Hyperfine Effect in μ^- Capture on ^{23}Na and g_p/g_a

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We report measurements of the rates and hyperfine (HF) dependences of μ^- capture on ^{23}Na, and the HF transition rate in Na metal. The measured capture rates are in general agreement with the predictions of the 1s-0d shell model. The measured HF dependences of the 1017 and 1823 keV γ rays from ^{23}Ne yield $g_p/g_a = 7.6\pm^{2.1}_{2.5}$ and $g_p/g_a \leq 7.1$ (1σ), consistent with partial conservation of axial-vector current, but in disagreement with claims of an enhancement of g_p/g_a in light nuclei. The measured HF transition rate $\Lambda_h = 15.5 \pm 1.1\ \mu s^{-1}$ is in agreement with the theory of Auger emission but twice the rate previously obtained in NaF (a $\sim 3\sigma$ effect).

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The weak interaction of the proton is influenced by its strong interaction, which modifies the weak axial coupling g_a, and induces the weak pseudoscalar coupling g_p. In the partially conserved axial current (PCAC) hypothesis [1] single pion exchange is responsible for the weak pseudoscalar coupling and this yields the Goldberger-Treiman estimate, $g_p/g_a = 6.7 \pm 0.2$ [2]. This estimate is in agreement with the average of all published measurements of the free proton coupling, $g_p/g_a = 6.9 \pm 1.9$ [3].

The weak pseudoscalar coupling may, however, be modified in nuclei. For example, Ericson [4] has suggested a progressive quenching of g_p/g_a from light to heavy nuclei due to changes in the nucleon pion field. Interestingly, some recent determinations of g_p/g_a from radiative μ^- capture (RMC) on nuclei have suggested a substantial enhancement in light nuclei and quenching in heavy nuclei; microscopic calculations for ^{12}C and ^{16}O yield $g_p/g_a = 16.2\ ^{+1.3}_{-0.7}$ and $13.6\ ^{+1.6}_{-1.9}$ [5] and Fermi gas calculations for Sn and Pb yield $g_p/g_a = 0.1\ ^{+1.4}_{-7.5}$ and ≤ 0.2 [6]. These interpretations of RMC data are, however, controversial, and recent determinations of the coupling from ordinary μ^- capture on ^{12}C and ^{16}O, $g_p/g_a = 10.1\pm^{2.4}_{2.6}$ [7] and $g_p/g_a = 7$–9 [8], are consistent with the Goldberger-Treiman estimate.

The $1S$ atomic ground state of the muonic atom, in the case of a $J_i \neq 0$ nucleus, is split into two hyperfine (HF) states with angular momenta $F_+ = J_i + 1/2$ and $F_- = J_i - 1/2$. The hyperfine dependence of μ^- capture can, for certain transitions, be strongly dependent on the weak pseudoscalar coupling and much less dependent on the nuclear wave functions [9–11]. For example, for transitions that decrease the spin of the nucleus by 1 (e.g., $3/2^+ \to 1/2^+$ in μ^{-23}Na), capture from the F_- state is generally dominated by g_a and the Gamow-Teller (GT) matrix element, whereas capture from the F_+ state is generally dominated by g_p and the GT matrix element. Consequently, the hyperfine dependence of μ^- capture, Λ_+/Λ_-, is a strong function of g_p/g_a, but, to the extent that the GT matrix element dominates other possible matrix elements, is independent of the nuclear wave functions.

Hyperfine transitions lead to the depopulation of the upper hyperfine state of the μ^- atom (F_+ in ^{23}Na) in favor of the lower hyperfine state, and yield a μ^- capture time dependence that exhibits the capture hyperfine dependence, Λ_+/Λ_-, and HF transition rate, Λ_h. This was used by and Winston and Telegdi [12] to establish the $V - A$ nature of the weak interaction in μ^- capture on ^{19}F and by Deutsch *et al.* [13] to set an upper limit on the weak pseudoscalar coupling in ^{11}B, $g_p \leq 15$. In this Letter we report measurements of the rates and hyperfine dependences of μ^- capture on ^{23}Na, and the hyperfine transition rate in Na metal, by observation of the resulting ^{23}Ne γ-ray spectrum.

