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ONE-BOSON EXCHANGE POTENTIALS AND THE NUCLEON-ANTINUCLEON SCATTERING

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ABSTRACT

There have been several suggestions recently that low-energy nucleon - antinucleon ($N\bar{N}$) resonances might exist. They were based on the real part of the Bryan-Phillips potential, taking the absorptive part as a small perturbation. We re-examine the $N\bar{N}$ scattering, taking into account the whole Bryan - Phillips potential. We find, as others, that the real part, the one-boson exchange potential (OBEP), produces many resonances. However, the inclusion of the dominant absorptive part eliminates all of them. In addition, we find that the $N\bar{N}$ scattering is sensitive to the unknown, short-range behaviour of this OBEP, therefore we question its predictive reliability. We argue that if experimentally one finds $N\bar{N}$ low-energy resonances, we would be able to learn more about the short-range behaviour of the OBEP.

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1. INTRODUCTION

Recently Shapiro and co-workers [1] and later Dover [2] have suggested the possibility of many nucleon-antinucleon ($N\bar{N}$) resonances and bound states. Their calculations were based on the Bryan-Phillips potential [3], but they essentially neglected the absorptive part of the Bryan-Philipps potential. We have therefore re-examined the question of the existence of the $N\bar{N}$ resonances taking into account the whole complex Bryan-Phillips potential.

The nucleon-nucleon scattering data are explained reasonably well by the semi-phenomenological one-boson exchange potential (OBEP) [4)-6)]. Taken at face value, this potential will have predictive power for the low-energy nucleon-antinucleon ($N\bar{N}$) system, since the OBEP for NN and $N\bar{N}$ are connected by G conjugation, see e.g., Ref. 3), provided one understands the $N\bar{N}$ annihilation. One disturbing feature of testing the OBEP in $N\bar{N}$ scattering is that at low energy the annihilation process is the dominant one [$\sigma_{tot}:\sigma_{ann}:\sigma_{el} \simeq 3:2:1$, see e.g., Ref. 7)]. Several OBEP exist, see Erkelenz Ref. 4), but we will concentrate on two discussed in connection with $N\bar{N}$ scattering: the static OBEP [5] and the non-static OBEP [6]. Only the latter can be used to reproduce NN S wave phase shifts.

To describe the $N\bar{N}$ scattering data, Bryan and Phillips [3] used the non-static OBEP plus an absorptive, scalar, isoscalar potential of range 0.2 fm to parametrize the annihilation [a potential describing the annihilation's influence of $N\bar{N}$ scattering should be of short range according to arguments presented by Martin [8]]. They [3] fitted σ_{tot}, σ_{el}, σ_{ex} ($ex = p\bar{p} \to n\bar{n}$), and $d\sigma/d\Omega$ at low energy quite well. One of their conclusions was that the $p\bar{p}$ elastic scattering is dominated by the absorptive potential. The reason is that although the absorptive potential is of short range, it is so strong that it is felt up to about 1 Fermi.

Shapiro et al. [1] and Dover [2] have investigated the consequences the static OBEP [5] will have in the $N\bar{N}$ system. They find that the OBEP for $N\bar{N}$ exhibits many bound states and low-energy resonances essentially because the ω exchange is attractive in $N\bar{N}$. However, when they [1),2)] calculate the positions of the $N\bar{N}$ bound states and resonances, they treat the $N\bar{N}$ absorptive potential of Ref. 3) as a small perturbation to the OBEP, affecting only the width of the resonances and giving a width to the $N\bar{N}$ bound state energies. As we will see later, such a treatment is inconsistent with the calculations of Bryan and Phillips.

The experimental situation is not clear. So far there is no evidence for the existence of $N\bar{N}$ bound states [9] as predicted by Refs. 1) and 2). In $p\bar{p}$ elastic scattering, a rather small bump in the cross-section has been seen by two groups [10),11)]. This might indicate a $p\bar{p}$ resonance. However, the striking fact is that no more resonances have been seen, given the predictions of Refs. 1) and 2).

In light of this experimental situation and the conclusion by Bryan and Phillips [3] that the absorption dominates the $p\bar{p}$ elastic scattering, we like to re-examine the question of possible existence of the low-energy $N\bar{N}$ resonances predicted by the real OBEP [1),2)] using the full Bryan-Phillips potential [3]. Another point which merits a re-examination of the $p\bar{p}$ resonances, is the use of the static OBEP in the $N\bar{N}$ system [1),2)]. The S waves are the only NN phases that probe the shorter ranges of the OBEP, and we know that the static OBEP cannot be used to fit S wave NN phase shifts [5),6)]. Since the postulated resonances in the $N\bar{N}$ are created by the shorter ranges of the OBEP, we question the use of the static OBEP for the $N\bar{N}$ system. To predict $N\bar{N}$ resonances we demand that the OBEP gives reasonable S wave NN phase shifts. Also for this reason we will concentrate upon the Bryan-Phillips potential which is based on the non-static OBEP.

2. THE NUCLEON-ANTINUCLEON POTENTIAL

We will in this Section present the real non-static OBEP [6] and discuss the sensitivity its cut-off parameter has on the NN and $N\bar{N}$ scattering. As is well known, the nucleon-nucleon (or antinucleon) OBEP is based upon t channel exchanges of the mesons π, η, ω and ρ. In addition, one has added two scalar mesons σ_0 and σ_1 with isospin $T=0$ and $T=1$, respectively. The σ_0, together with ρ, are supposed to simulate part of the uncorrelated and correlated 2π exchange. The 2π exchange, subtracted from the first iteration of the one-pion exchange term in OBEP, shows for $T=0$ a broad spectrum around 600 MeV, see Ref. 12). We will present here the OBEP in the form given by Bryan and Phillips [3].

The scalar, isoscalar meson exchange gives the NN potential as

$$V(r) = -g^2\mu\left[\left(1-\frac{\mu^2}{4M^2}\right)F(\mu r) + \frac{\mu^2}{2M^2}G(\mu r)\,\underset{\sim}{L}\cdot\underset{\sim}{S}\right] \qquad (1)$$

where μ and M are the meson and nucleon masses, $\underline{L}$ and $\underline{S}=\frac{1}{2}(\underline{\sigma}_1+\underline{\sigma}_2)$ are the orbital angular moments and total spin, and

$$F(x) = \exp(-x)/x$$
$$G(x) = -\frac{1}{x}\frac{\partial}{\partial x}F(x) \tag{2}$$

For pseudoscalar, isoscalar meson exchange, we have

$$V(r) = g^2 \frac{\mu^3}{12M^2}\left[F(\mu r)\,\underline{\sigma}_1\cdot\underline{\sigma}_2 + H(\mu r)\,S_{12}\right] \tag{3}$$

where

$$H(x) = (1 + 3/x + 3/x^2)F(x) \tag{4}$$

$$S_{12} = 3(\underline{\sigma}_1\cdot\underline{r})(\underline{\sigma}_2\cdot\underline{r})/r^2 - \underline{\sigma}_1\cdot\underline{\sigma}_2 \tag{5}$$

For vector, isoscalar meson exchange we have

$$V(r) = g^2\mu\Big[R_1F(\mu r) + R_2\big(2F(\mu r)(\underline{\sigma}_1\cdot\underline{\sigma}_2) - H(\mu r)S_{12}\big) - R_3\,G(\mu r)\,\underline{L}\cdot\underline{S}\Big] \tag{6}$$

where

$$R_1 = 1 + \frac{\mu^2}{2M^2}(1 + f/g)$$
$$R_2 = \frac{\mu^2}{12M^2}(1 + f/g)^2 \tag{7}$$
$$R_3 = \frac{\mu^2}{2M^2}(3 + 4f/g)$$

For the scalar and vector parts of the OBEP [Eqs. (1) and (6)] one also has a velocity-dependent term of the form

$$\frac{1}{2M^2}\left[\nabla^2\,U(r) + U(r)\,\nabla^2\right] \tag{8}$$

where

$$U(r) = -g^2 \mu \, F(\mu r) \tag{9}$$

with g and μ the respective scalar and vector meson coupling constants and masses. The parameters for each exchange are taken from Ref. 3) and are given in the Table. The Bryan-Phillips coupling constants equal those of Bryan-Scott times a reduction factor, see below.

