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Nucleon scattering from ^{34}S and the relative sign of neutron and proton transition matrix elements for the $(0 \rightarrow 2_2^+)$ transition

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Data obtained by scattering 29.8 MeV protons and 21.7 MeV neutrons from ^{34}S are used in a consistent analysis to obtain values and relative signs for proton (M_p) and neutron (M_n) multipole matrix elements for $E2$ transitions to the first three 2^+ states in ^{34}S. The data for the 0^+ (g.s.)$\rightarrow 2_2^+$ (3.30 MeV) transition are consistent only with the assumption of the same relative sign of M_p and M_n.

In a recent paper, Bernstein *et al.*[1] discuss the sensitivity of inelastic hadron scattering to determine relative signs of neutron and proton transition multipole matrix elements, M_n and M_p. As an example, they present proton inelastic scattering data from ^{34}S obtained at 650 MeV; the data for the 0^+ (g.s.)$\rightarrow 2_2^+$ (3.30 MeV) transition are compared with predictions which sensitively depend on the relative sign of M_n and M_p. The magnitudes of M_n and M_p needed in the analysis are obtained from electromagnetic (EM) data. The authors conclude that the relative sign of M_n and M_p for the 2_2^+ transition in ^{34}S is negative in agreement with shell model calculations reported by Wildenthal.[2]

The above conclusion on the relative sign of M_n and M_p has been challenged by Saha *et al.*[3] These authors report measurement of 120 MeV α inelastic scattering cross sections for the first two 2^+ states in ^{34}S to show that the relative sign of M_n and M_p for both 2^+ states are positive.

In both Refs. 1 and 3 EM data and hadronic data are needed to evaluate values for M_n and M_p. In this Rapid Communication we present hadronic data, neutron, and proton scattering data on ^{34}S, which in a self-consistent analysis, are used to estimate the values and relative signs of M_n and M_p for the first three 2^+ transitions in ^{34}S.

Neutron scattering data at 21.7 MeV were obtained using the Ohio University time-of-flight facility using an enriched (93.6%) ^{34}S cylindrical scattering weighting 18.02 g. The energy resolution obtained was less than 400 keV, which was sufficient to separate the excited states in ^{34}S up to 5.0 MeV. A complete description of the analysis of the neutron data is presented in Ref. 4.

The proton scattering experiment was performed using a 29.8 MeV proton beam from the Princeton University AVF cyclotron. Enriched (94.3%) ^{34}S targets of approximately 1 mg/cm^2 were prepared by evaporating ^{34}S onto 30 μg/cm^2 C backings. The protons were analyzed using the QDDD spectrometer and detected with a position-sensitive gas proportional counter backed by a plastic scintillator.[5] Spectra were obtained at intervals of 5° from 15° to 120° with a resolution better than 20 keV full width at half maximum (FWHM). Data were taken in two consecutive runs each covering approximately 3 MeV of excitation energy on the focal plane. In Fig. 1 we present a spectrum taken at 30° showing the 2–5 MeV region of excitation. Absolute differential cross sections could not be accurately measured because of target sublimation. Cross section normalizations were done using a BGO detector located in the scattering chamber at $\theta = 90°$ which was used as a monitor. An energy resolution better than 1 MeV (FWHM) was achieved with this detector.

Absolute cross section values were obtained by normalizing the elastic relative yield to a calculated elastic differential cross section at $\theta_L = 15°$. Several sets of proton optical model parameters[6-8] were used to calculate the elastic differential cross section. The calculated values obtained at $\theta_L = 15°$ agree with each other within 2%. As a check of the obtained absolute normalization, values for the ^{32}S elastic

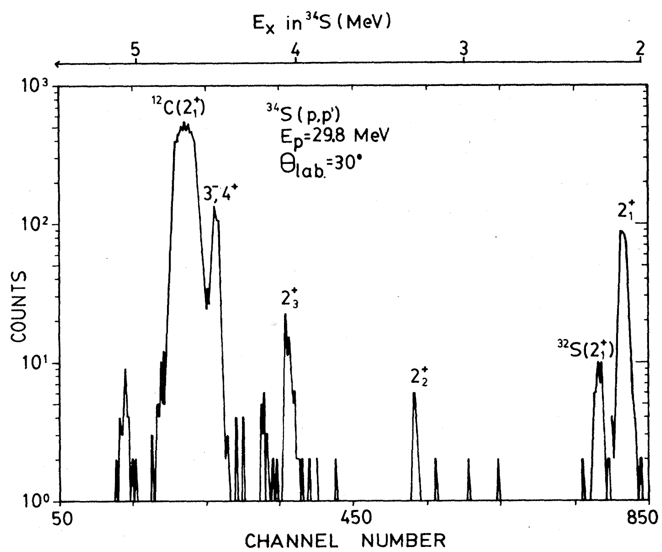

FIG. 1. Energy spectra taken at $\theta_{lab} = 30°$ for the reaction ^{34}(p,p′) at $E_p = 29.8$ MeV. Excited states in ^{34}S between 2.0 and 5.0 MeV are indicated with their J^π values. A small amount of ^{32}S (5.5%) in the target gives rise to the excitation of the ^{32}S (2_1^+) state.

