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Measurement of the resonance at $E_R = 1422$ keV in ^{36}Ar$(p,\gamma)^{37}$K

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A new resonance at $E_R = 1422$ keV has been found in the reaction ^{36}Ar$(p,\gamma)^{37}$K. From its measured resonance strength of $\omega\gamma = (6.0\pm1.5)\times10^{-4}$ eV the proton partial width Γ_p can be calculated. Our data suggest a value of $\Gamma_\gamma/\Gamma_p \approx 40$ for the ratio of γ to proton partial width for the corresponding state at $E_x = 3241$ keV in ^{37}K. We find that the corrected distribution of Gamow-Teller strength below the isobaric analog state as obtained from the β-delayed proton decay of ^{37}Ca is in agreement with the results inferred from the ^{37}Cl$(p,n)^{37}$Ar reaction.

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Measurements of Gamow-Teller (GT) transition strengths provide information both about the nature of the weak interaction and about the structure of nuclear wave functions. If experimental β-decay GT strengths are compared to shell-model calculations, it is found [1] that the measured B(GT) values are systematically smaller than those calculated using the free-nucleon single-particle matrix elements of the Gamow-Teller operator. Brown and Widenthal [1] found that in the middle of the *sd* shell the effective matrix elements for transitions to low-lying states are reduced (or "quenched") by a factor of 0.77 relative to the free-nucleon values based on the neutron β decay. Gamow-Teller transition strengths can also be deduced [2] from 0° cross sections of intermediate-energy (p,n) reactions permitting measurements to higher excited states, and it is again found [3] that the experimental data are quenched with respect to the shell-model calculations. A recent measurement of the β-delayed proton decay of ^{37}Ca by García *et al.* [4] resulted in a GT strength distribution which disagreed strongly with the results from a forward angle ^{37}Cl$(p,n)^{37}$Ar experiment performed by Rapaport *et al.* [5]. Both results should be identical as long as isospin is a good quantum number. Adelberger *et al.* [6] argued that the β-decay data show no evidence for the quenching of GT strength but do instead indicate inconsistencies both in the shell-model calculations and in the description of the (p,n) reaction. The β decay of ^{37}Ca has one of the largest energy releases of any nucleus in the *sd* shell ($Q_{\rm EC} = 11.64$ MeV). The $A = 37$ system, therefore, allows a detailed comparison of GT strength inferred from (p,n) experiments and β-decay studies over a significantly larger range of excitation energy than any other system studied so far. The largest disagreements between the two experiments were found at excitation energies of $E_x = 1.4$ and 3.2 MeV. The ^{37}Cl$(p,n)^{37}$Ar reaction was remeasured [7] with better resolution and reduced background. Preliminary results [7] of that experiment indicate a GT strength distribution below $E_x = 4$ MeV consistent with the previous [5] experiment.

García *et al.* [4] deduced logft values for the various transitions from the relative proton intensities, normalized by assuming log$ft = 3.30$ for the transition to the isobaric analog state (IAS) at $E_x = 5.0$ MeV. The transitions to the ground state and to the first excited state at $E_x = 1.37$ MeV in ^{37}K do not produce delayed protons, since these states are located below the proton threshold. Assuming isospin invariance, the strength of the GT transition to the ^{37}K ground state is determined by the electron capture rate ^{37}Ar(EC)^{37}Cl. The logft value for the remaining GT transition to the first excited state at

$E_x = 1.37$ MeV is then given by the ^{37}Ca lifetime, since the sum of all β^+ branching ratios must be unity. García *et al.* assumed [4] that each β^+ decay to an unbound level of ^{37}K produces a delayed proton. It was noted by Goodman *et al.* [8] that if the level at $E_x = 3.24$ MeV in ^{37}K predominantly decays through the γ channel rather than the proton channel its GT strength would not be observed in a β-delayed proton experiment. For the same reason the β-delayed proton work would also attribute incorrectly too much GT transition strength to the first excited state. We therefore attempted to determine the partial widths for the state at $E_x = 3.24$ MeV in ^{37}K and searched for the corresponding resonance at $E_R = 1.42$ MeV in the ^{36}Ar$(p,\gamma)^{37}$K reaction ($Q = 1.858$ MeV).

