Muon Capture in ^{28}Si and g_p/g_a

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Negative muon capture in ^{28}Si was used to determine the angular correlation between the neutrino and the 1229 keV γ-ray from the de-excitation of the 2201 keV 1^+ level in ^{28}Al. To suppress backgrounds in the HPGe detectors, a coincidence was required with the 942 keV γ-ray in the de-excitation cascade detected in a NaI array. The extracted angular correlation coefficient α is 0.360 ± 0.059, consistent with previous measurements. Using a recent shell model calculation employing a full 1s–0d model space and the USD empirical interaction, this value of α implies a value for the induced pseudoscalar coupling of $g_p/g_a = 0.0 \pm 3.2$, substantially smaller than the prediction of PCAC and pion-pole dominance.

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The weak axial current of the proton is modified from the simple form $\gamma_\mu\gamma_5$ due to the non point-like nature of the nucleon. The axial current of the nucleon in a semileptonic process becomes $g_a(q^2)\gamma_\mu\gamma_5 + ig_p(q^2)q_\mu\gamma_\mu\gamma_5/m$ where m is the lepton mass and q is the momentum transfer [1]. The axial coupling constant $g_a(0)$ is well-determined from neutron β-decay experiments [2]. The induced pseudoscalar coupling g_p, is unimportant in β-decay but can be observed in μ^- capture where its effect is much larger, since its contribution scales with the mass of the lepton involved. At the kinematics of ordinary μ-capture on the proton ($q^2 = -0.88m_\mu^2$) the prediction $g_p/g_a = 6.8$ arises from the partially conserved axial current hypothesis (PCAC) [3] and the assumption of single-pion exchange dominance of the coupling. This prediction is in accord with the average value $g_p/g_a = 6.9 \pm 1.9$ extracted from measurements of ordinary μ capture in hydrogen [4], albeit with a large uncertainty. The recent measurement at TRIUMF of radiative μ capture on hydrogen [5], however, gives the larger value $g_p/g_a = 9.8 \pm 0.8$, and so the situation is somewhat unclear.

The situation is less satisfactory for μ-capture in a nucleus. The axial couplings can, in principle, be modified by the nuclear medium. There have been predictions of substantial quenching of g_p (as well as a small quenching of g_a) in heavy nuclei due to changes in the pion field, modifications of pion-nucleon coupling etc. [6]. An unambiguous experimental verification of these nuclear-medium effects is not yet available. Recent measurements of radiative muon capture (RMC) [7,8] suggest a significant enhancement of g_p in light nuclei and a quenching to near zero in heavy nuclei. These results are controversial, as the extraction of g_p from these data is very sensitive to nuclear structure. In contrast, measurements using ordinary μ-capture on ^{12}C [9–11], ^{16}O [12], and ^{23}Na [13] show no evidence for quenching of g_p, and are consistent with the free nucleon value. More input from experiment is clearly required to clarify the situation.

In certain cases, the angular correlation between the neutrino and a specific nuclear de-excitation γ-ray following muon capture is sensitive to g_p, and is believed to be rather insensitive to nuclear structure uncertainties. The ν-γ correlation arises due to the fact that muon capture selectively populates certain magnetic substates of the recoiling nucleus. For allowed muon capture, in the case in which the γ-ray is emitted at 90° to the muon spin direction, the angular correlation is $I(\theta) = I_0[1 + \alpha P_2(\cos\theta)]$ where θ is the angle between the γ-ray and the neutrino [14–16]. The correlation coefficient α is a function of the nuclear matrix elements and the weak couplings.

Grenacs *et al.* [17] proposed a method to measure this angular correlation by measuring the energy distribution of the Doppler-broadened γ-ray. The nuclear recoil is opposite to the neutrino direction. Thus if the lifetime of the excited state is sufficiently short, the nucleus will be recoiling when the γ-ray is emitted and the observed shape of the γ-ray spectrum will reflect the angular correlation. Experimental [18,19] and theoretical [14,20–23] effort has concentrated on the $0^+ \rightarrow 1^+ \rightarrow 0^+$ muon capture sequence

$$\begin{aligned} \mu^- + {}^{28}\mathrm{Si}(0^+) \rightarrow \nu_\mu + {}^{28}\mathrm{Al}^*(1^+\ 2201\ \mathrm{keV}) & \\ \hookrightarrow {}^{28}\mathrm{Al}^{**}(0^+\ 972.4\ \mathrm{keV}) + \gamma. & \end{aligned} \tag{1}$$