The experiment was performed at the TRIUMF cyclotron using the backward-decay muon beam line M9B. After collimation, the 55 MeV/c beam gave a μ^- stopping rate of $1.1 \times 10^5\ \mu^-$/s, with electron and pion contaminations of 20% and ≤ 0.2%, respectively. The target was Na metal, 5 cm in diameter and 5 mm thick, enclosed in a polyethylene container with thin entrance and exit windows. The target was inclined at 45° to the beam axis, with two plastic scintillators upstream ($S1$, $S2$), and one plastic scintillator downstream ($S3$), defining a μ^- stop, $S1 \cdot S2 \cdot \overline{S3}$. Two high purity Ge detectors, Ge1 and Ge2, viewed γ rays emerging from the target at 90° to the beam axis. They had relative efficiencies of about 20% and 40%, respectively, and energy resolutions under beam conditions of 2.7 and 2.8 keV FWHM at 1.33 MeV. Both Ge1 and Ge2 were surrounded by Compton suppressors, CS1 and CS2: each Ge's own suppressor reduced the background from Compton scattering, and each Ge's opposing suppressor enabled the measurement

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of γ-γ coincidences.

To determine the Ge1 and Ge2 time resolutions as a function of energy, we measured the time spectra of muonic x rays from P, Ca, Fe, and Pb (energies from 457 to 2642 keV). Above 1000 keV the FWHM of the instrumental time resolution of both detectors was ≤ 10 ns. The x rays were also used to determine the Ge1 and Ge2 acceptances as a function of energy. In the case of P and Fe, the acceptances were obtained from the $K\alpha$, $K\beta$, and $K\gamma$ x-ray peaks using the yield data of Vogel [14] and Hartmann *et al.* [15]. In the case of Ca and Pb the summed counts in the K series (Ca) and L series (Pb) x-ray peaks were used to determine the acceptances.

Figure 1 shows the nine ^{23}Ne γ rays, and their yields, observed from μ^- capture on ^{23}Na. Corrections to the yields have been made for γ-ray absorption in the target ($\leq 4\%$) and coincident γ rays striking the Compton suppressors ($\leq 14\%$). The uncertainties in the yields arise from a 20% normalization error and statistical errors ranging from 3% to 10%. Table I lists the μ^- capture rates to six excited states in ^{23}Ne calculated from these γ-ray yields. For the states at 2315 and 3432 keV several weak γ-ray branches were not detected, and the branching ratios tabulated by Endt [16] were used in the calculation. The rapid HF transition rate in ^{23}Na (see below) meant the observed capture is mostly F_- capture; $\Lambda_{\rm obs} = 0.97\Lambda_- + 0.03\Lambda_+$.

Also listed in Table I are the predicted rates and hyperfine dependences using the $1s$-$0d$ shell model with the universal $1s$–$0d$ (USD) residual interaction [17]. This model is well tested [18], and reproduces the excitation energies of the observed states with a rms deviation of ~ 40 keV. The rates were calculated for $\Lambda_{\rm obs} = 0.97\Lambda_- + 0.03\Lambda_+$, an oscillator parameter $b = 1.804$ fm, and weak couplings constants of $g_v = 1.0$, $g_m = 3.706$, $g_a = 1.0$, and $g_p = 6.7$. We have used an effective weak axial coupling, $g_a = 1.0$, based on the work of Wilkinson [19] and Brown and Wildenthal [20]. The measured and calculated rates are in general agreement, the only obvious discrepancy being the $5/2^+$ state at 2315 keV. The calculation predicts that the six observed states account for $\sim$85% of capture to bound states in ^{23}Ne.