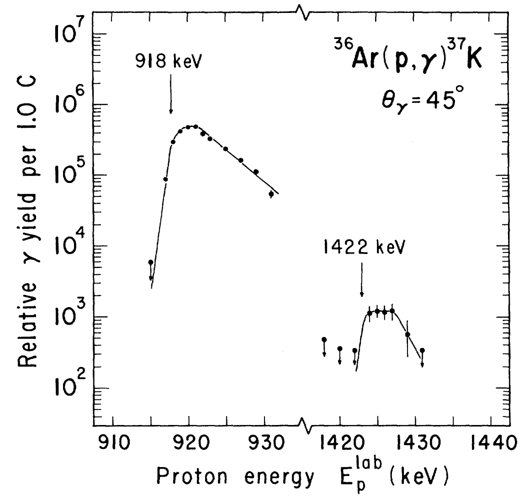

FIG. 1. Excitation function for ^{36}Ar$(p,\gamma)^{37}$K, measured at $\theta_\gamma = 45°$ for the primary transition to the ^{37}K ground state. The data points shown are not corrected for the γ-ray efficiency of the Ge detector. The resonance at $E_R = 1422$ keV has not been observed previously. The ratio of target thicknesses at $E_p = 918$ and 1422 keV agrees with the corresponding ratio of the effective stopping powers. The solid line is to guide the eye only.

The experiment was performed at the Ruhr Universität Bochum. The 4 MV Dynamitron tandem accelerator provided proton beams of 20–40 μA on target in the energy range $E_p = 900$–1450 keV. The particle energy was calibrated using proton-induced resonances of ^{27}Al$(p,\gamma)^{28}$Si ($E_R = 991.86 \pm 0.03$ keV [9]) and ^{36}Ar$(p,\gamma)^{37}$K ($E_R = 917.52 \pm 0.07$ keV [10]). The uncertainty in absolute energy and the energy spread are ±1 keV and 1 keV, respectively. The proton beam passed through a Ta collimator and was directed onto the target which was mounted at 45° with respect to the beam direction. A liquid-nitrogen-cooled copper tube was placed between the collimator and the target to minimize carbon deposition on the target. The target and chamber formed a Faraday cup for charge integration and a negative voltage (−300 V) was applied to the Cu tube to suppress secondary electron emission from the target. The ^{36}Ar target was produced by implanting ^{36}Ar ions into a 0.5 mm thick Ta backing and was used in earlier ^{36}Ar$(p,\gamma)^{37}$K [11] and ^{36}Ar$(\alpha,\gamma)^{40}$Ca reaction studies. The measured target thickness was 7.5 keV at $E_p = 918$ keV bombarding energy. The yield curve for the $E_R = 918$ keV resonance in ^{36}Ar$(p,\gamma)^{37}$K is shown in Fig. 1. The target stoichiometry was determined from the known strength of this resonance, $\omega\gamma = 0.208 \pm 0.030$ eV [12]. Using the stopping power tables of Andersen and Ziegler [13], a ratio of tantalum to argon of $N_{\mathrm{Ta}}/N_{\mathrm{Ar}} = 7.7 \pm 1.6$ has been obtained. The target was directly water cooled and was checked frequently. The target deteriorated by 12% over a total accumulated charge of 9 C. The γ rays were measured with a 100% Ge detector. The energy resolution was 2.0 keV at $E_\gamma = 1.33$ MeV. The detector was placed at $\theta_\gamma = 45°$ with respect to the beam direction in close geometry at a front-face-to-target distance of $d = 1.7$ cm. Relative γ-ray efficiencies were taken from Ref. [14]. The energy calibration of the detector was obtained using a ^{60}Co source and the known γ-ray energies from the room background contributions of ^{40}K and ^{208}Tl. The overall uncertainty in γ-ray energy was less than 0.5 keV.

Gamma-ray spectra were measured in the bombarding energy range $E_p = 900$–1450 keV with charge accumulations of 0.002–2.3 C. Figure 1 shows the excitation function for the primary decay into the ground state of ^{37}K ($R \rightarrow 0$). Two resonances were observed at $E_R = 918$ and 1422 keV. The resonance at $E_R = 918$ keV was known from earlier work [12]. Our measured excitation energy and the branching ratios are listed in Tables I and II, and they are in agreement with the values from the literature.