From each exchange potential, Eqs. (1), (3) and (6), one subtracts a cut-off exchange of mass Λ, but with the same coupling constant as the respective meson, see Ref. 6). This one-parameter Λ prevents the OBEP to have a bad behaviour as $r \to 0$ and Bryan and Scott were therefore able to find NN S wave phase shifts [6].

The isovector meson exchanges are added by including the isospin factor $\underline{\tau}_1 \cdot \underline{\tau}_2$.

Using this potential, Bryan and Phillips say that the fit to the NN phase shifts are reasonably good even by a variation in Λ of 50% (from $\Lambda = 1500$ MeV to $\Lambda = 1000$ MeV). We find that, e.g., the NN $^1S_0$ phase shift is too small at low energy with $\Lambda = 1000$ MeV using the OBEP of Ref. 6). Bryan and Phillips [3], with the coupling constants in the Table, choose $\Lambda = 1000$ MeV, but the coupling constants are slightly different from those of Ref. 6). They are related by

$$g_{BP}^2 = g_{BS}^2 \frac{\Lambda^2}{\Lambda^2 - \mu^2} \tag{10}$$

with $\Lambda = 1500$ MeV. With the coupling constants of Bryan and Phillips, we find several NN phase shifts to change from those of Ref. 6) with $\Lambda = 1500$ MeV, but again the largest difference is seen in S waves. But common for all these choices is that Λ must be changed by 20% or more to produce significant changes in the NN phase shifts.

However, when we use this real OBEP to predict the $N\bar{N}$ behaviour, this turns out to be very sensitive to <u>small</u> changes in the cut-off parameter Λ. With the real non-static OBEP, as given by Bryan and Phillips, we find many $N\bar{N}$ resonances at low energy very much like what Shapiro and co-workers find with the static OBEP [details like which $N\bar{N}$ angular momentum channels exhibit resonances and at what energy they occur differs from Ref. 1)]. But, a change in Λ of 2%, e.g., from 1000 MeV to 980 MeV change the $N\bar{N}$ phase shifts very much, as opposed to a possible 50% change for NN. With a different Λ we still find resonances, but not necessarily in the same partial wave channels. In addition the position of the resonances can be shifted drastically up or down in energy, depending upon the partial wave and the change in Λ. One should bear in mind that it is the ω exchange, which by construction provides the repulsive core in the NN potential, which produce the $N\bar{N}$ resonances. Analogously, a deep square well can also produce low-energy resonances. By varing Λ we alter the depth of the ω exchange well in the $N\bar{N}$ potential. Therefore, even at this preliminary stage, before considering the $N\bar{N}$ annihilation channel and fit to the $N\bar{N}$ data, one has to question the predictive power of the OBEP in its present form.

Before we present our results, we will for completeness, give the Bryan-Phillips parametrization of the annihilation channel's contribution to $N\bar{N}$ scattering. They added to the real OBEP an imaginary Wood-Saxon potential iW which is independent of spin and isospin

$$W(r) = -W_0 / [1 + \exp(br)] \tag{11}$$

where $b = 5\ \text{fm}^{-1}$. We will take W_0 as a free parameter, bearing in mind that W_0 equal to 8.3 GeV gives the best fit to $N\bar{N}$ data [7),13)] according to Bryan and Phillips.

3. RESULTS AND DISCUSSION

We solve the coupled channel Schrödinger equation with the complex potential presented in Section 2, using the standard Noumerov method also used by Bryan and Scott, see Refs. 6) and 14). In the numerical solution for the $N\bar{N}$ isospin triplet phases we encountered a singularity from the velocity dependent part of the $N\bar{N}$ potential if one uses the Bryan-Phillips potential. The scattered wave functions' second derivative has a pole for small positive radius, but changing Λ to 980 MeV this pole occurred at negative r and had no practical consequences. This is the reason we choose to work with $\Lambda = 980$ MeV. Because of the phenomenological nature of the OBEP, we do not think this is a very important point.

As mentioned in the previous Section, we find many resonances for $W_0 = 0.0$ GeV and $\Lambda = 980$ MeV. In Fig. 1 we show what effect a change in Λ has on the $^{11}P_4$ and $^{11}D_2$ partial waves keeping W_0 fixed at zero. Clearly, the OBEP in its present form will produce resonances in $N\bar{N}$ system ($W_0 = 0.0$ GeV), but it cannot predict where or in which partial wave these will occur.

In order to reproduce, e.g., the $p\bar{p}$ elastic cross-section, we have to include a strong absorptive potential. In Figs. 2 and 3 we show what happens to the $^{33}P_1$ and $^{33}D_2$ $N\bar{N}$ amplitudes as we turn on the imaginary potential (W_o is a parameter and $\Lambda = 980$ MeV). For $W_o = 8.3$ GeV one cannot possibly speak of a resonance behaviour in these amplitudes any more. Similar patterns, as in Figs. 2 and 3 with increasing W_o, occur for the other partial waves. To reproduce the experimental $p\bar{p}$ elastic cross-section with the Bryan-Phillips $N\bar{N}$ potential, one needs such a large W_o that this potential does not produce any bumps in the cross-sections as a function of energy. With $W_o = 8.3$ GeV we reproduce the experimental total, elastic and charge exchange $(p\bar{p} \to n\bar{n})$ cross-sections at low energies as do Bryan and Phillips [3),13)]. This potential will not produce the bumps in σ_{el} as observed by Refs. 10) and 11). This is obvious by looking at the Argand plots for the $N\bar{N}$ partial waves given in Fig. 4.

We also find that the OBEP gives an important contribution to the cross-sections. The reason is that the OBEP is attractive for $N\bar{N}$. It will therefore bring scattered waves into the absorption region and strongly increase the absorption [3)]. Because the OBEP plays a major part in giving the total and elastic cross-sections, a small change in Λ, i.e., a change in the attractiveness of the OBEP, can be detected.

4. CONCLUSIONS

We have shown that the Bryan-Phillips potential [3)] does not produce any bumps in the elastic or total cross-sections. It does reproduce reasonably well σ_{tot}, σ_{el}, $\sigma_{ex}(p\bar{p} \to n\bar{n})$ and $d\sigma/d\Omega$ for $p\bar{p}$ scattering at low energies [3),13)]. The reason it does not produce any bumps is that the absorptive part of the potential is extremely strong.

