	±15%
1359.02(15)	21	±16%	17	±16%	12	±16%
1403.83(12)	66	±15%	51	±15%	52	±15%
1411.36(23)	—	—	8	±20%	13	±17%
1431.48(15)	—	—	51	±15%	47	±15%
1449.58(18)	—	—	7	±20%	10	±17%
1542.06(10)	300	±15%	140	±22%	150	±16%
1573.31(12)	31	±15%	15	±23%	20	±15%
1615.92(10)	120	±15%	49	±20%	64	±17%
1632.45(13)	15	±16%	10	±16%	9	±16%
1708.12(10)	66	±18%	29	±15%	34	±14%
1719.15(13)	17	±16%	8	±19%	8	±23%
1764.03(12)	31	±15%	10	±16%	9	±16%
1773.87(10)	200	±15%	79	±21%	91	±17%
1785.98(12)	18	±16%	10	±16%	11	±15%
1824.7(10)	44	±16%	20	±15%	28	±15%
1828.23(10)	99	±16%	41	±15%	51	±15%
1895.83(13)	280	±14%	110	±14%	150	±14%
1904.84(13)	140	±15%	50	±15%	73	±14%
1913.97(17)	21	±19%	13	±17%	18	±16%
1957.7(19)	—	—	6	±18%	5	±17%
1983.63(22)	10	±23%	4	±29%	4	±18%
2002.24(11)	60	±18%	20	±15%	27	±17%
2038.66(18)	—	—	5	±21%	7	±16%
2059.67(10)	150	±15%	48	±14%	53	±14%
2098.9(20)	9	±27%	7	±19%	6	±17%
2102.1(3)	—	—	—	—	6	±19%
2120.6(15)	24	±20%	18	±15%	22	±15%
2127.6(5)	33	±22%	—	—	6	±21%
2148.43(9)	99	±14%	37	±15%	42	±14%
2237.6(10)	28	±15%	12	±16%	11	±15%
2244.3(3)	10	±27%	6	±26%	5	±17%
2255.65(10)	41	±16%	15	±15%	18	±15%
2267.3(3)	7	±25%	4	±35%	2	±34%
2294.02(24)	9	±22%	8	±22%	4	±22%
2301.97(22)	13	±20%	9	±23%	4	±21%
2311.1(4)	—	—	—	—	3	±25%
2322.6(3)	—	—	11	±23%	3	±28%
2336.72(13)	63	±15%	31	±15%	24	±15%
2347.11(18)	12	±22%	12	±18%	8	±19%

Table 2. (continued)

E (ΔE)* [keV]	$(d\sigma/d\Omega)_{15^\circ}$ [μb]		$(d\sigma/d\Omega)_{30^\circ}$ [μb]		$(d\sigma/d\Omega)_{40^\circ}$ [μb]	
2364.73(13)	64	±15%	40	±15%	24	±15%
2371.6(3)	—	—	8	±22%	5	±20%
2382.0(22)	—	—	5	±24%	5	±24%
2392.09(17)	17	±18%	11	±19%	10	±18%
2401(3)	5	±32%	6	±23%	7	±20%
2411.22(14)	24	±17%	17	±17%	16	±16%
2434.91(12)	50	±16%	21	±16%	24	±15%
2455.4(20)	—	—	13	±19%	16	±17%
2476.44(18)	—	—	15	±18%	18	±16%
2484.4(6)	—	—	—	—	4	±25%
2497.8(3)	—	—	10	±21%	10	±18%
2517.58(14)	—	—	37	±15%	39	±15%
2527.2(3)	—	—	—	—	6	±25%
2539.3(3)	—	—	—	—	2	±35%
2553.05(15)	31	±17%	11	±18%	10	±18%
2562.17(12)	59	±15%	32	±15%	32	±15%
2569.0(3)	—	—	8	±22%	5	±26%
2584.84(16)	27	±18%	19	±17%	19	±16%
2594.4(3)	14	±23%	12	±19%	15	±17%
2603.7(3)	10	±28%	10	±19%	13	±17%
2626.29(20)	17	±21%	11	±20%	11	±23%
2637.2(3)	9	±26%	—	—	5	±26%
2646.2(3)	11	±23%	8	±23%	4	±27%
2656.31(19)	62	±16%	27	±26%	29	±15%
2663.14(19)	25	±19%	28	±21%	19	±16%
2678.13(17)	29	±18%	22	±16%	18	±17%
2691.78(18)	13	±21%	17	±17%	12	±18%
2703.17(12)	59	±15%	37	±15%	28	±16%
2711.9(4)	—	—	7	±24%	6	±24%
2727.89(15)	43	±16%	25	±16%	17	±17%
2739.64(11)	55	±15%	29	±16%	22	±15%
2746.26(16)	11	±21%	—	—	5	±22%
2755.81(12)	6	±31%	18	±17%	18	±16%

*Uncertainty ΔE of the last digit of E.