TABLE I. Optical-model potential parameters for nucleon elastic scattering of ^{34}S. Potentials depths are in MeV. Geometrical OMP parameters (in fm) were obtained in the spherical search and were kept constant thereafter. The values are $r_R=1.184$, $a_R=0.706$, $r_I=1.213$, and $a_I=0.538$. The spin-orbit potentials were kept fixed at the values $V_{so}=5.46$ MeV and $W_{so}=-0.155$ MeV. The s.o. geometrical parameters are $r_{so}=0.90$, $a_{so}=0.76$ for protons and $r_{so}=1.00$, $a_{so}=0.875$ for neutrons (see Ref. 4).

Probe	Type	V_R	W_V	W_D	β_2	b_p^h	b_n^h
Proton $E_p=29.8$ MeV	Spherical OMP	46.90	8.48	5.95		0.25	0.75
	CC-OMP g.s. → 2_1^+	47.97	7.46	6.03	0.28 ± 0.01	0.33	0.67
Neutron $E_n=21.7$ MeV	Spherical OMP	44.55	0.00	7.88		0.75	0.25
	CC-OMP g.s. → 2_1^+	46.49	0.00	7.26	0.27 ± 0.01	0.67	0.33

and 2_1^+ (2.230 MeV) inelastic differential cross sections at angles where the states were resolved from ^{34}S peaks (Fig. 1) were compared with previously measured cross sections[6,8] at the same incident energy. The obtained agreement (better than 5%) was very good.

An initial set of spherical optical model potential (OMP) parameters was generated by fitting simultaneously the (n,n) and (p,p) elastic data. We use the energy dependence for the potential depths reported by De Leo *et al.*[7] on ^{32}S between 15 and 35 MeV. Another set of OMP parameters to be used in coupled channel (CC) analyses was obtained by coupling the ground state (g.s.) with the 2_1^+ (2.13 MeV) state in the framework of the vibrational model. Parameters for both OMP sets are shown in Table I.

The CC calculations were performed with the code ECIS.[9] The excited states in ^{34}S, 2_1^+ (2.13 MeV), 2_2^+ (3.30 MeV), 2_3^+ (4.11 MeV), 2_4^+ (4.89 MeV), and 4_1^+ (4.69 MeV) were coupled using a vibrational model form factor for the coupling matrix elements. The inclusion in the coupling of the 2_4^+ (4.89 MeV) and 4_1^+ (4.69 MeV) excited states have less than 5% effect in the results for the low lying states.

If we assume that the reaction mechanism is one step, we may write

$$\sigma_{hh'}(\theta) \simeq |M_{hh'}|^2 A(\theta) \ , \qquad (1)$$

where $A(\theta)$ contains the usual reaction dynamics and the second factor $M_{hh'}$ contains the nuclear structure matrix elements:[10]

$$M_{hh'} = b_p^h M_p \pm b_n^h M_n \ ,$$

where b_n^h and b_p^h are the hadron-neutron and hadron-proton interaction strengths. Empirical values for b_n^h and b_p^h may be obtained from the corresponding hadron OMP parameters; the results obtained from the spherical OMP parameters agree with the low energy hadron canonical value,[10] namely, $b_p^p=b_n^n=0.25$ and $b_p^n=b_n^p=0.75$. The values obtained from the CC OMP parameters are $b_p^p=b_n^n=0.33$ and $b_p^n=b_n^p=0.67$ (see Table I).

Shell model predictions for M_n and M_p values were used to estimate $M_{hh'}$ values. These shell model calculations were done using an empirical s-d shell effective interaction.[2]