The resulting 1229 keV γ-ray has a Doppler-broadened width of 9 keV, wide enough to allow a line-shape measurement of the angular correlation using detectors with $\sim$ 2 keV resolution. Until recently the only γ-ν experiment was the ground-breaking measurement of Miller *et al.* [18]. Low statistics and poor signal-noise precluded a sensitive measurement of g_p in that experiment. Recently, Brudanin *et al.* [19] performed a more precise measurement of the angular correlation in this reaction, and extracted the value $g_p/g_a = 3.4 \pm 1.0$, indicating a substantial quenching from the prediction of PCAC and pion-pole dominance. That experiment, however, suffered from serious backgrounds that distorted the observed line-shape of the 1229 keV γ-ray of interest.

Our initial studies [24,25] found background problems near the 1229 keV peak similar to those seen by Brudanin *et al.* [19]. These include peaks at 1216 keV and 1204 keV due to (n, n') reactions on ^{74}Ge and ^{70}Ge respectively and at 1238 keV from (n, n') on ^{56}Fe. The Ge peaks are especially problematic due to their asymmetric shapes, which arise when the detector responds to the recoil energy of the Ge ion as well as the γ-ray. Rather than attempting to estimate and subtract these backgrounds from the 1229 keV line-shape as was done by Brudanin *et al.* [19], we have adopted a γ-γ coincidence technique to eliminate these backgrounds.

Each 1229 keV γ-ray is followed by a 942 keV γ-ray (100% branching ratio) from the transition (972 keV $0^+ \rightarrow$ 31 keV 2^+) (see Fig. 1). A clean spectrum for the 1229 keV transition, measured in a Ge detector, can therefore be obtained by requiring a coincidence with the 942 keV γ-ray observed in a NaI(Tl) array. The 942 keV γ-ray is emitted isotropically (the 972 keV intermediate level is 0^+) and so the angular location of the NaI detectors will not affect the observed line-shape of the 1229 keV peak.

The M9B superconducting muon channel at TRIUMF was used to provide a 60 MeV/c μ^- beam with a stopping rate in the target of $1.2 \times 10^5 \mathrm{s}^{-1}$. The target was granulated natural silicon (92.2% ^{28}Si) encased in a thin-walled disk-shaped polyethylene container 6.3 cm in diameter and 1.0 cm thick, inclined at 45° to the beam direction. Two plastic scintillators upstream ($S1$, $S2$) and one downstream ($S3$) defined a μ^- stop via $S1 \cdot S2 \cdot \overline{S3}$. Two high-purity Ge (HPGe) detectors were situated on either side of the target, at 90° to the beam axis. These detectors, Ge1 and Ge2, had relative efficiencies of 44% and 30% respectively, with in-beam energy resolutions at 1.33 MeV of 2.2 keV and 2.4 keV FWHM respectively. Both HPGe detectors were surrounded by

6-segment NaI(Tl) Compton suppressors. An additional array of 12 NaI(Tl) detectors of various shapes and sizes were located above and below the target. The Compton suppressor surrounding Ge1 only rejected events in hardware in which a γ-ray was detected in Ge1, and similarly Ge2's suppressor only vetoed events in Ge2. This allowed us to accept coincidences between NaI's in a given suppressor and the opposing HPGe detector, thereby increasing our efficiency for coincidence detection significantly. Events were accepted during an updating $2.5\mu s$ time window after the muon stop. Data were taken in "singles" mode, with the coincidence requirements applied in software during the data analysis. A significant magnetic field at the location of the target could distort the observed angular correlation, due to muon spin precession. The stray magnetic field at the target was measured to be less than 0.5 G, which has negligible effect on the spectrum. A total of 3.4×10^{10} muon stops in the target were obtained.

In the coincidence analysis, individual energy and timing windows were placed on each element in the NaI array. Typical in-beam energy resolutions for the NaI's were 9-10% FWHM at 1 MeV, and the NaI-HPGe coincidence timing resolution varied from 7–15 ns FWHM, depending on the detector. The γ-γ coincidence efficiency of the array was $(15.9 \pm 0.5)\%$ for Ge1 and $(13.0 \pm 0.5)\%$ for Ge2. With the coincidence requirement imposed, the signal-to-noise at the 1229 keV was 4.0 and 4.8 for Ge1 and Ge2 respectively, an order of magnitude better than previous measurements [18,19].