Also we find, as do others [1),2)], that the real OBEP does produce $N\bar{N}$ resonances. If it would be possible to construct an absorptive potential which is weak in some angular momentum channels, then a few of the resonanaces might show up as bumps in the $p\bar{p}$ cross-sections [see here also Ref. 15)]. The absorptive part of the Bryan-Phillips potential, an isoscalar, scalar potential of Wood-Saxon type, removes all these resonances. This absorptive potential is a phenomenological guess; the proper form is not known up to now.

Another point we have made is that the OBEP is poorly known at short distances. We doubt if it has a detailed predictive power in its present form. The OBEP parameters are fixed to give, e.g., a repulsive core for NN. This core is given by the ω exchange. But if other exchanges, e.g.,

3π or 4π exchanges (analogous to the 2π exchange simulated by ρ and σ_0), one can reduce the ω coupling constant. Since in $N\bar{N}$ it is the strongly attractive ω exchange which produces the postulated $N\bar{N}$ resonances, a smaller ω coupling constant might not be able to support any $N\bar{N}$ resonances.

In view of this short-range OBEP uncertainty, we would like to turn the problem around. If experimentally one finds low-energy $N\bar{N}$ resonances and one understands the low-energy $N\bar{N}$ annihilation reasonably well, then the $N\bar{N}$ data will give information on the short-range NN forces. In short, we propose to use $N\bar{N}$ low-energy scattering to study the short-range behaviour of the OBEP.

ACKNOWLEDGEMENTS

We wish to thank T.E.O. Ericson for suggesting this work and for several useful discussions.

Table

Parameters for the Bryan - Phillips $N\bar{N}$ OBEP
These coupling constants include the reduced mass factors of Bryan-Scott's OBEP [2].

Meson	Mass (MeV)	g^2	f/g
π	138.7	12.66	
η	548.7	3.00	
ρ	763.0	2.44	1.13
ω	782.8	23.70	0.00
σ_1	600.0	1.97	
σ_0	550.0	9.46	

* * *

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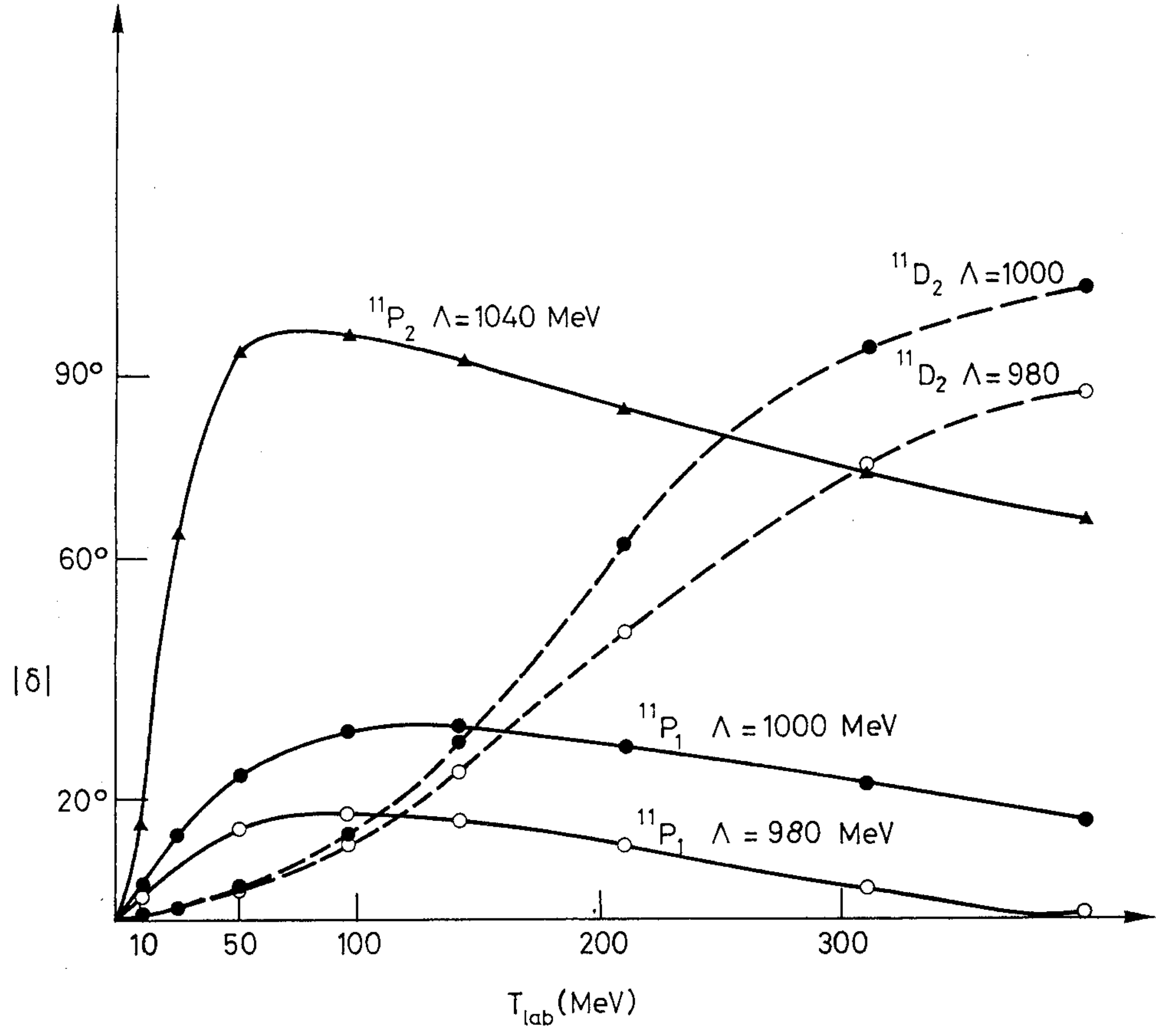
FIGURE CAPTIONS

Fig. 1 : Nucleon-antinucleon phase shifts as a function of the lab. kinetic energy with the OBEP's cut-off Λ as a parameter. The absorptive potential is zero here.

Fig. 2 : Argand plot for the $N\bar{N}$ $^{33}P_1$ amplitude for different values of the strength of the absorptive potentials W_o with the OBEP cut-off $\Lambda = 980$ MeV. The numbers in the diagram are kinetic lab. energy in MeV. The full line is for $W_o = 0.0$ GeV, the dashed line for $W_o = 0.3$ GeV, the long dashed line with small circles (—o—o—) is for $W_o = 2.0$ GeV, and the dashed dotted line for $W_o = 8.3$ GeV.

Fig. 3 : Argand plot for the $N\bar{N}$ $^{33}D_2$ amplitude, similar to Fig. 2. The full line is for $W_o = 0.0$ GeV, the dashed line for $W_o = 1.0$ GeV, the dashed line with small circles $W_o = 2.0$ GeV, and the dotted-dashed line for $W_o = 8.3$ GeV.

Fig. 4 : Argand plots for the $N\bar{N}$ partial waves (S, P, D and F) with the complete Bryan-Phillips potential. The whole lines are isospin singlet, and the dashed lines isospin triplet states. The numbers on the curves are lab. kinetic energies in MeV. The off-diagonal amplitudes are not plotted. Their contributions are small due to small mixing angles.



