The Reaction $p+p\rightarrow\pi^++d$ with Polarized Protons*†

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Marshak and Messiah[1] have pointed out that if mesons are present in both S and P states in the reaction $p+p\rightarrow\pi^++d$, then it is possible to obtain, through interference, a large azimuthal asymmetry in the angular distribution, provided that a polarized proton beam (or target) is used. If a substantial amount of such an asymmetry is indeed observed, then the relative amounts and phases of S and P waves can be estimated. De Carvalho *et al.*[2] looked for an asymmetry in meson production in the course of examining possible asymmetric background in the scattering from hydrogen of 439-Mev polarized protons. They obtained a null result of asym $=-0.07\pm0.085$.

Following the Rochester technique,[3] Chamberlain and co-workers[4] have obtained an external beam of 315-Mev protons from the Berkeley cyclotron having a polarization[5] estimated to be $|P|=|2\langle S_y\rangle|=0.73$. With this beam, we have made measurements of the left-right asymmetry of meson production in the plane perpendicular to the proton polarization, using coincidence detection of the meson and deuteron, and a liquid hydrogen target. Measurements were made at incident proton energies of 317 and 310 Mev. The results of the raw data are $(R-L)/(R+L)=0.16\pm0.03$ and 0.23 ± 0.04 at 317 and 310 Mev, respectively. R and L refer to the direction of the produced meson, as seen by the incident proton. (The polarized proton beam is produced by a "left" scatter.[4])

In the notation of Marshak and Messiah, $(R-L)/(R+L)=PQ(A\sin\theta)/(A+\cos^2\theta)$. Here, $A+\cos^2\theta$ is the angular dependence of the differential cross section in the c.m. system for unpolarized protons, and Q is the interesting quantity, involving the relative amplitudes and phases of the transitions involved. It is apparent that the angular factor becomes unity, independent of A, at $\theta=90°$. However, measurements were made at 69° because of meson energy loss in the target. We used $A=0.40$ and 0.49[6] at 317 and 310 Mev, respectively, to average the angular factor. With $|P|=0.73$ this gives $|Q|=0.37\pm0.06$ and 0.42 ± 0.07 at 317 and 310 Mev, respectively, Analysis[7] of the excitation function shows that Q is expected to vary by less than ten percent between 310 and 317 Mev, so that we may conveniently combine these data to obtain an average $|Q|=0.39\pm0.05$ at an average proton energy of 314 Mev. $(\text{K.E.}_\pi)_{\text{c.m.}}=11.3$ Mev.

We satisfied ourselves as to the following points: uniformity of counter sensitivity, insensitivity of counters to stray fields, target and counter alignment, exclusion of $p+p\rightarrow\pi^++p+n$, and reproducibility during many interchanges of counter positions. As an over-all check, the experiment was repeated using the ordinary "scattered" beam, which has been shown[4] to be unpolarized. The beam energy was degraded with a Be absorber to correspond to the measured energy of the polarized beam. At 317 and 310 Mev, $(R-L)/(R+L)=-0.02\pm0.06$ and 0.04 ± 0.04 were obtained, respectively. These results have convinced us that no hidden asymmetries were present in the equipment. The average of the left and right measurements with the polarized beam agreed with the results obtained with the unpolarized beam, and with our previous measurements.[6]

Rosenfeld[7] has compiled data on pion production from nucleons and compared it with the phenomenological theory of Watson and Brueckner.[8] In his notation, $Q=\sqrt{2}\eta_c\eta(\eta^2+\eta_c^2)^{-1}\sin(\psi-\tau_1)$, where $\eta=p_\pi/m_\pi c$, and η_c is obtained by fitting the 90° (c.m.) excitation function data to $4\pi d\sigma_{10}(90°)/d\Omega=\alpha_{10}(\eta+\eta^3\eta_c^{-2})$. The terms in η and η^3 come from S and P mesons, respectively. $S_0/S_2+\sqrt{\frac{1}{2}}=|S_0/S_2+\sqrt{\frac{1}{2}}|\exp(i\psi)$, and $S_1/S_2=|S_1/S_2|\exp(i\tau_1)$, where S_0 and S_2 are the complex transition amplitudes giving P-state meson production from ${}^1S_0$ and ${}^1D_2$ protons, respectively, and S_1 is the amplitude for S-state meson production from ${}^3P_1$ protons. Our data[6] yields $\eta_c=0.62\pm0.16$. With the measured Q, at $\eta=0.41$, this gives $|\sin(\psi-\tau_1)|=0.61\pm0.10$.