Even in the coincidence spectra there was some residual background around the 1229 keV γ-ray, so a side-band subtraction was made using windows above and below the 942 keV γ-ray in the NaI arrays. The details of this subtraction were not critical [26] and a final spectrum was obtained, completely devoid of background (see Fig. 2).

Accurate response functions for the HPGe detectors were required for fitting the observed γ-ray line-shape. These were determined from in-beam measurements of various non-broadened γ-rays in the spectrum. The response function included a gaussian core matched to high- and low-energy exponential tails, and a continuum with a small step below the peak [26]. The response function parameters were fit to smooth functions of γ-ray energy over a range overlapping the peaks of interest.

During the analysis it became plain that there was some slowing down of the recoiling ^{28}Al ion during the lifetime of the 2201 keV parent state. This will affect the Doppler-broadened spectrum, and therefore must be accounted for in fitting the line-shape and extracting α. As the 2171 keV γ-ray comes from the same level, this line became critical in obtaining the lifetime τ_{2201}. The 2171 keV peak was background free, so in this case the singles spectrum could be used.

The experimental line-shapes were fit with a function that represented a convolution of the angular correlation function, the effect of slowing-down of the recoiling ion, and the detector response functions. A simultaneous fit was made to the data from both detectors for both the 1229 keV and 2171 keV peaks (four spectra fit simultaneously). The free parameters included the lifetime of the 2201 keV level τ_{2201} and the correlation coefficients α for the 1229 keV and 2171 keV transitions. Also free in the fits were the amplitudes of the peaks, the centroid energies, and the amplitude of a flat background. The quality of the fit was entirely satisfactory (see Fig. 2), with a reduced χ^2 of 0.934. Completely consistent results were also obtained when the 2171 peaks were first fit separately to determine τ_{2201}, and this value was then fixed in individual fits to the 1229 keV spectra.

The extracted lifetime was $\tau_{2201} = 60.8 \pm 3.4 \pm 9.1$ fs. The first error is the statistical fitting error and the second is due to the uncertainty in the stopping power. The TRIM [27] program was used, which gives a fairly constant dE/dx for ^{28}Al *viz.* 2.2 MeV$\cdot$cm^2/mg at 183 keV. We estimate a conservative 15% uncertainty in the stopping power. Note that this uncertainty does not propagate to the fitted angular correlation, which is sensitive only to the product of the lifetime and the stopping power, which is well-determined in the fit. Previous DSAM measurements of τ_{2201} quoted values of 35 ± 10 fs [28] and 120 ± 70 fs [29], compatible with the present result. Brudanin *at al.* [19] quote a lifetime of 38.2 ± 2.8 fs, but do not indicate what value of the stopping power was used, nor do they give a systematic uncertainty for this value. Recently [30] they also reported the value $\tau_{2201} = 48.5 \pm 2.8$ fs from a second experiment.

For the 1229 keV transition, the correlation coefficient is found to be $\alpha = 0.360 \pm 0.059$. This is to be compared with Miller's values of 0.15 ± 0.25 for the natural silicon target and 0.29 ± 0.30 for the isotopically-enriched $^{28}SiO_2$ target. Brudanin *et al.* quote their results with a different coefficient x, but converting to our convention gives $\alpha = 0.307 \pm 0.041$, which is compatible with our value, however no uncertainty is quoted for systematic difficulties such as the background subtraction. In the measurement of Ref. [19], the HPGe detectors were not mounted at 90° to the beam polarization direction, so as to allow sensitivity to other angular correlation coefficients that involve the muon spin. The present experiment is not sensitive to these correlations, and so the two techniques are complementary.

The γ-ν angular correlation arises from the alignment of the 2201 keV intermediate state. Thus the line-shape of the 2171 keV γ-rays coming from this state is also sensitive to g_p, however, this is a mixed E2/M1 transition, and so the line-shape also depends on the mixing ratio. Thus extraction of g_p from the observed angular correlation function would require a precise independent value of the mixing ratio, which is not yet available. The fitted value was $\alpha_{2171} = -0.058 \pm 0.025$ for this line; this is to be compared with values of

-0.37 ± 0.10 for the natural silicon target and -0.17 ± 0.08 for the isotopically enriched $^{28}SiO_2$ target obtained by Miller et al. [18].