$^{11}P_2$ Λ=1040 MeV
$^{11}D_2$ Λ=1000
$^{11}D_2$ Λ=980
$^{11}P_1$ Λ=1000 MeV
$^{11}P_1$ Λ = 980 MeV
90°
60°
20°
|δ|
10
50
100
200
300
T_{lab}(MeV)

Fig. 1

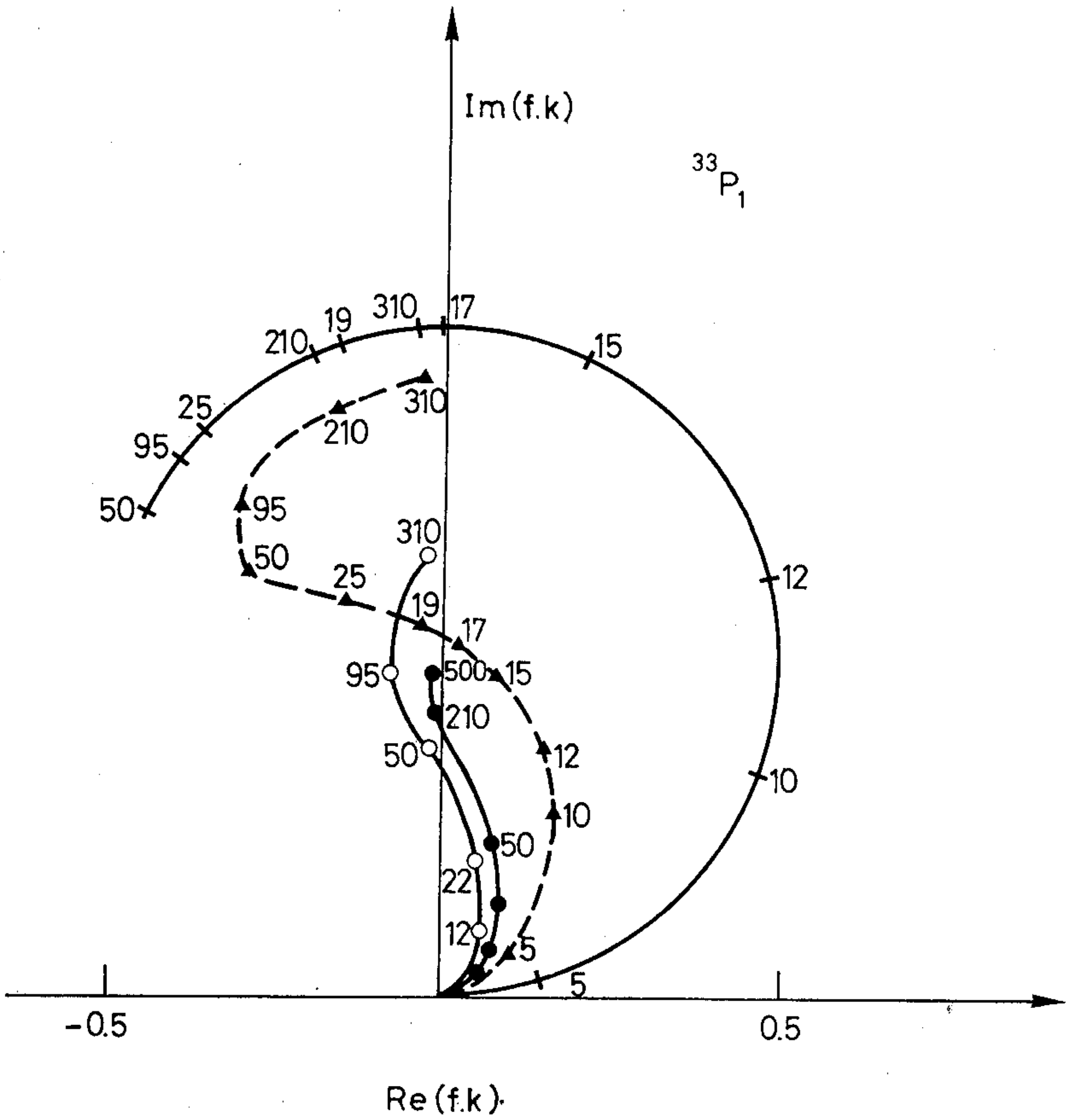


Fig. 2

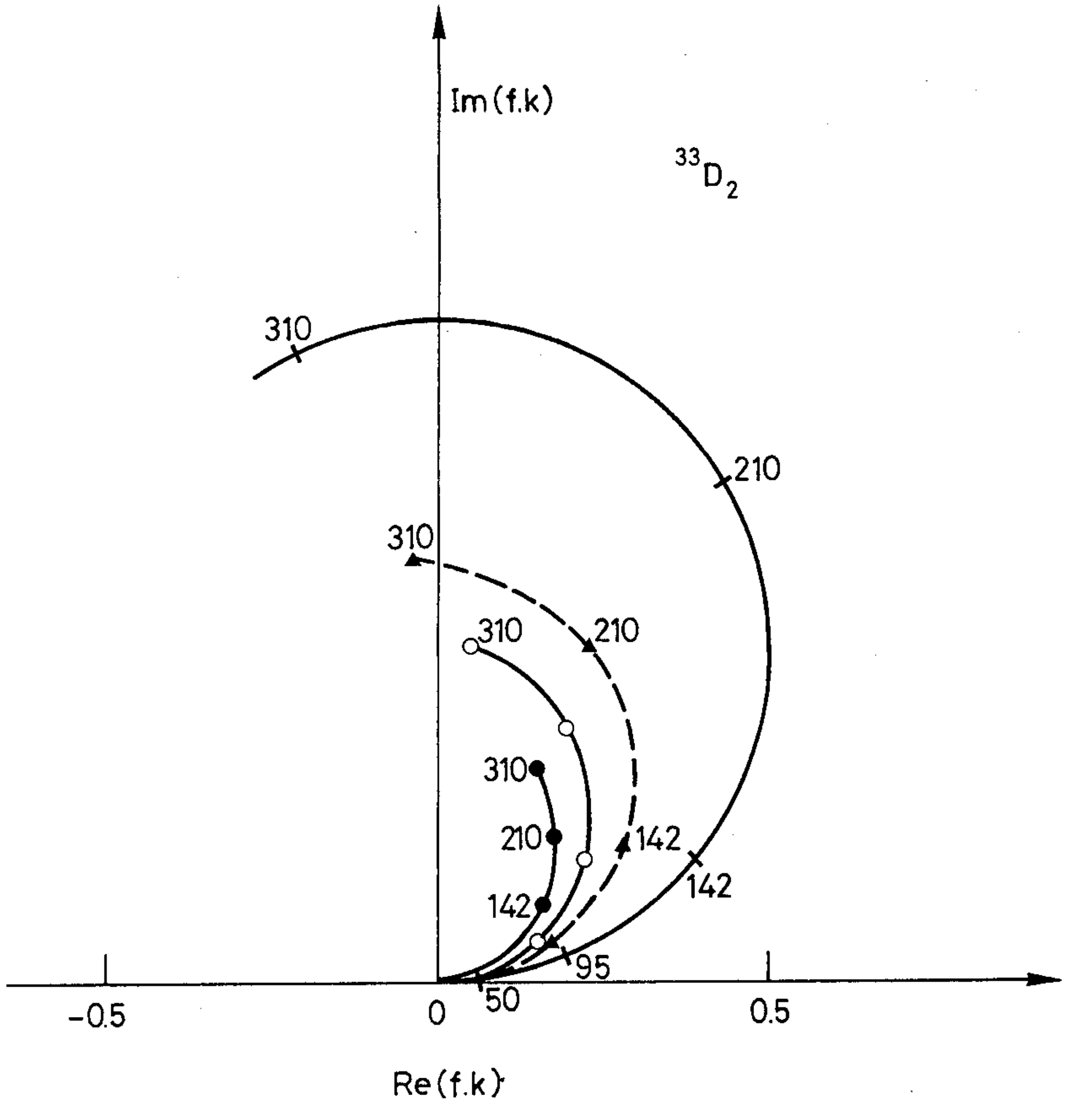

Im(f.k)
$^{33}D_2$
310
210
310
310
210
310
210
142
142
142
95
50
-0.5
0
0.5
Re(f.k)