The Λ_+/Λ_- analysis focused on the 1017 and 1823 keV γ rays from the first $1/2^+$ and $3/2^+$ states of ^{23}Ne; other ^{23}Ne γ rays were too weak or too contaminated. A third γ ray, at 2083 keV from the $(\mu^-, n\nu)$ reaction, was used in the determination of Λ_h. Their time spectra were obtained from fits to time binned energy spectra. In the fits to the 1017 and 1822 keV γ rays, lines at 1014 keV [from ^{27}Al(n,n')] and 1809 keV [from ^{27}Al(μ^-,ν)] were included. Background measurements showed these were the only γ rays in the vicinity of the interesting peaks. The Ge2 time spectra are shown in Fig. 2.

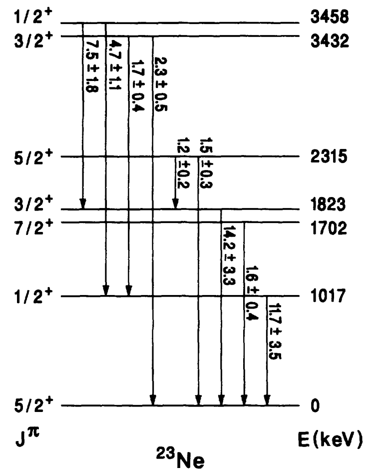

FIG. 1. The spectrum of γ rays observed from ^{23}Ne following μ^- capture on ^{23}Na. The yields are per 10^3 μ^- stops.

To obtain Λ_+/Λ_- and Λ_h the time spectra were fit by an equation representing the capture time dependence in the presence of the HF effect $N(t)$, convoluted with the instrumental time resolution. The equation is given by [12]

$$N(t) = Ae^{-\Lambda_D t}(1 + ke^{-\Lambda_h t}) \tag{1}$$

with

$$k = f_+(\Lambda_+/\Lambda_- - 1), \tag{2}$$

where Λ_D is the muon disappearance rate, Λ_h the HF transition rate, f_+ the initial population of the upper F_+ state, and Λ_+/Λ_- the capture HF dependence. It assumes the difference in the disappearance rates from the two HF states, $\Delta\Lambda_D = \Lambda_{D_-} - \Lambda_{D_+}$, is much smaller than Λ_h, which is the case in ^{23}Na ($\Delta\Lambda_D/\Lambda_h \sim 0.004$) [12,21]. It is also assumed that the hyperfine states are statistically populated at $t = 0$, which is the case when the target is unpolarized [22].

To extract the values of Λ_h and Λ_+/Λ_-, the six time

TABLE I. Comparison of the measured and calculated μ^- capture rates on ^{23}Na.

J^π Expt.	E (keV) Expt.	$\Lambda_{\rm obs}$ ($\times 10^3$ s^{-1}) Expt.	E (keV) Theory	$\Lambda_{\rm obs}$ ($\times 10^3$ s^{-1}) Theory	Λ_+/Λ_- Theory
$1/2^+$	1017	4.4 ± 1.2	995	5.5	0.11
7/2	1701	1.3 ± 0.3	1759	0.7	0.13
$3/2^+$	1823	4.2 ± 1.1	1769	6.2	0.21
$5/2^+$	2315	2.3 ± 0.6	2186	0.6	2.04
$3/2^+$	3432	3.8 ± 0.8	3237	2.5	0.32
$1/2^+$	3458	10.2 ± 2.4	3497	9.4	0.09

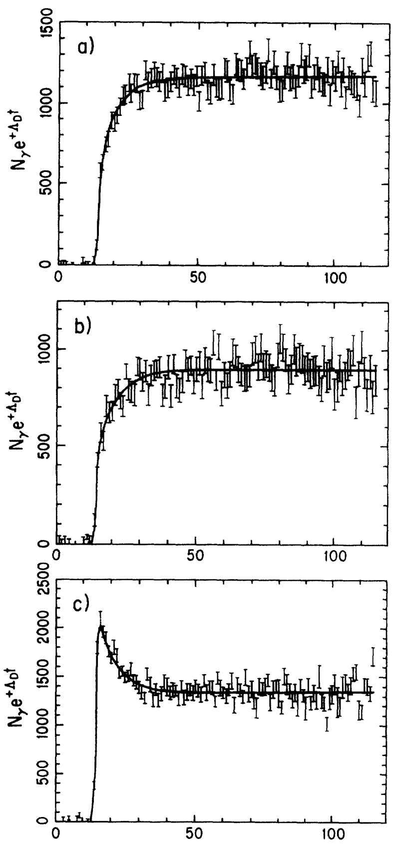

FIG. 2. The Ge2 time spectra of the (a) 1017, (b) 1823, and (c) 2083 keV γ rays following μ^- capture on ^{23}Na (9.58 ns/bin). The μ^- disappearance rate has been divided out to more clearly show the hyperfine effect. The solid lines are fits to the time spectra using Eqs. (1) and (2).