The observed angular correlations could be distorted if the 2201 keV parent level is not entirely fed directly via the μ-capture reaction. Cascade-feeding of the state from higher-lying levels was therefore a potential problem. Previous experiments [18,19] have relied on checking the γ-ray singles spectrum for indications of γ-rays known from other reactions to feed the 2201 keV level. In the present case our coincidence array allowed us to set stringent limits on cascade feeding: $< 2\%$ for the most likely candidate (the 3105 keV 1^+ level) and $< 5\%$ for overall cascade feeding. Assuming the maximal cascading allowed by these limits leads to a change in α of $\sim 5\%$, less than the statistical error.

Similarly, significant population of the 2201 keV level via the $^{29}\mathrm{Si}(\mu^-, n\nu)^{28}\mathrm{Al}$ or $^{30}\mathrm{Si}(\mu^-, 2n\nu)^{28}\mathrm{Al}$ reactions could distort the line-shape. Miller *et al.* [18] were able to set tight limits on feeding from ^{29}Si using an enriched $^{29}SiO_2$ target. Feeding from ^{30}Si would be expected to be smaller, as it must proceed via 2-neutron emission, but the possibility of some contribution cannot be ruled out.

To obtain g_p/g_a from the angular correlation α one needs to compare with calculations. Unfortunately there seems to be more sensitivity to the nuclear wavefunctions than had been originally believed (see Fig. 3). From our measured α, we obtain $g_p/g_a = 5.3\pm2.0$ using the calculation of Ciechanowicz [22] and $g_p/g_a = 4.2 \pm 2.5$, with the calculation of Parthasarathy and Sridhar [20] ("Model II" in that paper). In both cases the results are about 1σ below the PCAC prediction. The two calculations differ in their choice of nuclear wavefunctions; Ciechanowicz adopts those of Wildenthal [31] and Parthasarathy and Sridhar use those Donnelly and Walker [32].

If, instead, we use the recent calculation of Junker *et al.* [23], we obtain $g_p/g_a = 0.0 \pm 3.2$, which is 2σ smaller than the PCAC expectation, and is substantially smaller than that obtained using the two older calculations (see Fig. 3). Junker *et al.* use wavefunctions employing a full 1s–0d model space and the USD residual interaction, calculated with the OXBASH[33] code. They were also able to reproduce the results of the earlier calculations (Refs. [20,22]) by adopting the wavefunctions chosen by those authors, which would indicate that the differences between the results of the calculations arise primarily from the choice of wavefunctions. It should be noted that calculations using the full 1s-0d shell model space with the USD residual interaction have been shown to be very successful in reproducing observed Gamow-Teller strength (μ-capture, β^+/β^--decay, and $(n,p)/(p.n)$ data) for 1s-0d nuclei [34].

In summary, we have measured the γ-ν angular correlation coefficient $\alpha =$

0.360 ± 0.059 for the 1229 keV transition in ^{28}Al following μ-capture in ^{28}Si. A γ-γ coincidence technique allowed the elimination of backgrounds that have troubled previous measurements, and the measured angular correlation confirms the earlier results. The extracted pseudoscalar coupling g_p/g_a is found to be nuclear-model dependent, but the results suggest a quenching from the PCAC prediction.

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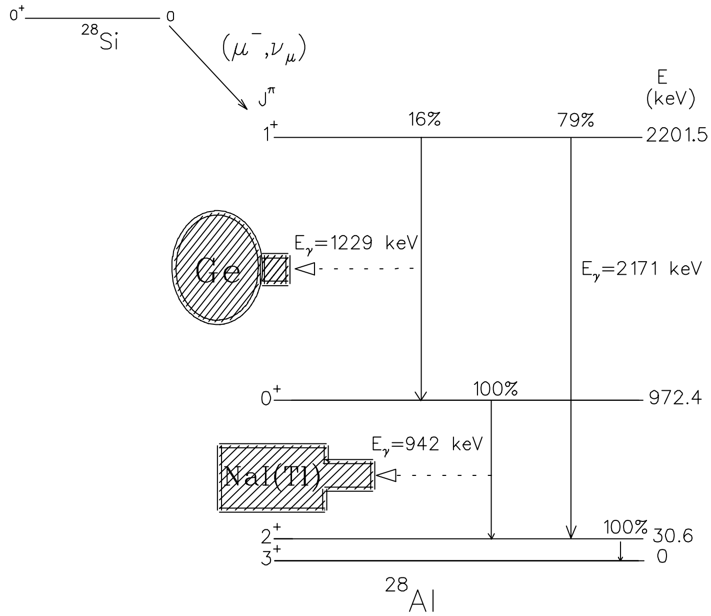

Fig. 1. Partial energy-level scheme for ^{28}Al showing the relevant states populated in the ^{28}Si(μ^-,ν) reaction.