TABLE I. Energies and strengths for ^{36}Ar$(p,\gamma)^{37}$K resonances.

E_R (keV)	E_x (keV)		$2J^\pi$	$\omega\gamma$ (eV)
	Present[c]	Previous	Ref. [9]	
917.52±0.07[a]	2749.9±0.6	2750.27±0.06[d]	5^+	0.208±0.030[f]
1422±2[b]	3241.2±1.7	3239.4±1.8[e]	$(5,7)^+$	$(6.0\pm1.5)\times10^{-4}$[g]

[a] Reference [10]; used for the beam energy calibration.

[b] Present work; deduced from the location of midpoint of front edge of thick-target yield curve.

[c] Determined from the observed primary γ-ray energy.

[d] Reference [10].

[e] Reference [4].

[f] Reference [12].

[g] Present work; this value has been calculated relative to the $E_R = 918$ keV resonance by comparing the thick-target yields (see text). An alternative analysis, i.e., integrating the resonance areas of the thick-target yield curves [17], gives identical results within the experimental uncertainties.

TABLE II. Gamma-ray branching ratios (in %) of ^{37}K states.

	E_R (keV):	918		1422
	E_{xi} (keV):	2750		3241
E_{xf}	J^π	$\frac{5}{2}^+$		$(\frac{5}{2},\frac{7}{2})^+$
(keV)		Present	Ref. [10]	Present
0	$\frac{3}{2}^+$	98.4 ± 0.5	98.2 ± 0.1	100
1371	$\frac{1}{2}^+$			<9
1380	$\frac{7}{2}^-$	1.6 ± 0.2	1.5 ± 0.1	<9
2170	$\frac{3}{2}^-$	<0.5	0.3 ± 0.1	<10

The resonance at $E_R = 1422 \pm 2$ keV had not been seen previously. For the corresponding state in ^{37}K an excitation energy of $E_x = 3241.2 \pm 1.7$ keV was obtained from the measured primary γ-ray energy. The quoted error includes Doppler shift corrections due to possible lifetime effects. Both the measured resonance energy and the observed primary γ-ray energy (Table I) correspond within the experimental errors to the known state at $E_x = 3.24$ MeV $[J^\pi = (\frac{5}{2},\frac{7}{2})^+]$ in the compound nucleus ^{37}K, which was observed in the β-delayed proton decay experiment [4] as well as in ^{39}K$(p,t)^{37}$K [15] and ^{40}Ca$(p,\alpha)^{37}$K [16] reaction studies. Relevant parts of an on- and off-resonance γ-ray spectrum, taken at proton bombarding energies of $E_p = 1425$ and 1420 keV, are shown in Figs. 2(a) and 2(b), respectively. A peak at the position of the primary ground state transition ($R \rightarrow 0$) can clearly be seen in the on-resonance spectrum which does not appear in the off-resonance spectrum. No other transitions originating from this resonance were observed. We also note that the ratio of observed target thicknesses at $E_p = 918$ and 1422 keV (Fig. 1) agrees with the corresponding ratio of the effective stopping powers. These features prove that this expected resonance has indeed been observed.

The strength $\omega\gamma$ of a (p,γ) resonance is defined by

$$\omega\gamma = \frac{(2J+1)}{(2j_p+1)(2j_t+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma} \tag{1}$$

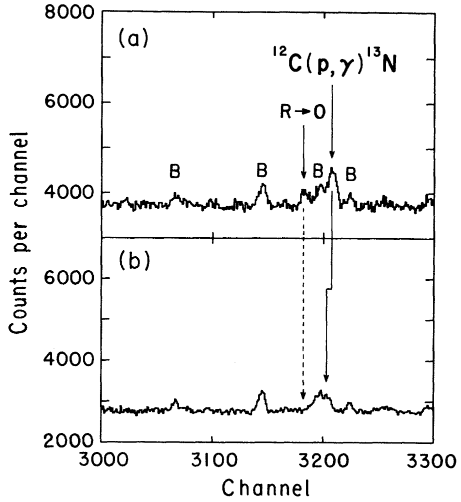

FIG. 2. Relevant sections of an (a) on-resonance and (b) off-resonance γ-ray spectrum, obtained at bombarding energies of $E_p = 1425$ and 1420 keV, respectively, for the reaction ^{36}Ar$(p,\gamma)^{37}$K. A peak arising from the primary decay to the ^{37}K ground state ($R \rightarrow 0$) is clearly observed in the on-resonance spectrum which is absent in the off-resonance spectrum. The flat background arises predominantly from the strong ^{19}F$(p,\alpha_2\gamma)^{16}$O contamination reaction. For the on-resonance spectrum shown, a total charge of 2.3 C was accumulated, corresponding to a running time of about 20 hours. Background contributions are labeled.