Fig. 3

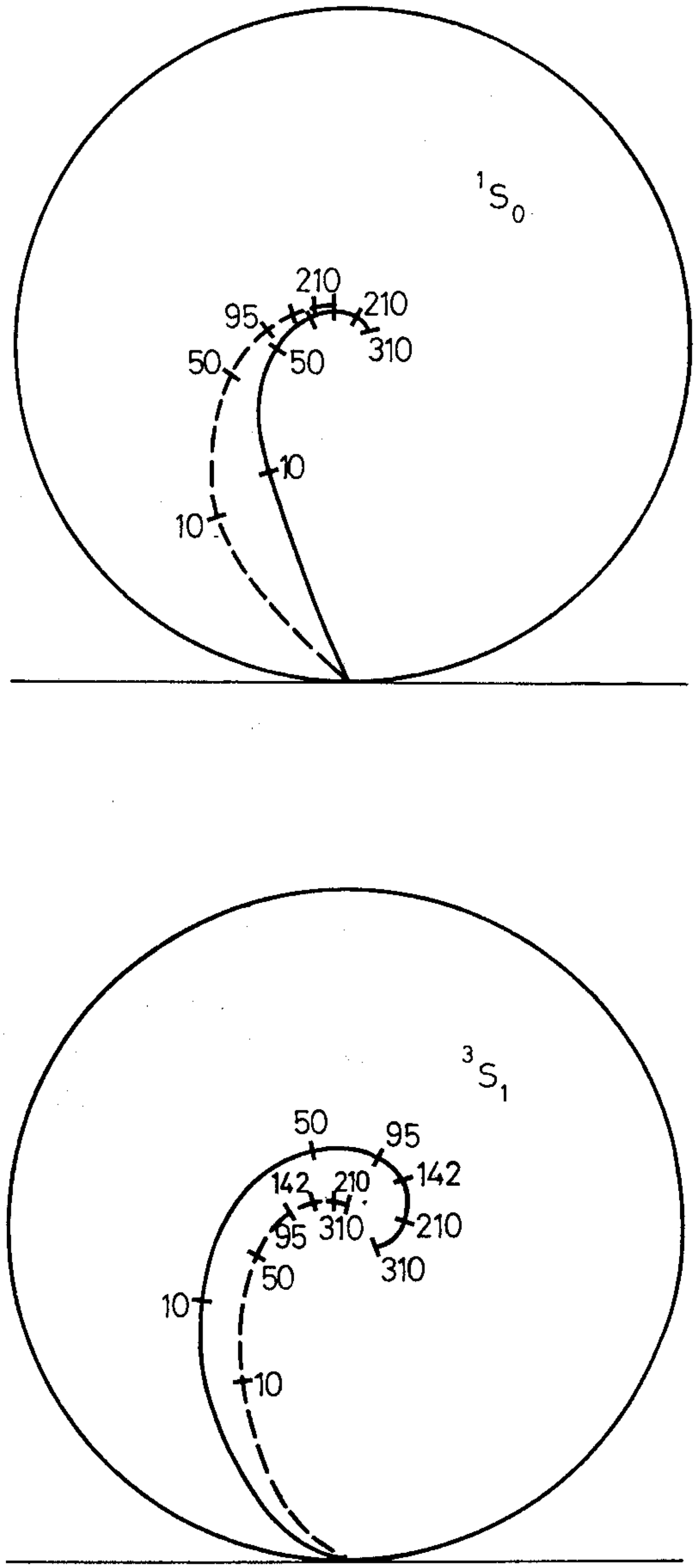
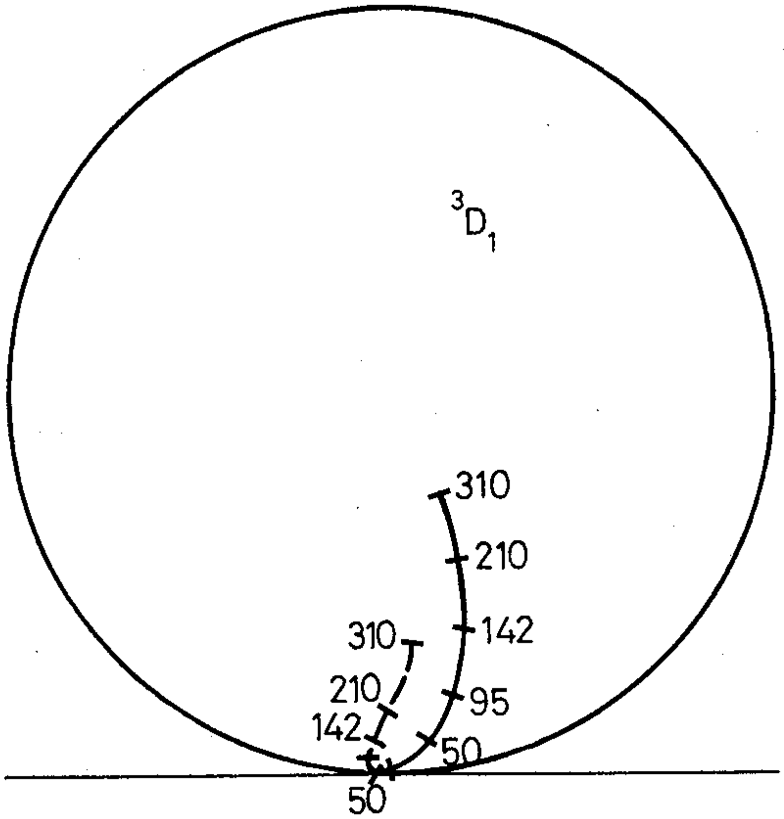
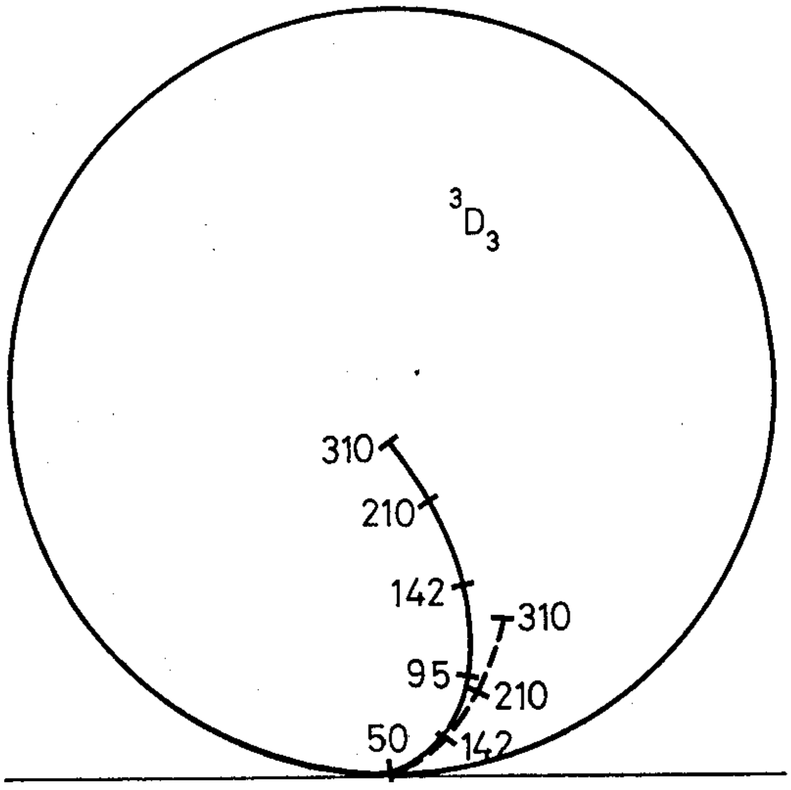