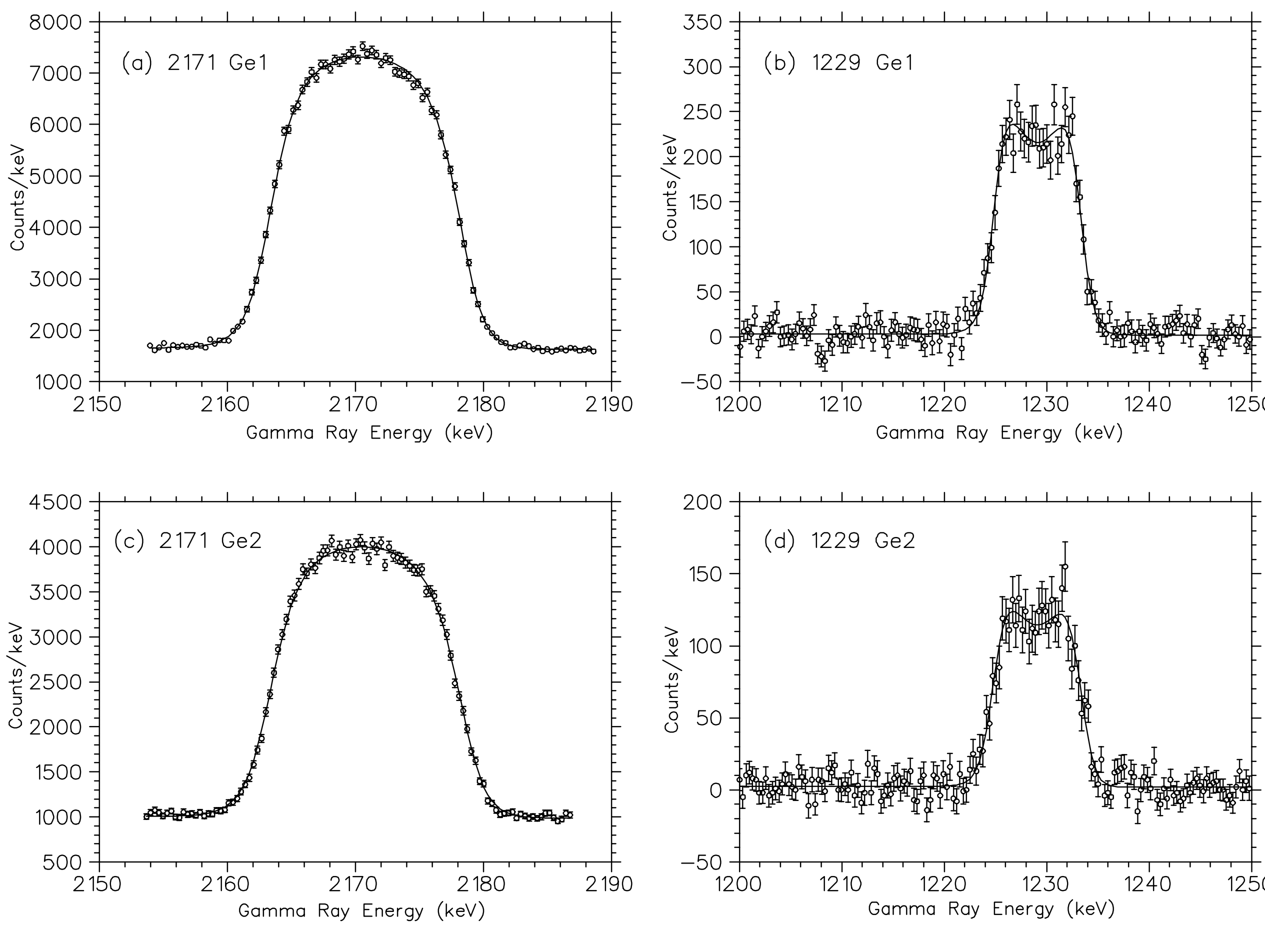

Fig. 2. Energy spectra from detectors Ge1 and Ge2 in the region of the 2171 keV (singles data) and 1229 keV (coincidence data) γ-rays, along with the result of the simultaneous fit.