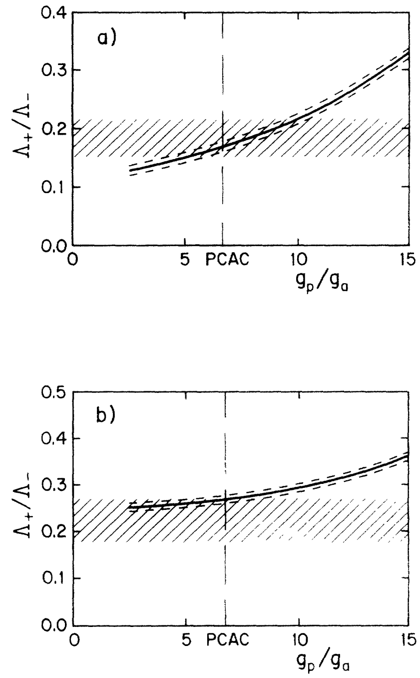

FIG. 3. The calculated HF dependence for (a) the 1017 and (b) the 1823 keV γ rays as a function of g_p/g_a. The dashed lines indicate the uncertainties due to the origin of the γ rays; the hatched areas indicate the measured values of Λ_+/Λ_- ($\pm 1\sigma$).

spectra of the three γ rays in Ge1 and Ge2 were individually fit, and then weighted means of Λ_+/Λ_- and Λ_h calculated. The results of these fits are shown in Fig. 2. They yielded $\Lambda_+/\Lambda_- = 0.184 \pm 0.032$ and 0.225 ± 0.043 for the 1017 and 1823 keV γ rays, and $\Lambda_h = 15.5 \pm 1.1\ \mu\text{s}^{-1}$ (the errors include the correlations between Λ_+/Λ_- and Λ_h). The χ^2 per degree of freedom (pdf) for the fits to the 1017 and 1823 keV γ rays for Ge1 and Ge2 were 1.27, 1.08, 1.94, and 1.35 (the χ^2 pdf of 1.94 is a consequence of two data points having large deviations from the best fit). The same results (within $\sim 0.3\sigma$) were obtained whether Λ_D was fixed at its known value [23] or allowed to vary. Varying the parameters of the instrumental energy and time resolutions within their uncertainties changed the values of Λ_+/Λ_- and Λ_h by $\leq 0.3\sigma$.

To test for distortions of the time spectra we also fit the time spectra of events following μ^- stops in P, Ca, Fe, and Pb where HF effects are absent. Good fits were obtained using a prompt x-ray peak and a single exponential with the appropriate lifetime (after small corrrections for μ^- pileup). The effect of μ^- pileup in the Na target on Λ_+/Λ_- and Λ_h is negligible.