with J, j_p, and j_t as spin of the resonance, the projectile, and the target nucleus, respectively; Γ is the total width of the resonance, and Γ_p, Γ_γ, are the corresponding partial widths. The strength for the $E_R = 1422$ keV resonance was calculated relative to the well-known strength of the $E_R = 918$ keV resonance ($\omega\gamma = 0.208 \pm 0.030$ eV [12]) by comparing the measured thick-target yields [17] for the ground state transitions. The two $\omega\gamma$ values are connected through the relation

$$\frac{\omega\gamma(1422)}{\omega\gamma(918)} = \frac{\varepsilon_{\rm eff}(1422) E_R(1422) N_\gamma(1422) N_p(918) \varepsilon_\gamma(918) B_\gamma(918) W_\theta(918)[1-{\rm DT}(918)]}{\varepsilon_{\rm eff}(918) E_R(918) N_\gamma(918) N_p(1422) \varepsilon_\gamma(1422) B_\gamma(1422) W_\theta(1422)[1-{\rm DT}(1422)]} \tag{2}$$

with N_γ, ε_γ, and B_γ the measured intensity, efficiency, and branching ratio for the primary γ-ray transition into the ground state, respectively [here assumed: $B_\gamma(1422) = 1$]; N_p denotes the number of accumulated incident protons, E_R the resonance energy, W_θ the angular distribution of the observed transitions at $\theta_\gamma = 45°$ and DT the dead time of the electron system. The effective stopping power $\varepsilon_{\rm eff}$ of the TaAr target compound is given by

$$\varepsilon_{\rm eff} = \varepsilon_{\rm Ar} + (N_{\rm Ta}/N_{\rm Ar})\varepsilon_{\rm Ta} \quad \text{with } N_{\rm Ta}/N_{\rm Ar} = 7.7 \pm 1.6 \,. \tag{3}$$

The stopping power values for $\varepsilon_{\rm Ar}$ and $\varepsilon_{\rm Ta}$ were taken from Ref. [13]. For the newly observed resonance at $E_R = 1422$ keV, a value of $\omega\gamma = (6.0 \pm 1.5) \times 10^{-4}$ eV has been obtained (Table I). The quoted error includes the uncertainty of the reference value ($\pm 14\%$), the relative effective stopping powers ($\pm 5\%$), the relative γ-ray efficiencies ($\pm 5\%$), and the charge measurement ($\pm 5\%$). The value of $\omega\gamma(E_R = 1422$ keV) was corrected for the observed target deterioration. The dead time given by the computer was checked via intrinsic monitors, the room background lines of ^{40}K and ^{208}Tl. The measured [10] angular distribution for the ground state transition of the $E_R = 918$ keV ($J^\pi = \frac{5}{2}^+$) resonance indicates a $P_2(\cos\theta)$ Legendre polynomial term only ($A_2 = -0.56 \pm 0.01$). For the resonance at $E_R = 1422$ keV $[J^\pi = (\frac{5}{2},\frac{7}{2})^+]$ we have calculated the angular distributions assuming different values for the mixing ratio.

Taking also the large opening angle of the Ge detector into account, we have estimated that angular distribution effects change the resonance strength $\omega\gamma(E_R = 1422$ keV) by at most 7% and therefore no correction was applied. We also note that our deduced value for $\omega\gamma(E_R = 1422$ keV) is independent of the exact stoichiometric ratio of the ArTa target compound, since $\varepsilon_{\mathrm{Ta}} \gg \varepsilon_{\mathrm{Ar}}$ and $N_{\mathrm{Ta}} \gg N_{\mathrm{Ar}}$, as can be seen from Eqs. (2) and (3). Furthermore, since both the resonances at $E_R = 918$ keV and $E_R = 1422$ keV decay predominantly to the ground state of ^{37}K (Table II), no correction for coincident summing was necessary.

