Scattering of 20.4 MeV polarized protons from even-mass zinc isotopes

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Scattering of 20.4 MeV polarized protons from even-mass zinc isotopes

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Abstract. Measurements are reported on polarized-proton scattering from the even-mass zinc isotopes at 20.4 MeV beam energy. The elastic and first-order inelastic processes are represented well by standard theory. The analysis of the two-phonon multiplets presents difficulties which may indicate a change in the nuclear structure between isotopes or the occurrence of an energy-dependent interfering process.

NUCLEAR REACTIONS ^{64,66,68,70}Zn (polarized p,p') $E \approx 20.4$ MeV; measured $\sigma(\theta)$, $A(\theta)$; deduced optical model parameters, deformation strengths for 2_1^+ and 3_1^- states. DWBA calculations; for ^{64}Zn and ^{68}Zn also CC.

1. Introduction

In this paper we wish to communicate some results on the scattering of 20.4 MeV polarized protons from the even-mass zinc isotopes ^{64,66,68,70}Zn. While this work was in progress, the Stichting voor Fundamenteel Onderzoek der Materie (FOM) announced its decision to end the support that our group had received for many years, because of the necessity to reduce its budget. Concurrently, the Netherlands government imposed a programme of economies on the Netherlands universities. Because of these developments the work of our group had to be terminated before the zinc experiments could be finished. We believe, however, that the results obtained so far may be of interest to others because they contain items not included in other work.

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Earlier publications on proton scattering from the zinc isotopes include papers by Jabbour *et al* [1, 2] at an energy close to ours (22 MeV), but using an unpolarized beam. Tait *et al* [3, 4] used a polarized beam at a somewhat higher energy (30.5 MeV). In their work the ground state and the 2_1^+ and 3_1^- levels were studied for ^{64,66,68}Zn and no polarization data were reported for ^{66}Zn. Calderbank, Lewis and co-workers [5, 6] have done experiments with a polarized beam on all four isotopes. These authors have also studied two-phonon levels, but used an energy of 50 MeV, which is even more different from ours.

Further references to earlier work are listed in Nuclear Data Sheets [7–10]. Parts of our results have been communicated at the Santa Fe, Amsterdam and Florence conferences [12–14].

2. Experimental conditions

The experiments have been carried out using the polarized-beam facility of the Eindhoven AVF cyclotron [15–18]. We used a beam energy of 20.4 MeV. The data have been collected in two sets of experiments. In the first set we used an unanalysed beam and surface-barrier detectors in a similar setup to that used by Wassenaar *et al* [16]. This resulted in an overall energy resolution of about 100 keV FWHM. A sample spectrum showing scattering from ^{68}Zn taken in this configuration is shown in figure 1.

After the upgrading of the polarized-ion source employing a new ionizer [19], we could analyse the beam using a dispersive mode [20] for the beam transport. Together with the use of cooled detectors this resulted in an overall energy spread of 35 keV. This setup is the same as used in the paper by Moonen *et al* [19]. After a suitable normalization to the forward-angle data points of the elastic scattering, the results of the two sets of experiments were in good agreement with one another.

The targets were self-supporting metallic foils of about 1 mg cm^{-2} obtained from AERE, Harwell. They were enriched to over 96% in the relevant isotope, except for

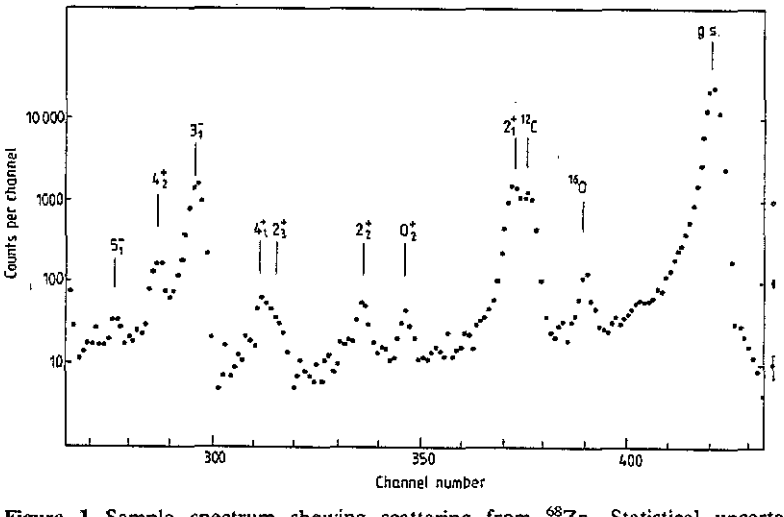

Figure 1. Sample spectrum showing scattering from ^{68}Zn. Statistical uncertainties indicated at the right-hand side.