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Regularity in Magnetic Moments of Odd Nuclei*

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Wangsness[1] and de-Shalit[2] have observed a regularity between the magnetic moment of an odd-even nucleus (Z, N) and that of the nucleus $(Z+2, N)$ or $(Z, N+2)$. De-Shalit formulated this regularity in the rule: An addition of either two protons or two neutrons to an odd nucleus, provided it leaves its spin I unchanged, pushes its magnetic moment toward the Schmidt line.

TABLE I. Comparison of intrinsic gyromagnetic ratios in odd-even nuclei (Z,N) and $(Z+2, N+2)$.[a]

Nucleus$_1$	G_1	State$_1$	Nucleus$_2$	G_2	State$_2$	G_1–G_2
H^3	2.98	$s_{1/2}+$	Li^7	2.26	$p_{3/2}+$	+0.72
Li^7	2.26	$p_{3/2}+$	B^{11}	1.69	$p_{3/2}+$	+0.57
Be^9	1.18	$p_{3/2}+$	C^{13}	2.11	$p_{1/2}-$	−0.93
B^{11}	1.69	$p_{3/2}+$	N^{15}	2.85	$p_{1/2}-$	−1.16
C^{13}	2.11	$p_{1/2}-$	O^{17}	1.89	$d_{5/2}+$	+0.22
N^{15}	2.85	$p_{1/2}-$	F^{19}	2.63	$s_{1/2}+$	+0.22
F^{19}	2.63	$s_{1/2}+$	Na^{23}	1.70	$D_{3/2}+$	+0.93
Na^{23}	1.70	$D_{3/2}+$	Al^{27}	1.64	$d_{5/2}+$	+0.06
Mg^{25}	0.85	$d_{5/2}+$	Si^{29}	0.55	$s_{1/2}+$	+0.30
Al^{27}	1.64	$d_{5/2}+$	P^{31}	1.13	$s_{1/2}+$	+0.51
Si^{29}	0.55	$s_{1/2}+$	S^{33}	1.07	$d_{3/2}-$	−0.52
P^{31}	1.13	$s_{1/2}+$	Cl^{35}	1.63	$d_{3/2}-$	−0.50
Cl^{35}	1.63	$d_{3/2}-$	K^{39}	2.35	$d_{3/2}-$	−0.72
Cl^{37}	1.86	$d_{3/2}-$	K^{41}	2.64	$d_{3/2}-$	−0.78
K^{41}	2.64	$d_{3/2}-$	Sc^{45}	1.76	$f_{7/2}+$	+0.88
Ca^{43}	1.32	$f_{7/2}+$	Ti^{47}	1.10	$F_{5/2}+$	+0.22
Ti^{49}	1.10	$f_{7/2}+$	Cr^{53}	0.47	$p_{3/2}+$	+0.63
V^{51}	2.15	$f_{7/2}+$	Mn^{55}	1.85	$F_{5/2}+$	+0.30
Cr^{53}	0.47	$p_{3/2}+$	Fe^{57}	∼0	$p_{3/2}+$	+0.47
Mn^{55}	1.85	$F_{5/2}+$	Co^{59}	1.65	$f_{7/2}+$	+0.20
Co^{59}	1.65	$f_{7/2}+$	Cu^{63}	1.23	$p_{3/2}+$	+0.42
Cu^{65}	1.38	$p_{3/2}+$	Ga^{69}	1.02	$p_{3/2}+$	+0.36
Ga^{71}	1.56	$p_{3/2}+$	As^{75}	0.44	$p_{3/2}+$	+1.12
Ge^{73}	0.88	$g_{9/2}+$	Se^{77}	1.60	$p_{1/2}-$	−0.72
As^{75}	0.44	$p_{3/2}+$	Br^{79}	1.11	$p_{3/2}+$	−0.67x
Br^{81}	1.27	$p_{3/2}+$	Rb^{85}	2.11	$f_{5/2}-$	−0.84
Kr^{83}	0.97	$g_{9/2}+$	Sr^{87}	1.09	$g_{9/2}+$	−0.12x
Rb^{85}	2.11	$f_{5/2}-$	Y^{89}	2.41	$p_{1/2}-$	−0.30
Sr^{87}	1.09	$g_{9/2}+$	Zr^{91}	1.1	$d_{5/2}+$	−0.01x
Y^{89}	2.42	$p_{1/2}-$	Nb^{93}	2.17	$g_{9/2}+$	+0.25
Zr^{91}	1.1	$d_{5/2}+$	Mo^{95}	0.91	$d_{5/2}+$	+0.19
Tc^{99}	1.68	$g_{9/2}+$	Rh^{103}	2.26	$p_{1/2}-$	−0.58
Rh^{103}	2.26	$p_{1/2}-$	Ag^{107}	2.34	$p_{1/2}-$	−0.08
Ag^{109}	2.39	$p_{1/2}-$	In^{113}	1.49	$g_{9/2}+$	+0.90
Cd^{111}	0.60	$s_{1/2}+$	Sn^{115}	0.92	$s_{1/2}+$	−0.32x
Cd^{113}	0.62	$s_{1/2}+$	Sn^{117}	1.00	$s_{1/2}+$	−0.38x
Sn^{119}	1.05	$s_{1/2}+$	Te^{123}	0.73	$s_{1/2}+$	+0.32
Sb^{123}	1.72	$g_{7/2}-$	I^{127}	0.81	$d_{5/2}+$	+0.91
Te^{125}	0.88	$s_{1/2}+$	Xe^{129}	0.77	$s_{1/2}+$	+0.11
I^{127}	0.81	$d_{5/2}+$	Cs^{131}	1.48	$d_{5/2}+$	−0.67x
I^{129}	1.64	$g_{7/2}-$	Cs^{133}	1.69	$g_{7/2}-$	−0.05
Xe^{131}	1.14	$d_{3/2}-$	Ba^{135}	1.39	$d_{3/2}-$	−0.25
Nd^{143}	1.0	$f_{7/2}+$	Sm^{147}	0.32	$f_{7/2}+$	+0.68
Nd^{145}	0.62	$f_{7/2}+$	Sm^{149}	0.26	$f_{7/2}+$	+0.36
Ta^{181}	2.56	$g_{7/2}-$	Re^{185}	1.14	$d_{5/2}+$	+1.42
Re^{187}	1.18	$d_{5/2}+$	Ir^{191}	2.72	$d_{3/2}-$	−1.54
Ir^{193}	2.72	$d_{3/2}-$	Au^{197}	2.77	$d_{3/2}-$	−0.05
Pt^{195}	1.82	$p_{1/2}-$	Hg^{199}	1.51	$p_{1/2}-$	+0.31x
Tl^{205}	1.63	$s_{1/2}+$	Bi^{209}	1.06	$h_{9/2}-$	+0.57x