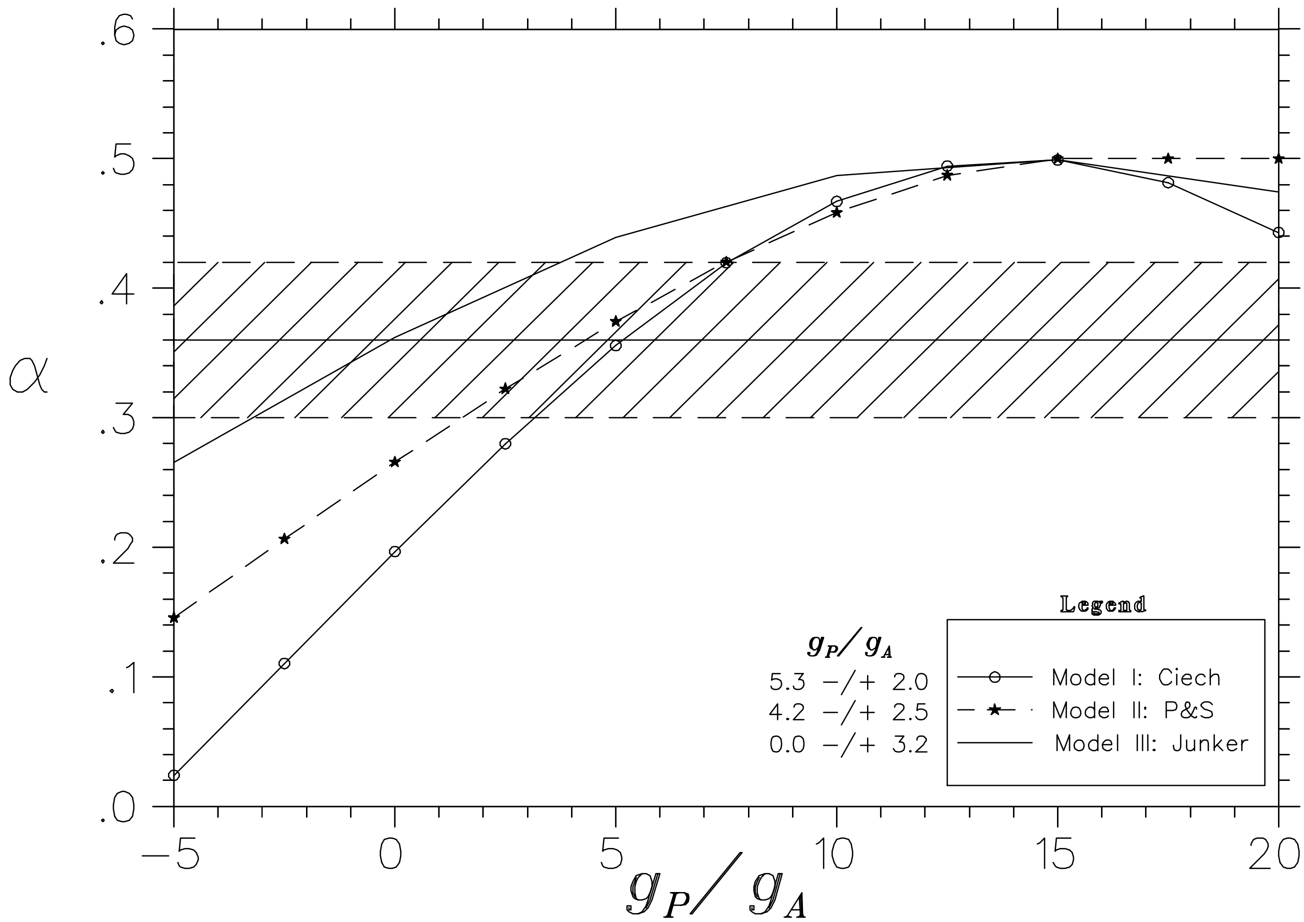

Fig. 3. The angular correlation coefficient α as a function of g_p/g_a, for various theoretical calculations (see text). Model I is that of Ciechanowicz [22], Model II is that of Parthasarathy and Sridhar [20], and Model III is that of Junker *et al.* [23]. Our result for α is also indicated.