Table 1. Levels studied in this work (excitation energies in keV).

Level	^{64}Zn	^{66}Zn	^{68}Zn	^{70}Zn
3_1^-	2999	2827	2750	2859
4_1^+	2307	2451	2417	
2_2^+	1799†		1883	
0_2^+	1910†		1656	
2_1^+	992	1039	1077	885
gs	0	0	0	0

† Note reversed order.

the rare isotope ^{70}Zn where the corrections for isotopic impurities were appreciable. Inevitably the targets also contained some contamination of carbon and oxygen. Corrections were made using data obtained by scattering from mylar and polyethylene foils.

The excitation energies of the levels studied in this paper are given in table 1.

3. Analysis, results and discussion

We started our analysis with a fit to the elastic data using the optical-model code OPTIMO [21]. When fitting the data for each nuclide separately, we obtained the best-fit (BF) parameters given in table 2. From these we deduced an average geometry (AG; table 3(*a*)). The data were fitted again using these geometric values,

Table 2. Best-fit optical-model parameters, deduced from calculations with the program OPTIMO [21]. Coulomb radius constant $r_C = 1.25$ fm.

A	V_r	r_r	a_r	W_V	W_D	r_i	a_i	V_{so}	r_{so}	a_{so}
64	52.96	1.17	0.74	1.09	8.24	1.24	0.63	5.49	0.96	0.51
66	52.67	1.18	0.70	0.00	9.10	1.22	0.64	6.21	0.96	0.62
68	53.24	1.17	0.71	0.00	8.33	1.21	0.74	5.98	0.96	0.58
70	53.58	1.17	0.70	0.36	8.75	1.20	0.74	5.90	0.94	0.56

All lengths in fm; all energies in MeV.

Table 3. Average-geometry optical-model parameters.
(*a*) Assumed geometry parameters

r_r	a_r	r_i	a_i	r_{so}	a_{so}	r_C	W_V
1.17	0.72	1.22	0.67	0.96	0.57	1.25	0.00

(*b*) Deduced potential strengths

A	V_r	W_D	V_{so}
64	52.96	8.50	5.63
66	53.33	8.91	5.93
68	53.82	9.34	5.85
70	53.49	10.04	5.35

All lengths in fm; all energies in MeV.

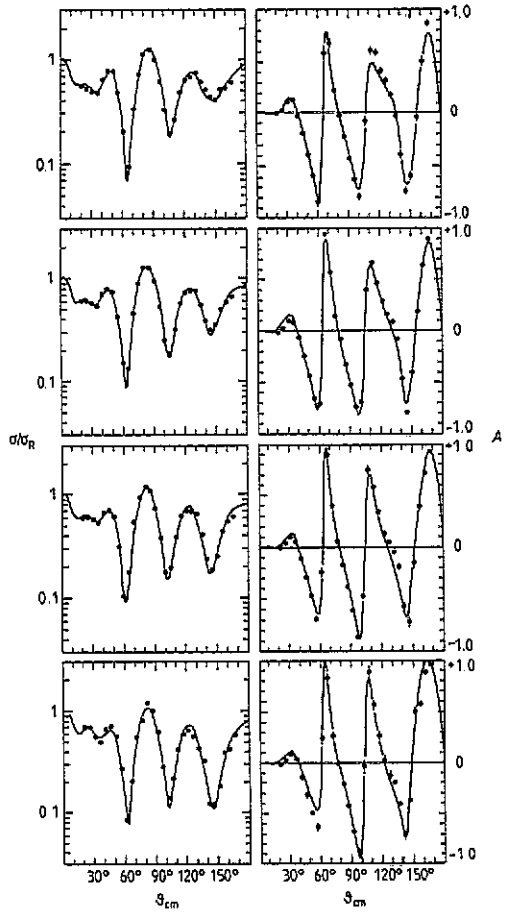

Figure 2. Elastic scattering from the even zinc isotopes. Top to bottom: ^{64}Zn, ^{66}Zn, ^{68}Zn, ^{70}Zn. Curves calculated using average-geometry parameters (see table 3).