$^1S_0$
210
210
95
50
50
310
10
10
$^3S_1$
50
95
142
210
142
210
95
310
50
310
10
10

Fig. 4



$^3D_1$
310
210
142
95
50
310
210
142
50



$^3D_3$
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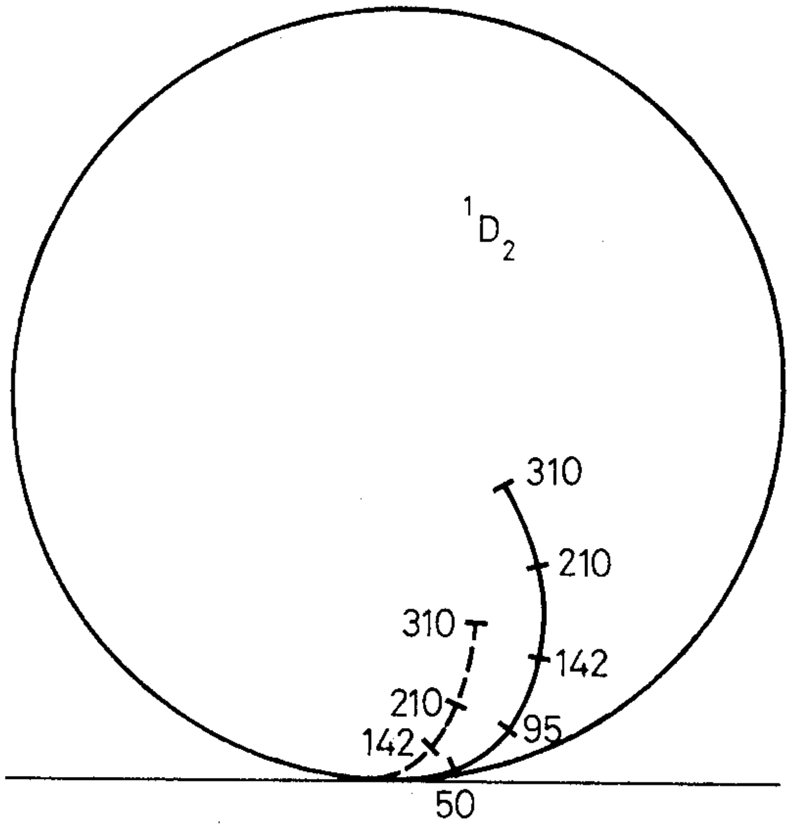
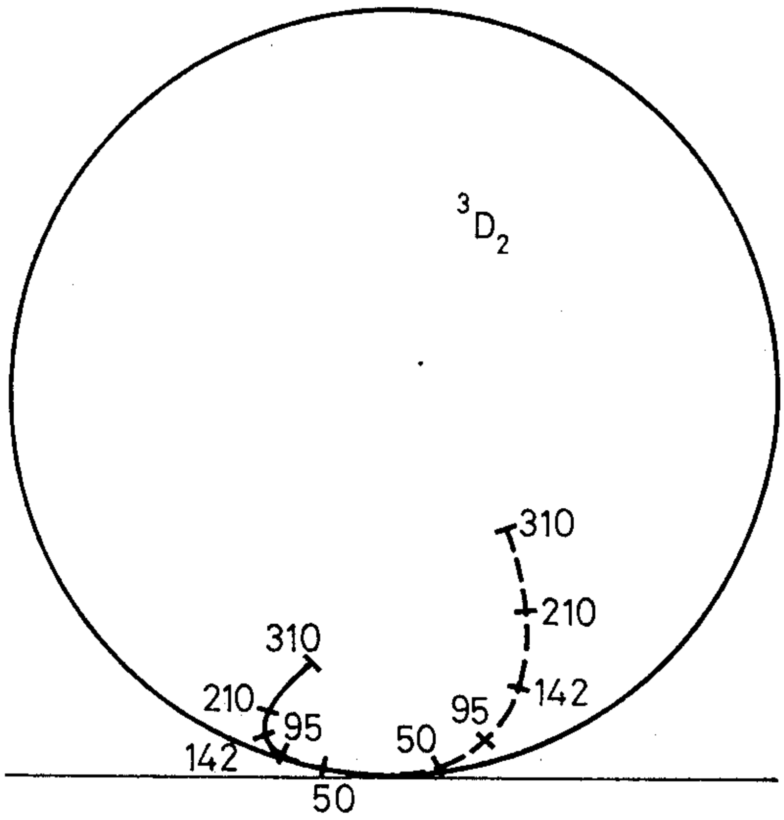
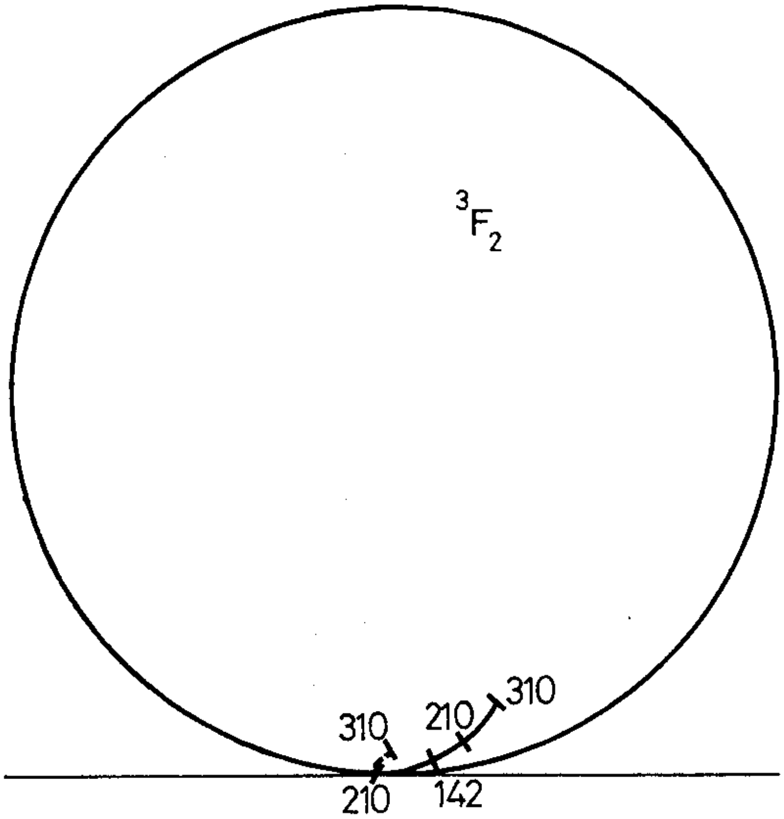
210
142
95
50
310
210
142