Based on the yield data in Fig. 1 and the branching ratios from Ref. [16], the origins of 1017 keV γ rays are $(38 \pm 10)\%$ from the 3458 keV state, $(14 \pm 3)\%$ from the 3432 keV state, $(1.9 \pm 0.6)\%$ from the 2315 keV state, and $(46 \pm 7)\%$ direct capture. Likewise, the origins of 1823 keV γ rays are $(50 \pm 5)\%$ from the 3458 keV state, $(2.6 \pm 0.7)\%$ from the 3432 keV state, $(7.7 \pm 0.9)\%$ from the 2315 keV state, and $(39 \pm 8)\%$ direct capture. To determine g_p/g_a we have calculated the hyperfine dependences of the 1017 and 1823 keV γ rays using their measured origin and the calculated HF dependences of the contributing states. The results, as a function of g_p/g_a, are shown in Fig. 3. Very similar curves are obtained for $g_a = 1.0$ and 1.25. Using these curves the measured HF dependences of the 1017 and 1823 keV γ rays yield $g_p/g_a = 7.6 \pm^{2.1}_{2.5}$ and $g_p/g_a \leq 7.1$ (1σ), respectively. The errors include the statistical uncertainties, uncertainties in the Ge1 and Ge2 relative acceptances, and the branching ratio uncertainties. They do not include the model dependence of the extraction of g_p/g_a from Λ_+/Λ_-, however, investigations of the model dependence of the $\mu^- {}^{23}\text{Na}(3/2^+, 0) \to \nu {}^{23}\text{Ne}(1/2^+, 1017)$ HF dependence showed an uncertainty in Λ_+/Λ_- of only ± 0.015 at $g_p/g_a = 6.7$ [24]. The results for g_p/g_a are consistent with the Goldberger-Treiman estimate, $g_a/g_p = 6.7$, but in disagreement with claims of a large enhancement of g_p/g_a in light nuclei [5].

A possible source of error in the extraction of g_p/g_a could be undetected feeding of the 1017 and 1823 keV states. To search for further feeding we determined the total number of γ rays coincident with 1017 and 1823 keV photons by measuring the ratio of counts in the 1017 and 1823 keV peaks in the Ge1 singles and Ge1·CS2 coincidence spectra. The coincidence efficiency was measured using a ^{60}Co source, and a CS2 software energy threshold of ~0.5 MeV ensured a uniform photon efficiency from 1.0 to 5.0 MeV. This procedure yielded 0.56 ± 0.03 and 0.56 ± 0.05 coincident γ rays per 1017 and 1823 keV photon, respectively, consistent with values of 0.55 ± 0.11 and 0.63 ± 0.16 calculated from Fig. 1. Last, limits of $\leq 4\%$ (1017) and $\leq 5\%$ (1823) were set on feeding from a level at 3836 keV; the only ^{23}Ne bound state not observed that is known to decay via the 1017 and 1823 keV levels [16].

Our determination of the HF transition rate in Na metal, $\Lambda_h = 15.5 \pm 1.1\ \mu s^{-1}$, is in reasonable agreement with the rate calculated by Winston [12], $\Lambda_h = 14\ \mu s^{-1}$, based on Auger emission. However, the value in Na metal is nearly twice the value obtained from a previous measurement in NaF, $\Lambda_h = 8.4 \pm 1.9\ \mu s^{-1}$ [25]. One possible explanation is a slower refilling of the electrons ejected during the μ^- atomic cascade in the insulator NaF compared to the metal Na [26]. A chemical dependence of Λ_h would be important in possibly enabling the extension of HF effect experiments to other nuclei. However, the difference in Λ_h for Na and NaF is only $\sim 3\sigma$, and it requires confirmation.

In summary, we have measured the rates and hyperfine dependences of exclusive μ^- capture on ^{23}Na, and the hyperfine transition rate in Na metal. The measured capture rates to six excited states in ^{23}Ne are in general agreement with a calculation using the $1s$-$0d$ shell model and the USD residual interaction. The measured hyperfine dependences of the 1017 and 1823 keV γ rays from the first $1/2^+$ states and $3/2^+$ states in ^{23}Na yield, using the shell model, weak pseudoscalar couplings of $g_p/g_a = 7.6 \pm ^{2.1}_{2.5}$ and $g_p/g_a \leq 7.1$, respectively. These results are consistent with the Goldberger-Treiman estimate for g_p/g_a, but in disagreement with suggestions of a large enhancement of g_p/g_a in light nuclei. The measured hyperfine transition in Na metal was found to be $\Lambda_h = 15.5 \pm 1.1\ \mu s^{-1}$ in reasonable agreement with the theory of Auger deexcitation, but nearly twice the measured rate in NaF. This $\sim 3\sigma$ difference in Λ_h in Na and NaF merits further investigation.

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