at the same time ignoring volume absorption. The potential strengths deduced in this way are given in table 3(*b*). As can be seen in figure 2, the fits to the data are very satisfactory. The curves represent the AG calculations, the results obtained for the BF parameters being hardly discernible from the former ones.

All parameters found have reasonable values. A possible exception is the depth of the real well for ^{70}Zn, which is somewhat less than would be expected from a simple $(N-Z)/A$ dependence. This may be a (small) effect of the $N=40$ sub-shell closure.

Next we performed DWBA calculations for the strongly excited 2_1^+ and 3_1^- states, using a code written by Verhaar *et al* [22]. This code includes full Thomas coupling for the deformed spin–orbit potential, necessary to describe the analysing-power data. As usual, the maxima at forward angles have been used to find the deformation parameters β. The results are given in table 4 together with values found by Jabbour *et al* [1, 2] at a slightly higher energy (22 MeV). We find somewhat lower deformation, especially for the 3_1^- level and for the 2_1^+ level in the heavier isotopes. This may be partly due to differences in the optical-model parameters, where Jabbour *et al* used the Becchetti–Greenlees set [23], which is appropriate for forward angles but which needs some modification in order to describe the complete angular range as covered in our work.

Table 4. Deformation parameters for the 2_1^+ and 3_1^- levels.

Level	*Author*	*Model*†	^{64}Zn	^{66}Zn	^{68}Zn	^{70}Zn
2_1^+	Jabbour‡	DWBA	0.26	0.24	0.22	0.24
		ARM	0.31	0.29	0.24	0.25
		VM1	0.31	0.29	0.28	0.26
		VM2	0.30	0.28	0.26	0.25
	This work	BF	0.26	0.23	0.21	0.20
		AG	0.25	0.23	0.21	0.20
3_1^-	Jabbour‡	DWBA	0.24	0.24	0.22	0.21
		VM	0.25	0.26	0.25	0.22
	This work	BF	0.22	0.22	0.21	0.20
		AG	0.21	0.22	0.21	0.19

† ARM: CC calculations using asymmetric-rotor model.
VM(1, 2): CC calculations using (first-, second-order) vibrator model.
BF: DWBA calculations using vibrator model and best-fit parameters (see table 2).
AG: DWBA calculations using vibrator model and average-geometry parameters (see table 3).
‡ Reference [1] for ^{64}Zn and ^{66}Zn; reference [2] for ^{68}Zn and ^{70}Zn.

When we look at figure 3, where the results for the 2_1^+ level are displayed, we observe an effect that was also found in our work on the nickel isotopes [15, 16], namely that the experimental cross sections fall off more rapidly than the theoretical predictions. An exception is ^{70}Zn, which has a closed neutron sub-shell ($N = 40$). This points to an inadequacy of the collective form factor in this mass region, which

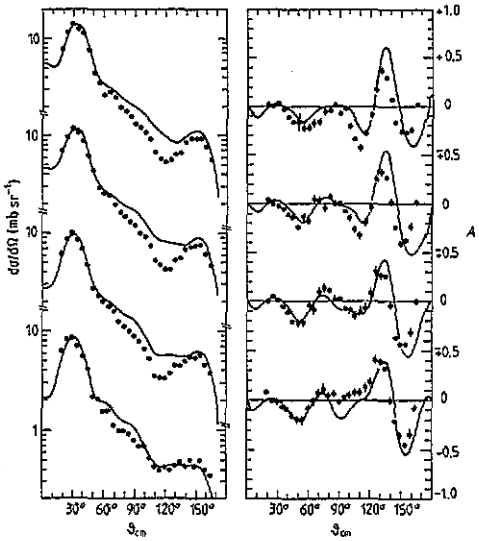

Figure 3. Inelastic scattering leading to the 2_1^+ states. Top to bottom: ^{64}Zn, ^{66}Zn, ^{68}Zn, ^{70}Zn. Curves calculated using DWBA and AG parameters.

