Positron-Neutrino Correlations in $^{32}\text{Ar}$ and $^{33}\text{Ar}$
Decays: Probes of Scalar Weak Currents and Nuclear Isospin Mixing

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The positron-neutrino correlation in the $0^+ \rightarrow 0^+ \beta$ decay of $^{32}\text{Ar}$ was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the Standard Model prediction; for vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0036$. Our result leads to improved constraints on scalar weak interactions. The positron-neutrino correlation in $^{33}\text{Ar}$ decay was measured in the same experiment; for vanishing Fierz interference we find $a = 0.944 \pm 0.002 \pm 0.003$. The $^{32}\text{Ar}$ and $^{33}\text{Ar}$ correlations, in combination with precision measurements of the half-lives, superallowed branching ratios and beta endpoint energies, will determine the isospin impurities of the superallowed transitions. These will provide useful tests of isospin-violation corrections used in deducing $|V_{ud}|$ which currently indicates non-unitarity of the KM matrix.

Keywords: Elementary Particles: leptonic and semileptonic decays; Elementary Particles: leptonic angular correlations; Elementary Particles: Cabbibo angle; Nuclear Physics: nuclear beta decay; Nuclear Physics: isospin mixing;
1. The \((e, \nu)\) Correlation as a Probe of Physics Beyond the Standard Model

In the Standard Model, nuclear \(\beta\) decay is mediated by the exchange of W bosons which have only vector and axial-vector couplings. However, extensions of the standard model, such as super-symmetric theories with more than one charged Higgs doublet, or leptoquarks, naturally predict scalar or tensor weak couplings [1]. A general effective Hamiltonian for allowed \(\beta\) transitions that respects Lorentz invariance is [2]

\[
H = (\bar{\psi}_p \gamma_\mu \psi_n) (C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C'_V \bar{\psi}_e \gamma_5 \gamma_\mu \psi_\nu)
+ (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n) (C_A \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma_\mu \psi_\nu)
+ (\bar{\psi}_p \psi_n) (C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu)
+ \frac{1}{2} (\bar{\psi}_p \sigma_{\lambda \mu} \psi_n) (C_T \bar{\psi}_e \sigma_{\lambda \mu} \psi_\nu + C'_T \bar{\psi}_e \gamma_5 \psi_\nu)
+ \text{Hermitian conj.}\quad (1)
\]

where a term proportional to \((\bar{\psi}_p \gamma_5 \psi_n)\) has been neglected because nucleons are non-relativistic. In the Standard Model, \(C_V = C'_V\), \(C_A = C'_A\), and \(C_S = C'_S = C_T = C'_T = 0\). Jackson et al. [2] computed the nuclear-\(\beta\)-decay rate from this Hamiltonian; for an unoriented initial state and summation over the lepton helicities

\[
dW = dW_0 (1 + a \frac{p_e \cdot p_\nu}{E_e E_\nu} + b \frac{m_e}{E_e}), \quad (2)
\]

where

\[
a_\xi = |M_F|^2 (|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2)
- \frac{1}{3} |M_{GT}|^2 (|C_A|^2 + |C'_A|^2 - |C_T|^2 - |C'_T|^2)
- \frac{1}{2} |M_{GT}|^2 (C_A^* C_T + C'_A^* C'_T)\quad (3)
\]

\[
b_\xi = \pm 2 \gamma \text{Re} [\bar{M}_F^2 (C_V^* C_S + C'_V^* C'_S) + |M_{GT}|^2 (C_A C_T + C'_A C'_T)]\quad (4)
\]

\[
\xi = |M_F|^2 (|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2)
+ |M_{GT}|^2 (|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2), \quad (5)
\]

where \(M_F\) and \(M_{GT}\) are rank-0 and rank-1 nuclear matrix elements. We have simplified the expressions by neglecting the small Coulomb effects, and adopting the allowed approximation (ignoring curvature in the lepton wave functions and
the recoil-order corrections). In what follows we shall assume $C_V = C'_V$ and express the scalar couplings in terms of:

$$\tilde{C}_S = C_S / C_V, \quad \text{and} \quad \tilde{C}'_S = C'_S / C_V.$$  \hfill (6)

Precise measurements of the $e$-$\nu$ correlation coefficient, $a$, and of the Fierz-interference term, $b$, can potentially yield information about physics beyond the standard model. Equations 2-5 are complicated and depend on nuclear physics information through $M_F$ and $M_{GT}$. However, for pure Fermi or pure GT transitions the expressions simplify and the $M_F$ and $M_{GT}$ factors cancel. In pure Fermi transitions, a positron-neutrino correlation coefficient $a < 1$ would immediately imply the presence of scalar currents; while in GT decays a value $a > -1/3$ would imply tensor currents.