3. *Discussion*

A total of 78 energy levels were observed in the ^{167}Er(d,p)^{168}Er reaction. The results are compared with previous data in Table 3. The agreement with the previous (d,p) energies [11] and the level energies in the Nuclear Data Sheets [2] is very good. Since the nuclear structure of ^{168}Er has been carefully discussed in previous publications, we do not repeat it here. The new data confirm these interpretations. The two-phonon excitations in ^{168}Er, 4^+ at 2055 keV and 5^+ at 2169 keV [8, 22], are not observed in the (d,p) reaction as expected for collective excitations. The limited agreement between our new (d,p) data and the latest ^{167}Er(n,γ) ^{168}Er coincidence measurements [10] for levels above 2 MeV demonstrates that the high level density in this region makes firm assignments very difficult as already discussed in this reference.

TABLE 3.

Comparison of the present (d,p) data with previous transfer–reaction results [11], the Nuclear Data Compilation [2] and newest (n,γ) *measurements. The energy errors of the present results include only fit errors. For total energy errors a systematic error of* 0.33 keV *has to be added in quadrature below* 2 MeV *of* 1 keV *above* 2 MeV.

Present results	Burke et al.		Nuclear Data Sheets	
^{167}Er(d,p)^{168}Er	^{167}Er(d,p)^{168}Er	^{169}Tm(t,α)^{168}Er		
E [keV]	E [keV]	E [keV]	E [keV]	I^π
	76(3)		79.804(1)	2^+
	261(3)		264.089(2)	4^+
	545(3)		548.745(2)	6^+
	819(3)	822(5)	821.169(2)	2^+
		895(5)	895.795(2)	3^+
		994(5)	994.750(2)	4^+
1093.84(14)	1094(3)	1092(5)	1094.040(2)	4^-
1193.45(14)	1192(3)	1191(5)	1193.026(2)	5^-
1276.3(4)	1275(3)		1276.274(2)	2^+
1311.49(14)	1311(3)	1309(5)	1311.463(2)	6^-
1359.02(15)	1358(3)		1358.898(5)	1^-
1403.83(12)	1404(3)		1403.736(3)	2^-
1411.36(23)			1411.098(2)	4^+
1431.48(15)	1431(3)		1431.466(4)	3^-
1449.58(18)	1450(3)		1448.957(2)	7^-
		1490(5)	1493.135(4)	2^+
1542.06(10)	1542(3)		1541.558(2)	3^-
			1541.710(3)	4^-
	1565(3)		1569.452(3)	2^-
1573.31(12)	1574(3)		1574.117(3)	5^-
1615.92(10)	1616(3)		1615.343(2)	4^-
1632.45(13)	1634(3)		1633.461(3)	3^-
1708.12(10)	1709(3)		1707.995(2)	5^-
1719.15(13)	1720(3)		1719.179(3)	4^-
1764.03(12)	1761(3)			
1773.87(10)	1775(3)		1773.203(3)	$(6)^-$
1785.98(12)	1788(3)		1786.113(11)	1^-
1820.47(10)	1821(3)	1825(5)	1820.134(2)	6^-
			1820.477(3)	5^-
1828.23(10)	1830(3)		1828.065(2)	3^-
1895.83(13)	1895(3)	1895(5)	1896.377(3)	7^-
1904.84(13)	1909(3)		1905.092(3)	4^-
1913.97(17)			1913.900(6)	3^-

Table 3. (continued)

Present results	Burke et al.		Nuclear Data Sheets	
^{167}Er(d,p)^{168}Er	^{167}Er(d,p)^{168}Er	^{169}Tm(t,α)^{168}Er		
E [keV]	E [keV]	E [keV]	E [keV]	I$^{\pi}$
	1939(3)		1936.590(9)	1^-
1950.77(19)	1953(3)		1950.808(2)	7^-
1983.63(22)	1984(3)	1984(5)	1983.042(3)	5^-
2002.24(11)	2005(3)	2001(5)	2002.471(5)	$(4)^+$
	2019(3)		2022.329(6)	3^-
		2030(5)	2031.090(8)	4^+
2038.66(18)	2039(3)		2038	(8^-)
2059.67(10)	2060(3)		2059.976(2)	4^-
2090.89(20)	2092(3)	2091(5)	2089.347(3)	4^-
			2091.270(5)	6^-
2102.1(3)	2101(3)		2100.363(4)	(7^+)
	2108(3)		2108.986(6)	5^+
2120.06(15)	2121(3)	2120(5)	2118.793(5)	$(6)^-$
			2122.426(3)	7^-
2127.6(5)	2127(3)			
	2136(3)		2137.08(9)	2^+
2148.43(9)	2152(3)	2147(5)	2148.370(3)	5^-