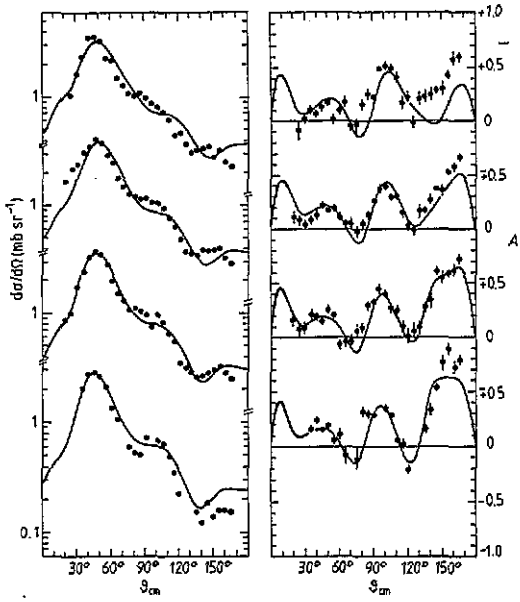

Figure 4. Inelastic scattering leading to the 3_1^- states. Top to bottom: ^{64}Zn, ^{66}Zn, ^{68}Zn, ^{70}Zn. Curves calculated using DWBA and AG parameters.

is not too surprising since only a few neutron orbits are involved so that ample space is left for contributions from the nuclear interior. Contrary to our nickel results, we do not need an enhancement of the spin–orbit coupling to reproduce the analysing power of the zinc isotopes.

The experimental and theoretical results for the 3_1^- states are shown in figure 4. We notice a good agreement for the cross sections as well as for the analysing powers.

For the isotopes ^{64}Zn and ^{68}Zn we also have data at our disposal for the two-phonon multiplet 2_2^+, 0_2^+, 4_1^+. For the isotope ^{66}Zn the analysis had to be left unfinished because of the reasons mentioned in the introduction. For this nuclide only the 4_1^+ data are available. We have analysed these experiments using a second-order coupled-channels approach by means of the code ECIS [24]. We assumed pure two-phonon states, and used the optical-model parameters and quadrupole deformation strength found above. The results are given in figure 5 for ^{64}Zn and in figure 6 for ^{68}Zn.

There is a striking difference between the two nuclei. The excitation of the two-phonon multiplet in ^{68}Zn can be described quite well by these simple cc

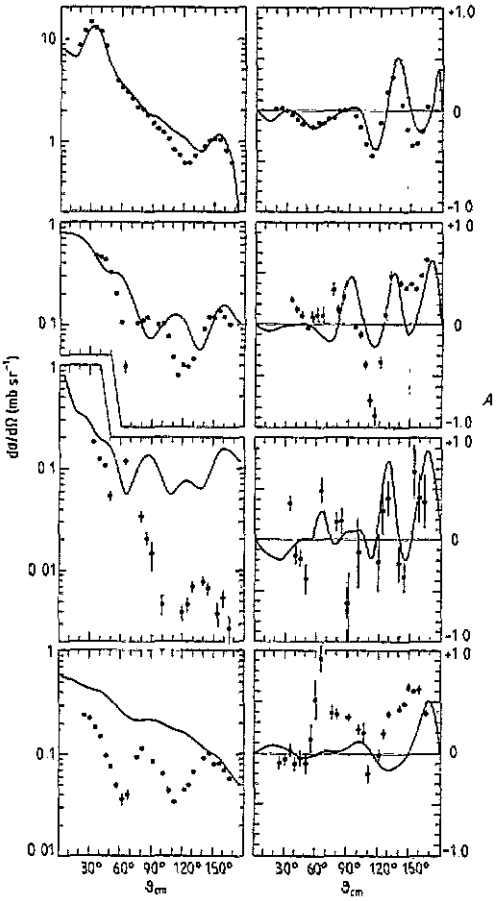

Figure 5. Coupled-channels calculations for ^{64}Zn. Top to bottom: 2_1^+, 2_2^+, 0_2^+ and 4_1^+ levels.