To measure the $e$-$\nu$ correlation one must determine the daughter’s velocity, because it is out of the question to detect the low-energy neutrino. But, in general, measuring the daughter’s recoil velocity is not a trivial task: the velocities are very small and the interaction of the daughter with the surrounding medium can jeopardize the measurement. Fortunately nature has provided us with cases where the daughter states are unbound to proton emission, so that the daughter’s velocity can be determined via the ‘Doppler’ broadening of the beta-delayed proton groups. Protons are preferred over other $\beta$-delayed radiations because they are emitted before the daughter nucleus has slowed appreciably and can be detected with high resolution and good efficiency. Neutrons, on the other hand, are hard to detect with high resolution and high efficiency simultaneously. Gamma rays are generally emitted too slowly to probe the daughter velocity before it has been reduced by interaction with the surrounding medium. This paper discusses superallowed transitions from proton-rich nuclei with proton-unbound daughter states. These transitions are strong, which enhances the signal-to-noise ratio, and the widths of daughter states are ideally suited for probing the $e$-$\nu$ correlation:

- the time scale for proton decay is short enough so that the decays occur before the daughter looses any appreciable velocity due to interactions with the medium (in the superallowed decay of $^{32}\text{Ar}$, the daughter travels $\lesssim 2 \times 10^{-2}$ Å before the proton is emitted).
- because proton decays in these cases violate isospin symmetry the time scale for proton decay is long enough so the widths are much narrower than the lepton-recoil broadening (in the superallowed decay of $^{32}\text{Ar}$, the daughter state
has a width of $\approx 20$ eV while the lepton-recoil broadening has a full-width at half-maximum of $\approx 25$ keV).

2. Limits on Scalar Weak Interactions from $^{32}$Ar $\beta^+$ Decay

We performed an experiment at ISOLDE that measured with high precision the energies of protons following the $0^+ \rightarrow 0^+ \beta^+$ decay of $^{32}$Ar. Except for this experiment and a previous ISOLDE study of $^{32}$Ar by Schardt and Riisager [3], there are no other precise determinations of $e$-$\nu$ correlations in pure Fermi transitions, which explains why, prior to our new result, limits on scalar couplings were rather poor in comparison to those on tensor currents [4]. We here describe the salient features of our experiment and the extracted limits on scalar currents. More details on the $^{32}$Ar experiment can be found in Ref. [5].

Critical challenges for this kind of experiment are:

1. obtaining an intense and pure source of radioactivity,
2. eliminating proton-$\beta^+$ summing, which distorts the shape of the proton peak,
3. and optimizing the energy resolution of the proton counter.

ISOLDE solved problem 1 by producing very pure beams of both $^{32}$Ar and $^{33}$Ar from a CaO target and a plasma ion source, providing an average of $\approx 94$ $^{32}$Ar's/s and $\approx 3900$ $^{33}$Ar's/s on our catcher foil over the 9-day-long run. We solved problem 2 by immersing our detection system in a 3.5 T magnetic field. The $^{32}$Ar beam from ISOLDE was stopped in a $\approx 23$ $\mu$g/cm$^2$ C foil at 45 degrees to the beam. Our proton detectors were located at $\pm 90$ degrees with respect to the beam and at about 1.6 cm from the beam spot. In the 3.5 T field superallowed $\beta$'s had a maximum radius of $\approx 0.55$ cm, while protons had $\approx 7.14$ cm. We solved problem 3 by using cooled PIN-diode proton detectors ($\approx 0.9 \times 0.9$ cm) and temperature-controlled electronics to obtain a proton energy resolution of $\approx 4.5$ keV ($\approx 3.0$ keV electronic noise). This greatly enhanced our sensitivity to the $e$-$\nu$ correlation.

Fig. 1 shows Monte-Carlo predictions for the shape of the proton peak assuming the proton detector had infinitely good energy resolution. If one assumes $b = 0$ in Eq. 2 one can extract $a$ by producing linear combinations of these two shapes, folding them with the detector response function (assumed to be two exponentials with adjustable tails and areas, convoluted with a Gaussian of adjustable width) and determining the values of the parameters that minimize $\chi^2$. 
Figure 1. Intrinsic shapes of the delayed proton group from $^{32}\text{Ar}^+ ightarrow 0^+$ decay for $a = +1$, $b = 0$ (unshaded curve) and $a = -1$, $b = 0$ (light-shaded curve).