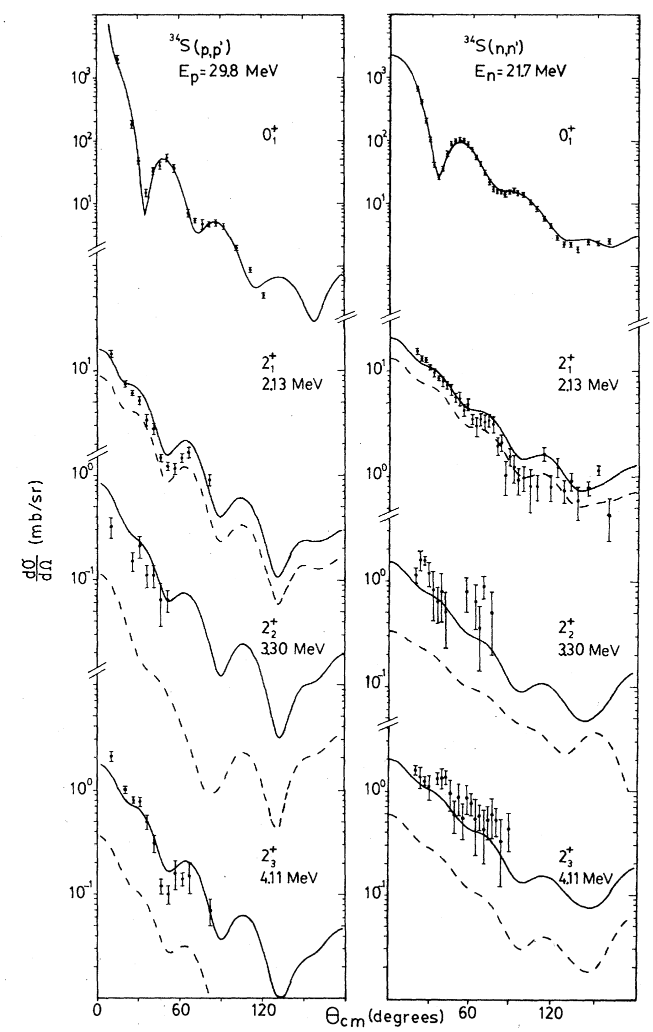

FIG. 2. Measured nucleon angular distributions for the ground state and the first three 2^+ states in ^{34}S. Dashed lines indicate the shell model predictions and the solid lines the results of considering values for M_n and M_p from EM measurements (see text).

TABLE II. (M_n/M_p) values for g.s.$\rightarrow 2^+$ transitions in ^{34}S.

Transition	Method	Energy	$\lvert M_n/M_p \rvert$	Sign
$0^+ \rightarrow 2_1^+$ (2.13 MeV)	EM		1.5+0.3	From Refs. 11 and 12,[a]
	$\alpha\alpha'$	120 MeV	1.6	(+) Ref. 3,[a]
	pp′	650 MeV	. . .	(+) Ref. 1
	pp′	29.8 MeV	1.25 ±0.35	(+) Present
	nn′	21.7 MeV		
	Shell model		1.13	(+) Ref. 2
$0^+ \rightarrow 2_2^+$ (3.30 MeV)	EM		0.55+0.15	From Refs. 11 and 12,[a]
	$\alpha\alpha'$	120 MeV	0.55+0.15	(+) Ref. 3,[a]
	pp′	650 MeV	. . .	(−) Ref. 1
	pp′	29.8 MeV	0.30+0.18	(+) Present[b]
	nn′	21.7 MeV	0.46+0.16	
	Shell model		0.6	(−) Ref. 2
$0^+ \rightarrow 2_3^+$ (4.11 MeV)	pp′	29.8 MeV	1.10 ±0.35	(+) Present
	nn′	21.7 MeV		
	Shell model		0.70	(+) Ref. 2

[a]Values for M_n and M_p reported in the indicated references or calculated from the indicated data by the present authors were used to obtain the ratio (M_n/M_p).
[b]See text.

These calculations predict a negative (M_n/M_p) value for the 0^+ (g.s.)$\rightarrow 2_2^+$ (3.30 MeV) transition and positive for all the others. Using these calculated M_n and M_p matrix elements and the CC values for b_n^h and b_p^h (Table I), the code ECIS was used to estimate the inelastic nucleon cross section. The results are shown in Fig. 2 as dashed lines. It is quite clear that the shell model predictions, with opposite sign for M_n and M_p, do not agree with the $0^+ \rightarrow 2_2^+$ transition data. It is also clear that the shell model predictions underestimate the results for the 0^+ (g.s.)$\rightarrow 2_3^+$ (4.11 MeV) transition.

Electromagnetic data in mirror nuclei[1] may be used to obtain M_n and M_p values. Values reported in Endt's compilation[11] for ^{34}Ar and ^{34}S are used to obtain the M_n and M_p values for the 0^+ (g.s.)$\rightarrow 2_1^+$ (2.13 MeV) and 0^+ (g.s.)$\rightarrow 2_2^+$ (3.30 MeV) transitions. For the 0^+ (g.s.)$\rightarrow 2_3^+$ (4.11 MeV) transition we obtain the M_p value from EM measurements on ^{34}S (11) and we estimate the M_n value from (α,α') results.[3] These empirical transition matrix elements together with calculated shell model transition matrix elements were used in a CC formalism to calculate the hadronic cross sections. The results assuming same sign for all the M_n and M_p transitions are shown in Fig. 2 as solid lines. The agreement with the experimental values seem quite good.