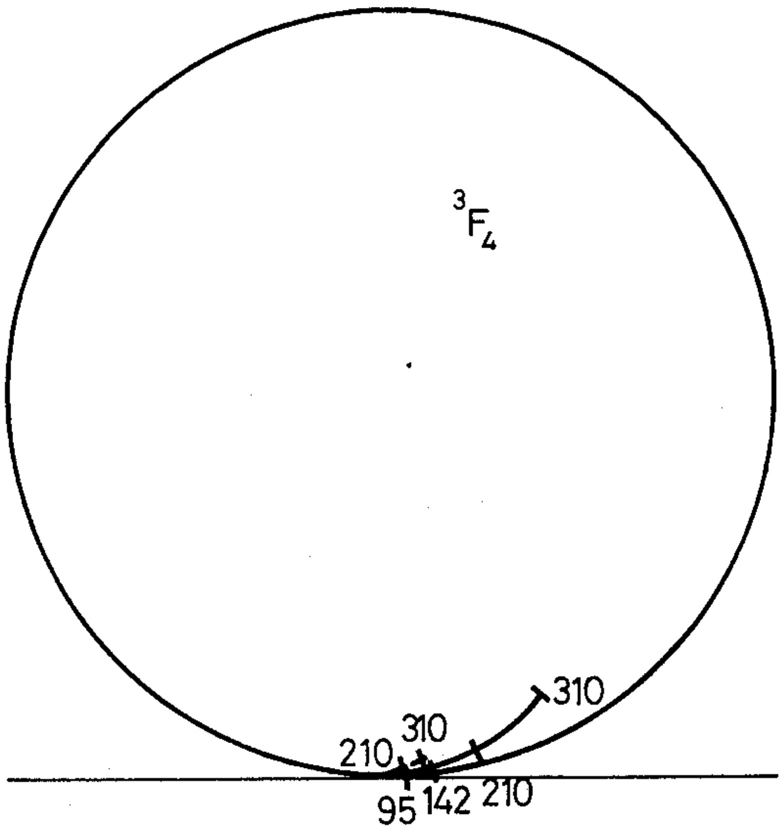
$^1D_2$
310
210
142
95
310
210
142
50



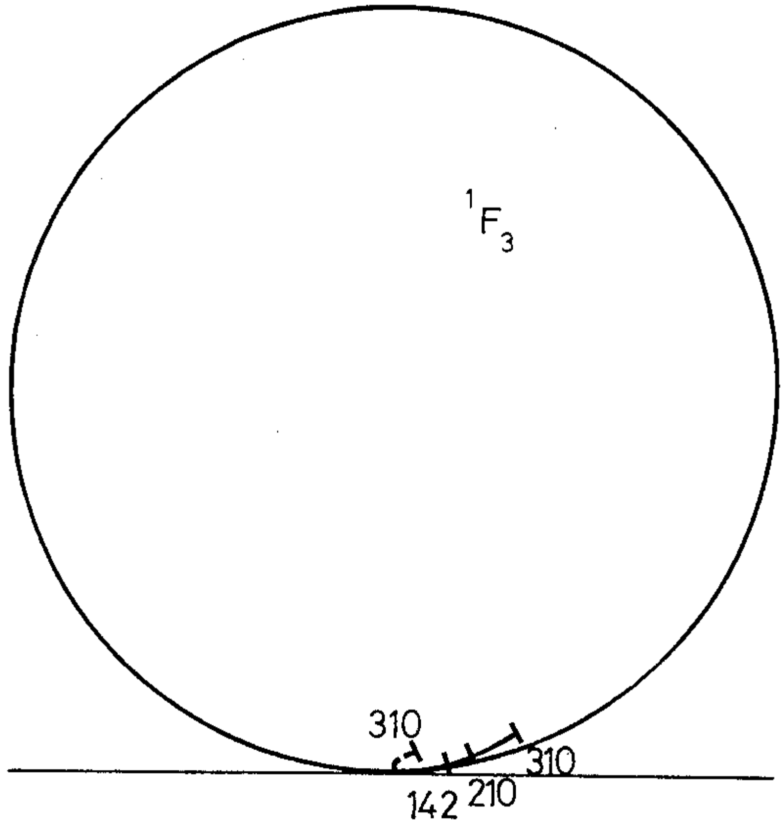
$^3D_2$
310
210
142
95
50
310
210
95
142
50