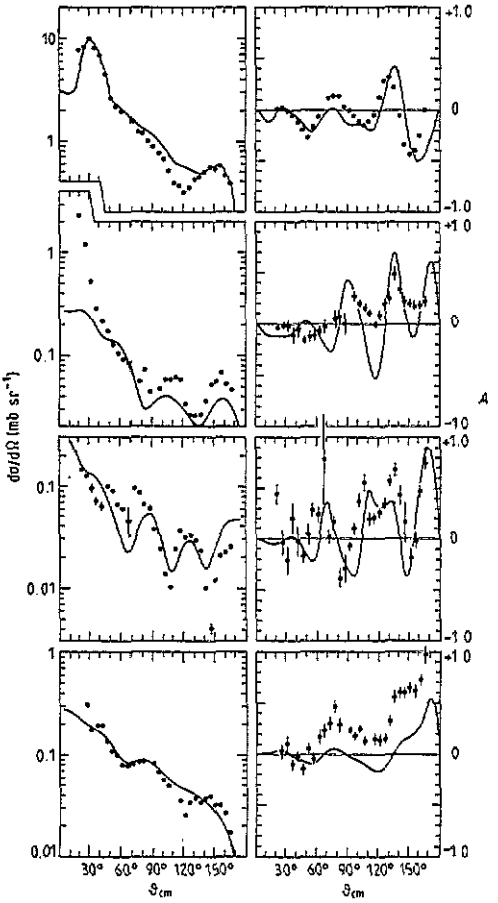

Figure 6. Coupled-channels calculations for ^{68}Zn. Top to bottom: 2_1^+, 2_2^+, 0_2^+ and 4_1^+ levels.

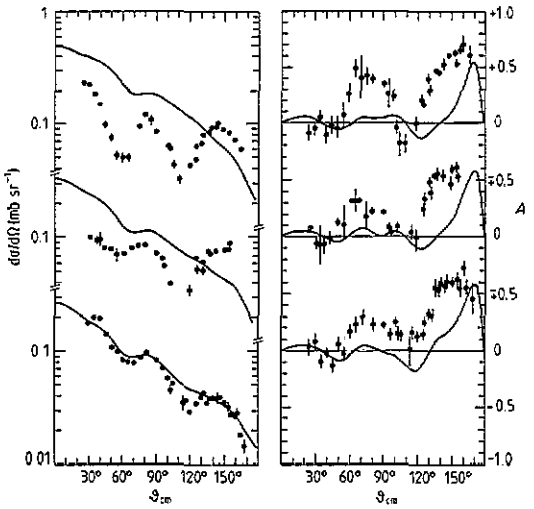

Figure 7. Comparison of the 4_1^+-state results for ^{64}Zn, ^{66}Zn and ^{68}Zn (top to bottom).

calculations, in which there occur no adjustable parameters. The sharp rise at forward angles of the cross section for the 2_2^+ state is probably an artefact due to protons scattered elastically in the target that excite the 2_1^+ state of silicon in the detector material. On the other hand the calculations for ^{64}Zn grossly miss the experimental data for the 0_2^+ and 4_1^+ states. The failure for the 4_1^+ state is especially remarkable since this type of state is usually described quite well [25]. In figure 7 we compare the results for the three 4_1^+ states. We observe that ^{66}Zn is intermediate between ^{64}Zn and ^{68}Zn.

As is shown in our paper [19] the 4_1^+ states in germanium and selenium can be described satisfactorily. The differential cross sections of these states are rather featureless in sharp contrast with the data presented in this paper for ^{64}Zn and ^{66}Zn. Obviously, we need a second process that interferes destructively. We have tried some mixtures of one-phonon and two-phonon coupling in order to obtain the interference pattern in the cross section. All calculations, however, yielded similarly unstructured cross-section curves.