In principle, the observed primary γ-ray intensity at the $E_R = 1422$ keV resonance can also have contributions from direct proton capture (DC) into the ground state of ^{37}K and from the low-energy tails of broad resonances located at higher bombarding energy. We have estimated both effects. The DC into the ^{37}K ground state was calculated using the formalism described by Rolfs [18]. For the target-projectile interaction a Woods-Saxon potential with radius $R = 1.25 A_t^{1/3}$ fm and diffuseness $a = 0.65$ fm was used [19]. It has been shown [18,20,21] that the simple direct capture description is capable of reproducing the experimental cross sections for target nuclei in the mass range $A \leq 40$. Using the single-particle spectroscopic factor from Ref. [22] we obtain a cross section of $\sigma(\mathrm{DC} \rightarrow 0) = 9.4 \times 10^{-3}$ μb at $E_p = 1422$ keV. The low-energy tails of broad resonances were calculated for resonances with known strengths $\omega\gamma$ and widths Γ using Breit-Wigner cross sections. The strongest contributions originate from the resonances at $E_R = 1497$ keV ($\omega\gamma = 3.1 \times 10^{-2}$ eV, $\Gamma = 2.2$ keV), 2203 keV ($\omega\gamma = 7.0 \times 10^{-2}$ eV, $\Gamma = 35$ keV), and 2802 keV ($\omega\gamma = 0.7$ eV, $\Gamma = 83$ keV). The ground state branching ratios were taken from Ref. [10] when available. Otherwise a values of $B_\gamma(R \rightarrow 0) = 1$ was assumed in order to estimate the maximum contribution. The resulting upper limit for the total cross section of the low-energy tails is $\sigma(\mathrm{TAILS}) \leq 4.3 \times 10^{-4}$ μb at $E_p = 1422$ keV. Both effects together contribute less than 7% to the observed primary ground state intensity in our setup and therefore no correction was applied for the calculation of the resonance strength $\omega\gamma(E_R = 1422$ keV).

In order to obtain a values for the ratio of partial widths for the $E_x = 3241$ keV state in ^{37}K, we make the following assumptions.

(i) The $E_x = 3241$ keV $[J^\pi = (\frac{5}{2}, \frac{7}{2})^+]$ state in ^{37}K is the mirror of the $E_x = 3171$ keV ($J^\pi = \frac{5}{2}^+$) state in ^{37}Ar. The experimentally established level structure for the $A = 37$ system below $E_x = 4$ MeV allows clear analog assignments [10], which are in excellent agreement with shell-model calculations [23]. Our measured γ-ray branching ratio (Table II) is also in agreement with the decay [24] of the $E_x = 3171$ keV state in ^{37}Ar. Although no unique value for J^π has been measured we adopt for the ^{37}K state at $E_x = 3241$ keV the spin and parity of $J^\pi = \frac{5}{2}^+$ from its proposed [10] mirror state.

(ii) $\Gamma_\gamma \gg \Gamma_p$ (or $\Gamma \approx \Gamma_\gamma$), which is supported by shell-model calculations [25] and by preliminary results [26] of a recent ^{40}Ca$(p,\alpha)^{37}$K experiment. It immediately follows from Eq. (1) that the proton partial width Γ_p is given by our measured resonance strength, $\Gamma_p = \omega\gamma/\omega = (2.0 \pm 0.5) \times 10^{-4}$ eV. This result implies a reduced proton width (or equivalently, proton spectroscopic factor) of about 10^{-7}.

(iii) The γ-partial width for the $E_x = 3241$ keV state in ^{37}K is about $\Gamma_\gamma = 8.2 \times 10^{-3}$ eV. We adopt this value from the measured lifetime of the bound mirror state in ^{37}Ar ($\tau = 80 \pm 10$ fs [24]). Shell-model calculations [25] yield a similar value for $\Gamma_\gamma(3241)$. We note that a lifetime of that magnitude for the $E_x = 3241$ keV state in ^{37}K could in principle be determined by measurement of the attenuated Doppler shift for the ground state transition, as can be seen from Fig. 3 of Ref. [10]. However, in view of the weakness of the $E_R = 1422$ keV resonance and the high γ-ray background (see Fig. 2), we did not attempt to perform a Doppler-shift attenuation (DSA) lifetime measurement.