Present res.	Burke et al.		Nucl. Data Sheets		Jungclaus et al.	
^{167}Er(d,p) ^{168}Er	^{167}Er(d,p) ^{168}Er	^{169}Tm(t,α) ^{168}Er			^{167}Er(n,γ)^{168}Er	
E [keV]	E [keV]	E [keV]	E [keV]	I$^{\pi}$	E [keV]	I$^{\pi}$
	2186(3)		2186.738(4)	$(3)^+$	2188.573(4)	$(2\text{-}4)^+,3^-$
	2204(3)	2198(5)	2200.421(3)	5^-		
	2221(3)					
2230.76(10)			2230.335(16)	2^-		
2239.5(4)	2238(3)		2238.178(3)	4^+		
2244.3(3)			2243.523(19)	$(3)^+$		
2255.65(10)	2259(3)	2256(5)	2255.345(3)	6^-	2254.708(20)	2^+
2267.3(3)			2267.620(4)	$(5)^+$		
	2274(3)		2272.9(9)	$(4)^+$	2273.579(21)	$(2\text{-}4)^+,3^-$
2294.02(24)	2291(3)	2286(5)				
2301.97(22)	2303(3)		2302.685(5)	3^-		
2311.1(4)	2312(3)		2311.07(3)	$(4)^+$		
2322.6(3)			2323.20(9)	3^-		
	2330(3)	2330(5)	2331.987(3)	6^-		
2336.72(13)			2336.26(6)	4^+		
			2337.126(19)	3^-		
2347.11(18)	2343(3)		2348.560(5)	4^-	2345.295(24)	3^-
2364.73(13)		2356(5)	2365.173(13)	$(5)^-$		
			2365.33(11)	(1^+)		
2371.6(3)	2370(3)				2373.654(13)	2,3

Table 3. (continued)

Present res. ^{167}Er(d,p)^{168}Er	Burke et al. ^{167}Er(d,p)^{168}Er	Burke et al. ^{169}Tm(t,α)^{168}Er	Nucl. Data Sheets		Jungclaus et al. ^{167}Er(n,γ)^{168}Er	
E [keV]	E [keV]	E [keV]	E [keV]	I$^{\pi}$	E [keV]	I$^{\pi}$
2380.20(22)	2383(3)		2383.2(5)		2382.582(9)	2^+
2392.09(17)	2399(3)	2394(5)	2392.626(9)	$(4)^-$	2393.694(83)	$(1,2)^+$
2400.1(3)					2398.553(65)	$(4,5)^+$
					2401.880(24)	$1,2^+$
2411.22(14)	2417(3)		2411.640(22)	4^-		
2434.91(12)		2428(5)	2434.6(7)			
	2441(3)		2439.7(8)		2440.069(9)	2^+
2450.54(20)			2451.182(6)	$(5)^-$		
	2460(3)	2456(5)			2455.721(14)	$3^+,4,5^+$
2476.44(18)	2480(3)	2482(5)	2477.13(6)	$(5)^-$	2477.21(5)	
					2479.144(122)	$(3\text{-}5)^-$
2484.4(6)			2484.57(6)	$(3)^+$		
2497.8(3)	2497(3)		2499.1 (5)		2494.021(75)	$(2,3)^-$
2510.83(16)	2513(3)		2513.70(6)	$(5)^-$	2513.694(55)	4^-
2517.58(14)			2517.0 (5)		2517.434(11)	$(3,4)^+$
2527.2(3)	2526(3)		2526.582(12)	$(5)^-$	2528.686(47)	$(3\text{-}5)^-$
2539.3(3)		2540(5)	2538.1(5)			
2553.05(15)			2552.7(4)		2551.583(13)	(3-6)
2562.17(12)	2560(3)		2561.57(4)	4^+	2558.637(47)	$3^-,4,5^-$
2569.0(3)	2573(3)		2571.3(4)			
2584.84(16)			2586.2(6)			
2594.4(3)	2592(3)					
2603.7(3)	2609(3)	2602(5)	2601.54(24)			
2626.29(20)						
2637.2(3)	2639(3)					
2646.2(3)						
2656.31(19)	2657(3)	2657(5)	2656.7(6)			
2663.14(19)	2668(3)		2663.234(21)	$(4)^+$	2660.447(7)	$(4,5)^+$
2678.13(17)						
2691.78(18)	2687(3)					
2703.17(12)						
2711.9(4)			2713.2(6)			
2727.89(15)			2727.9(4)			
2739.64(11)			2739.1(4)			
2746.26(16)			2746.6(5)			
2755.81(12)						

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PROUČAVANJE JEZGRE ^{168}Er REAKCIJOM (d, p)

Izvršili smo mjerenja reakcije ^{167}Er(d,p)^{168}Er s deuteronima energije 22 MeV, na kutovima 15°, 30° i 40°. Do energije uzbude od 2.8 MeV našli smo 78 stanja. U radu se prikazuju izmjereni diferencijalni udarni presjeci. Rezultati se uspoređuju s ranijima, posebno onima iz mjerenja reakcije (n, γ).