There are some other papers in which a possible difference in nuclear structure for the zinc isotopes is discussed. Matsuki *et al* [26] investigated inelastic scattering of polarized protons at 65 MeV and also found differences in the 4_1^+ data for the zinc isotopes. From the cc analysis these authors deduced a change of the sign of the hexadecapole deformation β_4 when going from ^{64}Zn to ^{70}Zn. This also points to the idea of two reaction paths interfering differently for the lighter and for the heavier zinc isotopes.

The analysis of (e, e') data by Neuhausen [27] gave different results for the form factors of direct transitions to the 2_2^+ states. In ^{64}Zn and ^{66}Zn we see a shape resembling the second derivative of a Saxon–Woods potential, while in ^{68}Zn there is no change of sign. It should be pointed out, however, that these form factors are much broader than the collective form factors, which are located at the nuclear surface. Unfortunately, for the 4_1^+ state only (e, e') results in ^{64}Zn are available. Also, here, there is a form factor showing a broad structure with a change of sign in the nuclear interior.

Passoja *et al* [28] have investigated the character of the two-phonon multiplet in the even zinc isotopes by studying the decay properties of these states. They conclude that the 0^+ state of the multiplet should be identified with the 0_2^+ state in ^{64}Zn, but with the 0_3^+ state in ^{66}Zn and ^{68}Zn. This is in contrast with our findings as presented here, where we see a normal behaviour for the 0_2^+ state in ^{68}Zn but a large discrepancy with theory for the same state in ^{64}Zn.

A comparison of our results with those of Jabbour *et al* [1,2] shows a good agreement for ^{66}Zn and ^{68}Zn. For ^{64}Zn our minimum in the 4_1^+ cross section at 60° hardly shows up in Jabbour's data. Unfortunately, their angular range does not extend far enough to clearly show our second minimum.

In order to understand the origin of the anomalies found in the 4_1^+ states we have performed a number of cc calculations in a 0^+–2_1^+–4_1^+ coupling scheme. The (p, d) cross sections are too small to expect a sizeable contribution from processes such as (p, d)(d, p′). Employing the full flexibility of the code CHUCK [29], it turned out not to be possible to obtain a pronounced pattern, as observed in ^{64}Zn. The two-step (0^+–2_1^+–4_1^+) amplitude and that for the one-step (0^+–4_1^+) transition seem to be nearly perpendicular. Then the only possibility would be a fully imaginary form factor. It is, however, difficult to understand why such a form factor should be employed in ^{64}Zn and not in ^{68}Zn.

A tentative explanation of the effect could be the following. In an analysis of the ^{54}Fe($\vec{p}$, p′) reaction [30] we used an intermediate bound state, viz a resonance [11], to describe the anomalies found in the analysing power. The coupling coefficient is of the Breit–Wigner type and is purely imaginary in the vicinity of the resonance. This would provide us with the necessary 90° rotation of the amplitude. The introduction of such a resonance also explains that in the data of Jabbour, at a slightly different beam energy, the anomalies show up much more weakly.

4. Conclusion

We have measured and analysed the scattering of 20.4 MeV polarized protons from the even zinc isotopes. The elastic and first-order inelastic processes could be described quite well by standard analyses. The excitation of the two-phonon multiplet seems to be very different between isotopes. It is not clear whether this is due to a difference in the nuclear structure or to an energy-dependent interfering resonance process.