From these assumptions we obtain for the $E_x = 3241$ keV state in ^{37}K a ratio of γ-to proton partial width of $\Gamma_\gamma/\Gamma_p \approx 40$. Since García *et al.* [4] assumed $\Gamma \approx \Gamma_p$ for this state, the B(GT) values for both the states at $E_x = 1371$ and 3241 keV in ^{37}K have to be corrected. We calculated from the B(GT) values given in Table I of Ref. [4] the proton branching ratios and corrected the value for the $E_x = 3241$ keV state using $\Gamma_\gamma = 8.2 \times 10^{-3}$ eV and $\Gamma_p = 2.0 \times 10^{-4}$ eV. The excess branching was subtracted from the branching ratio for the $E_x = 1371$ keV state. Both corrected branching ratios were transformed back into B(GT) values. For this procedure the phase space factors of Wilkinson and Macefield [27] were used. Our results were $B^{\mathrm{new}}(\mathrm{GT}, 3241) = 0.16 \pm 0.05$ [old value: $B^{\mathrm{old}}(\mathrm{GT}, 3241) = 0.0039 \pm 0.0009$] and $B^{\mathrm{new}}(\mathrm{GT}, 1371) = 0.019 \pm 0.021$ [old value: $B^{\mathrm{old}}(\mathrm{GT}, 1371 = 0.074 \pm 0.010$]. The quoted errors for the corrected B(GT) values include the uncertainty of the old B(GT) values [4], our measured strength for the $E_R = 1422$ keV resonance, and the measured lifetime of the mirror state at

TABLE III. Comparison of β-decay GT strengths with values from (p,n) reaction studies.

E_x[a] (Mev)	B(GT)[b]		
	β decay[c]	β decay[d]	(p,n)[e]
0	0.0483±0.0014	0.0483±0.0014	0.054±0.011
1.37	0.074±0.010	0.019±0.021	<0.014
2–4[f]	0.239±0.007[f]	0.39±0.05[f]	0.36±0.06

[a] Excitation energy in ^{37}K or ^{37}Ar.

[b] We adopt the definition of B(GT) from Refs. [1,4].

[c] From Table I of Ref. [4].

[d] Reference [4], but corrected using $\Gamma_\gamma = 8.2 \times 10^{-3}$ eV and $\Gamma_p = 2.0 \times 10^{-4}$ eV for the $E_x = 3241$ keV state in ^{37}K (see text).

[e] Reference [5]. Since a different definition of B(GT) is used in the (p,n) work the values have been multiplied by $(g_A/g_V)^2 = (1.26)^2$ (see text).

[f] For the comparison with the (p,n) work, the B(GT) values for excitation energies of $E_x = 2$–4 MeV from Ref. [4] have been added together (see text).

$E_x = 3171$ keV in ^{37}Ar, but do not consider any systematic deviation due to the fact that we used the actual lifetime of the mirror state. Table III compares the corrected GT strength distribution as obtained from the β-delayed proton decay studies [4] with the values deduced from the (p,n) experiment [5] for excitation energies below the IAS. Since a different definition of B(GT) is used in Ref. [5], we multiplied the values from the (p,n) work by $(g_A/g_V)^2 = (1.26)^2$. This value for the ratio of weak-interaction coupling constants for the free neutron decay is recommended by Ref. [28]. Furthermore, only one broad peak is observed in the $^{37}\mathrm{Cl}(p,n)^{37}\mathrm{Ar}$ experiment for excitation energies of $E_x = 2-4$ MeV due to the poor energy resolution. For the comparison in Table III, the B(GT) values from Ref. [4] have been added together for that excitation energy range. It can be seen that both experiments are now in agreement within the uncertainties in the excitation energy range considered. Conclusions concerning the renormalization of the weak-axial vector current and the (p,n) reaction as a probe of GT strength, however, must await the results of a recent remeasurement [7] of the $^{37}\mathrm{Cl}(p,n)^{37}\mathrm{Ar}$ reaction and a more detailed comparison between the B(GT) distributions from both experiments has to be performed.

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