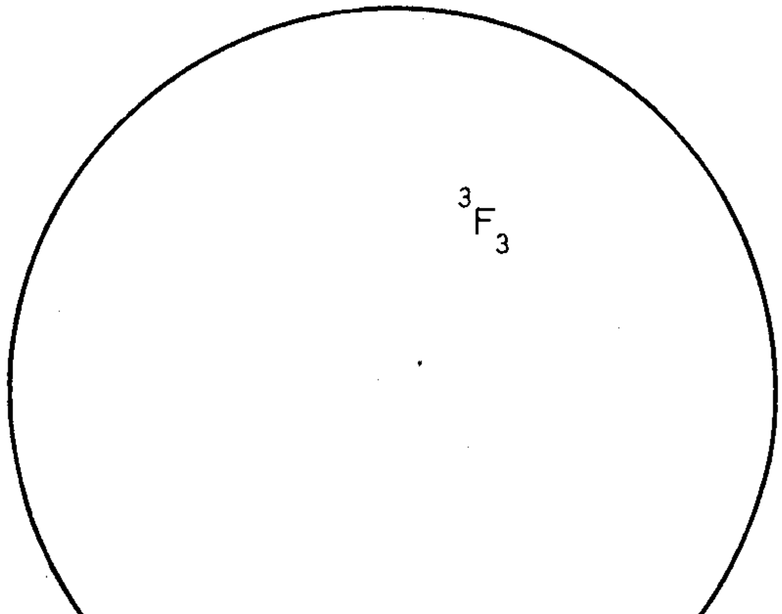
$^3F_2$
310
210
310
210
142



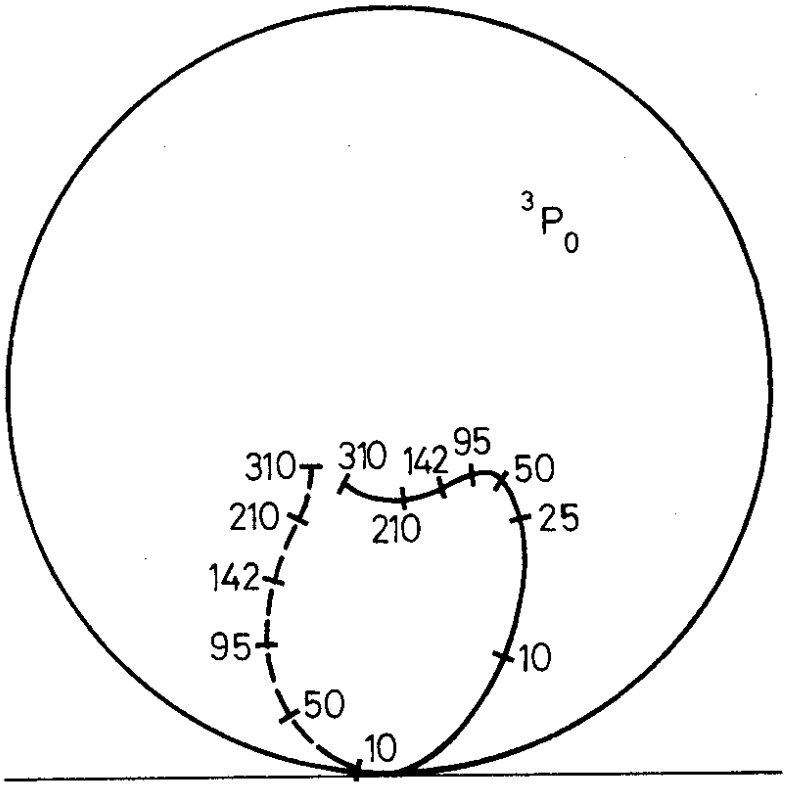
$^3F_4$
310
310
210
95
142
210



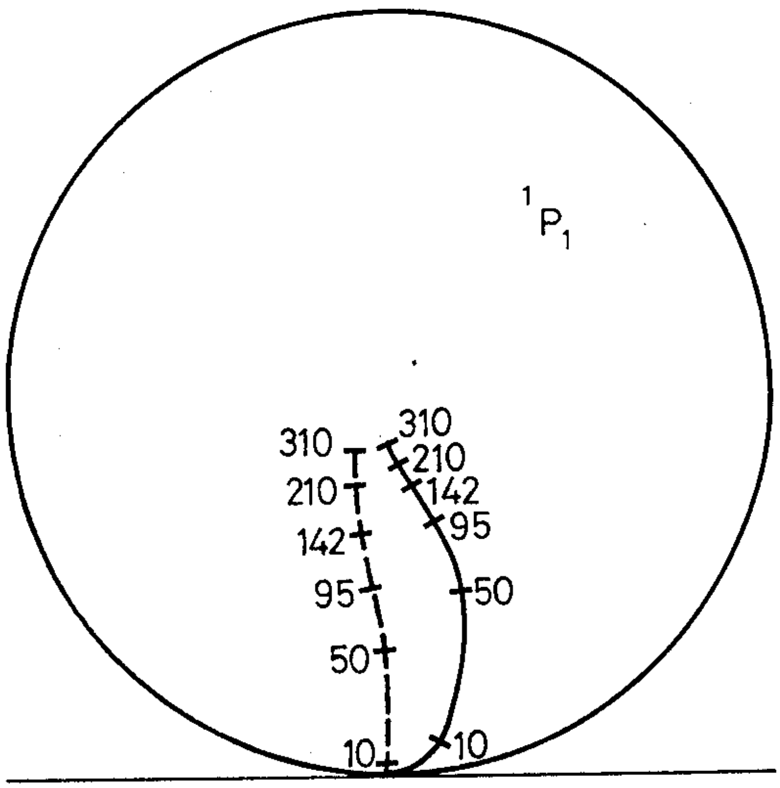
$^1F_3$
310
310
142
210



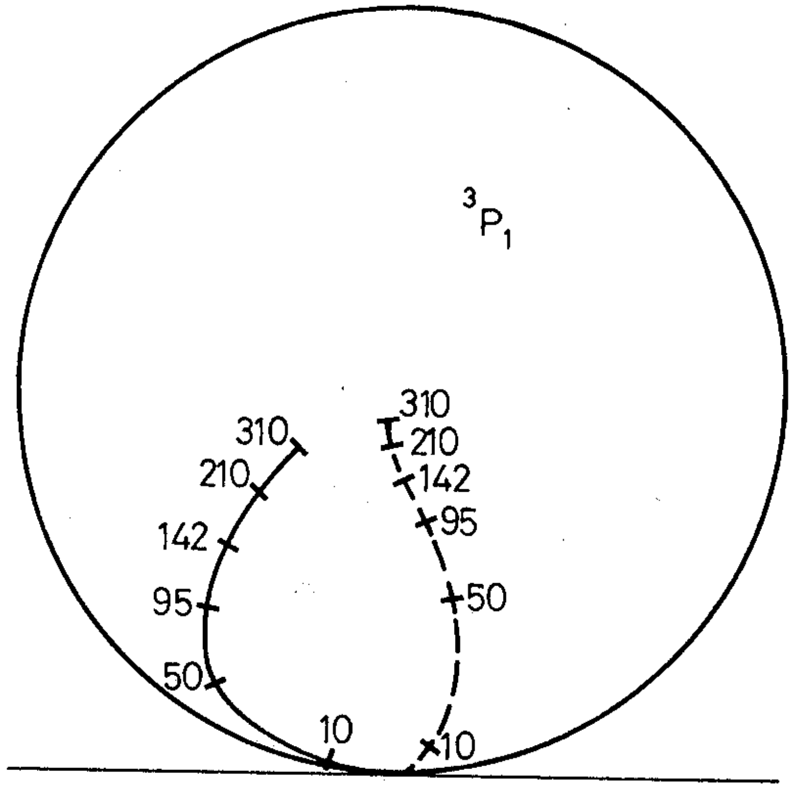
$^3F_3$
310
142
310
210
95
210



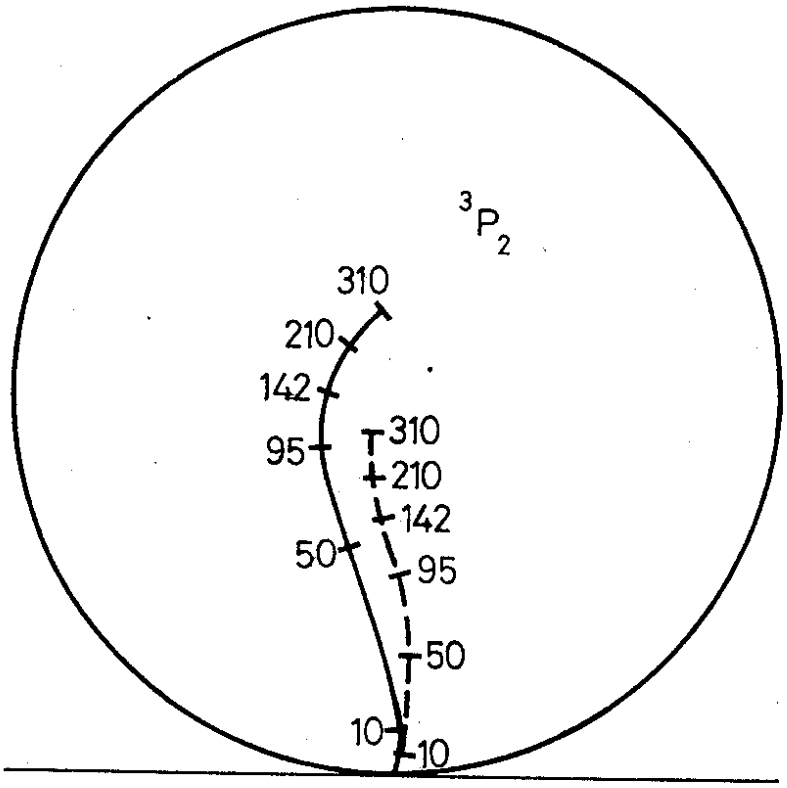
$^3P_0$
310
210
142
95
50
10
310
142
95
50
210
25
10



$^1P_1$
310
210
142
95
50
10
310
210
142
95
50
10



$^3P_1$
310
210
142
95
50
10
310
210
142
95
50
10



$^3P_2$
310
210
142
95
50
10
310
210
142
95
50
10