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References

[1] Jabbour J, Rosier L H, Ramstein B, Tamisier R and Avignon P 1987 *Nucl. Phys.* A **464** 260
[2] Jabbour J, Rosier L H, Ramstein B, Tamisier R and Avignon P 1987 *Nucl. Phys.* A **464** 287
[3] Tait W H, Burge E J and Edwards V R W 1971 *Nucl. Phys.* A **176** 390
[4] Tait W H and Edwards V R W 1973 *Nucl. Phys.* A **203** 193
[5] Calderbank M, Burge E J, Lewis V E, Smith D A and Ganguly N K 1967 *Nucl. Phys.* A **105** 601
[6] Lewis V E, Calderbank M, Ganguly N K and Fricke M P 1968 *Nucl. Phys.* A **117** 673
[7] Halbert M L 1979 *Nucl. Data Sheets* **28** 179 ($A = 64$)
Singh B 1991 *Nucl. Data Sheets* **62** 603 ($A = 64$, update)
[8] Ward N J and Kearns F 1983 *Nucl. Data Sheets* **39** 1 ($A = 66$)
Bhat M R 1990 *Nucl. Data Sheets* **61** 461 ($A = 66$, update)
[9] Bhat M R 1988 *Nucl. Data Sheets* **55** 1 ($A = 68$)
[10] Bhat M R 1987 *Nucl. Data Sheets* **51** 95 ($A = 70$)
[11] Geramb H V, Sprickmann R and Strobel G L 1973 *Nucl. Phys.* A **199** 545
[12] Van Hall P J, Ruyl J F A G, Krabbenborg J, Moonen W H L and Offermans H 1981 *Polarization Phenomena in Nuclear Physics—1980 (Proc. 5th Int. Symp. (Santa Fe))* ed G G Ohlsen *et al* (New York: AIP) (*AIP Conf. Proc.* **69** 514)
[13] Moonen W H L, Van Hall P J, Klein S S, Nijgh G J, Van Overveld C W A M, Petit R M A L and Poppema O J 1982 *Int. Conf. on Nuclear Structure* (*Amsterdam*) Contributed paper (unpublished)
[14] Moonen W H L, Van Hall P J, Klein S S, Nijgh G J, Van Overveld C W A M, Petit R M A L and Poppema O J 1983 *Proc. Int. Conf. on Nuclear Physics* (*Florence*) vol 1, ed P Blasi and R A Ricci (Bologna: Tipografia Compositori) p 260
[15] Van Hall P J, Melssen J P M G, Wassenaar S D, Poppema O J, Klein S S and Nijgh G J 1977 *Nucl. Phys.* A **291** 63
[16] Wassenaar S D, Van Hall P J, Klein S S, Nijgh G J, Polane J H and Poppema O J 1989 *J. Phys. G: Nucl. Phys.* **15** 181
Van Hall P J, Wassenaar S D, Klein S S, Nijgh G J, Polane J H and Poppema O J 1989 *J Phys. G: Nucl. Phys.* **15** 199, 221
[17] Polane J H, Feix W F, Van Hall P J, Klein S S, Nijgh G J, Poppema O J and Wassenaar S D 1989 *J. Phys. G: Nucl. Phys.* **15** 1715, 1735, 1749
[18] Van der Heide J A 1972 *PhD Thesis* Eindhoven University of Technology
[19] Moonen W H L, Van Hall P J, Klein S S, Nijgh G J, Van Overveld C W A M, Petit R M A L and Poppema O J 1993 *J. Phys. G: Nucl. Part. Phys.* **19** 635
[20] Hagedoorn H L, Broer J W and Schutte F 1970 *Nucl. Instrum. Methods* **86** 253
[21] Vos H 1972 *PhD Thesis* Vrije Universiteit Amsterdam
[22] Verhaar B J, Hermans W C and Oberski J 1972 *Nucl. Phys.* A **195** 379
[23] Becchetti F D Jr and Greenlees G W 1969 *Phys. Rev.* **182** 1190
[24] Raynal J 1982 *Notes on ECIS79* (Saclay: Service de Physique Théorique du CEN)
[25] Tamura T 1965 *Rev. Mod. Phys.* **37** 679
[26] Matsuki S, Ohsawa T, Okamura H, Ogino K, Haga K, Sakamoto N, Matoba M and Komatuzaki T 1986 *J. Phys. Soc. Jpn Suppl.* **55** 608
[27] Neuhausen R 1977 *Nucl. Phys.* A **282** 125
[28] Passoja R, Julin R, Kantele J, Kumpulainen J, Luontama M and Trzaska W 1985 *Nucl. Phys.* A **438** 413
[29] Kunz P D 1969 *Privately circulated report* University of Colorado
[30] Van Hall P J, Wassenaar S D and Melssen J P M G 1981 *Polarization Phenomena in Nuclear Physics—1980 (Proc. 5th Int. Symp. (Santa Fe))* ed G G Ohlsen *et al* (New York: AIP) (*AIP Conf. Proc.* **69** 508)