[a] Nuclei giving different signs in the last two columns are marked with x after the figure in the last column.

Another such regularity has been observed by the author between the magnetic moment of an odd-even nucleus (Z, N) and that of the nucleus $(Z+2, N+2)$. It may be formulated as follows: The addition of an alpha particle to an odd nucleus pushes its magnetic moment toward the Schmidt line if the spin of the heavier nucleus is given by $I=l-\frac{1}{2}$ and away from the Schmidt line if the spin of the heavier nucleus is given by $I=l+\frac{1}{2}$. The value of l is that assigned the last odd nucleon by the jj-coupling shell model.[3]

An unambiguous definition of distance from the Schmidt lines in the case of nuclei with different spins I is obtained by solving the Landé formula for g_s, taking g_l equal unity for odd proton nuclei and zero for odd neutron nuclei, and μ and I equal their experimentally measured values. We define $G=|g_s/2|$, i.e., the absolute value of the "quenched" intrinsic moment[4] of the odd particle. Then both proton Schmidt lines are located at $G=2.79$ and both neutron Schmidt lines at $G=1.91$. All values of G were obtained in the above manner except those for Na^{23}, Ti^{47}, and Mn^{55} whose experimentally observed magnetic moments were multiplied by $j/(j-1)$ to compensate for the coupling of nucleons of total angular momentum j to the spin $I=j-1$.

In Table I we have listed all pairs of odd nuclei whose magnetic moments are experimentally known, the odd-particle state assigned by the shell model, and the value of G. The + or − following the state designation indicates whether the state has $I=l\pm\frac{1}{2}$ (except for the three nuclei mentioned above, where the + indicates the state was formed by nucleons with $j=l+\frac{1}{2}$). We shall take an increase in the value of G to mean motion toward the Schmidt line, although a few light nuclei have G greater than the free nucleon values.

The regularity may be observed by comparing the signs in the last two columns. These match in 41 of 49 cases, a circumstance which would happen by chance less than one time in five million. A comparison of the signs in the last column with those for the lighter nucleus shows they match in 27 of the cases, about the proportion to be expected by chance. The correspondence of the last two columns appears to hold regardless of the sign of the lighter nucleus. It is an interesting feature that the rule depends on the state of the heavier nucleus only.

The exceptions have been marked with an "x" after the figure in the last column. There are no exceptions for nuclei below $A=75$; the first 24 pairs obey the rule. Two of the exceptional pairs are $As^{75}-Br^{79}$ and $I^{127}-Cs^{131}$. As^{75} and I^{127} are the only two nuclei which fall within an odd-proton "forbidden zone" bounded by the two Dirac lines at $G=1$. The other six exceptions occur near the magic numbers 50 and 82, associated with the marked phenomena of closed nuclear shells.

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