The present analysis supports the conclusion of Saha *et al.*[3] and Keinonen *et al.*[12] that the excitation of the ^{34}S (2_2^+) state requires that M_n and M_p have the same sign. This is in disagreement with the shell model calculation results and those inferred[1] from the 650 MeV inelastic proton data. We present in Table II a summary of results for the ratio and sign of (M_n/M_p) for the first three 2^+ transitions in ^{34}S. Values for M_n and M_p reported in the indicated references have been used to calculate (M_n/M_p). For the 0^+ (g.s.)$\rightarrow 2_2^+$ (3.30 MeV) transition, M_n/M_p is partic-

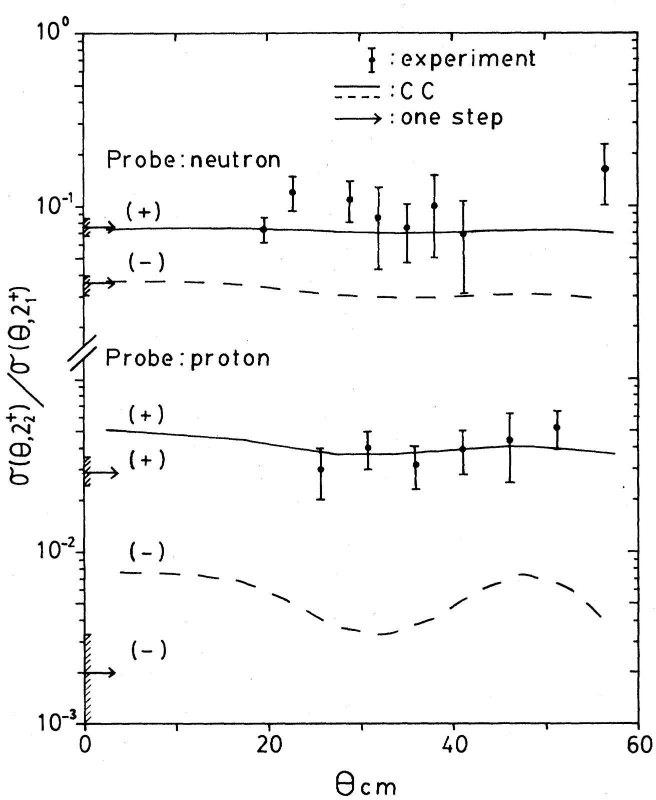

FIG. 3. Ratios of the 2_2^+ and 2_1^+ cross sections. CC with positive relative sign for M_n and M_p are solid lines and with negative relative sign are dashed lines. Ratio values obtained using Eq. (1) are indicated with arrows.

ularly sensitive to the interaction strength values. Our CC analysis (see Table II) gives $M_n/M_p = 0.30 \pm 0.18$ if the interaction strengths are calculated using the OMP parameters obtained in the CC analysis and $M_n/M_p = 0.46 \pm 0.16$ if we use the interaction strengths obtained with the spherical (OMP) parameters.

Certainly Eq. (1) is an approximation if the reaction mechanism is not a one-step process. However, the simultaneous analysis of the hadronic data allows us to form the experimental ratios

$$R^{n}_{\rm exp} = \frac{\sigma_{nn'}(\theta, 2_2^+)}{\sigma_{nn'}(\theta, 2_1^+)} , \quad R^{p}_{\rm exp} = \frac{\sigma_{pp'}(\theta, 2_2^+)}{\sigma_{pp'}(\theta, 2_1^+)} ,$$

which are shown in Fig. 3. Also plotted in this figure are the values obtained for these ratios from a CC analysis done with the assumption that M_n and M_p have the same sign (solid lines) and with M_n and M_p of opposite sign (dashed lines). The results uniquely point out that M_n and M_p have the same sign for the 0^+ (g.s.) $\rightarrow 2_2^+$ (3.30 MeV) transition and indicate the sensitivity of the method for low-energy incident nucleons (20–30 MeV).

The value $(b_n^p/b_p^p) = 0.81$ quoted in Ref. 1 and used in the 650 MeV proton inelastic scattering as compared with the present empirical value $(b_n^p/b_p^p) = 2.03$ points towards the reason why the present results at 30 MeV bombarding energy are more sensitive to admixtures of M_n and M_p.

Using Eq. (1) and the b_p^h and b_n^h values (Table I) obtained in the spherical OMP analysis, we obtain R values which are almost angle independent. These values are also indicated in Fig. 3 with arrows and are very similar to the CC analysis results, indicating the importance of the one-step transition.

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