Fig. 2 shows our best fit to a subset of our data containing approximately 1/10 of the statistics. The very good energy resolution obtained in this study also allowed us to extract valuable spectroscopic information on $^{32}\text{Cl}$. The fit was performed using an R-matrix parametrization of the resonances. Reduced total widths, $\Gamma_p$, and ratios $\Gamma_{p1}/\Gamma_{p0}$ can be extracted for many of the resonances. For the general case when $b \neq 0$ one has to fold an additional distribution (taking into account the $m/E$ term in Eq. 2). We produced a grid in the $\tilde{C}_S, \tilde{C}_S'$ space and, for each point, minimized $\chi^2$ with respect to the response function parameters. The resulting confidence regions are shown in Fig. 3. We found that our $\tilde{C}_S, \tilde{C}_S'$ constraints are well reproduced by the single parameter

$$\tilde{a} \equiv a/(1 + 0.1913b)$$

where $a$ and $b$ are given in Eqs. 3, 4. In other words, replacing $m/E$ by an appropriate average reproduces the regions of interest and allows us to quote our results in terms of $\tilde{a}$. Our experiment yields the constraint

$$\tilde{a} = 0.9989 \pm 0.0052(\text{stat.}) \pm 0.0036(\text{syst.}) \text{ 68% c.l.}$$
The systematic error was evaluated by redoing the whole analysis under different conditions. We found $\partial \tilde{a}/\partial \Delta = -1.2 \times 10^{-3}$ keV$^{-1}$ where $\Delta$ is the $\beta$-decay endpoint; and $\partial \tilde{a}/\partial Q_p = -0.9 \times 10^{-3}$ keV$^{-1}$, where $Q_p$ is the energy of the emitted proton. We measured $Q_p$ with an uncertainty, $\delta Q_p = \pm 1.2$ keV, by alternating between $\sim 2$ h $^{32}$Ar runs with 10-15 min $^{33}$Ar runs that gave us a continuous calibration of the energy scale. The mass of $^{32}$Ar has been determined only to within 50 keV [8], which would impose a systematic error of $\approx 6\%$ on our measurement. Fortunately, as shown in Table [9], the masses of all other members of the $T = 2$ isospin multiplet are known with high precision. We use
Figure 3. 95% conf. limits on $\tilde{C}_S$ and $\tilde{C}_S'$, including statistical and systematic errors. Left panel: time-reversal-even couplings. The annulus is from this work, the diagonal band is the Fierz interference result of Ref. [6]. Right panel: time-reversal-odd couplings. The circles are from this work and correspond to phases of $\tilde{C}_S$ and $\tilde{C}_S'$ of $\pm 90^\circ$, $+45^\circ$ and $-45^\circ$. The shaded oval is the constraint with no assumptions about this phase. The diagonal band is from the $R$-coefficient in $^{19}$Ne decay [7].

Table 1
Comparison of the measured mass excesses of the lowest $T = 2$ quintet in $A = 32$ to predictions of the Isospin-Multiplet Mass Equation $[P(\chi^2, \nu) = 0.73]$.

| isobar  | $T_3$ | $M_{\text{exp}}$ (keV)$^a$ | $M_{\text{IMME}}$ (keV) |
|---------|------|--------------------------|------------------------|
| $^{32}\text{Si}$ | +2   | $-24080.9 \pm 2.2$       | $-24081.9 \pm 1.4$     |
| $^{32}\text{P}$  | +1   | $-19232.88 \pm 0.20^b$   | $-19232.9 \pm 0.2$    |
| $^{32}\text{S}$  | 0    | $-13970.98 \pm 0.41^c$   | $-13971.1 \pm 0.4$    |
| $^{32}\text{Cl}$ | -1   | $-8296.9 \pm 1.2^d$      | $-8296.6 \pm 1.1$     |
| $^{32}\text{Ar}$ | -2   | $-2180 \pm 50$           | $-2209.3 \pm 3.2$    |

$^a$unless noted otherwise, ground state masses are from Ref. [8].
$^b$ $E_x = 5072.44 \pm 0.06$ keV from Ref. [8].
$^c$ $E_x = 12045.0 \pm 0.4$ keV from Ref. [8-10].
$^d$from delayed proton energy measured here and masses of Ref. [8].

the Isospin-Multiplet Mass Equation $[10]$, $M(T_3) = a + bT_3 + cT_3^2$, to obtain

$$\Delta = 6087.3 \pm 2.2 \text{ keV}.$$ (9)
As shown in Fig. 4 we obtain an excellent fit to the IMME with \( P(\chi^2, \nu) = 0.71 \). On the other hand, modifying the IMME by adding a \( dT_3^3 \) term we obtain \( \Delta = 6086.7 \pm 4.9 \text{ keV} \) and \( d = 0.25 \pm 0.47 \text{ keV} \), but with a lower probability, \( P(\chi^2, \nu) = 0.52 \), indicating that there is no empirical basis for adding a term to the IMME. We expect the IMME to work very well for the \( A = 32 \) multiplet where
the states are relatively well-bound and the Coulomb barriers relatively high. Small non-zero $d$ terms (never more significant than $3\sigma$) have been observed in light nuclei where the $T_3 = T$ members are much closer to being unbound (or even unbound) and the Coulomb barriers much lower. We here assume $\delta \Delta = \pm 2.2$ keV which combined with the uncertainty in $Q_p$ yields a *kinematic* systematic error $\delta \tilde{a} = \pm 0.0032$. Note that even when $d$ is allowed to vary freely the uncertainty is only about twice this value. We also checked the dependence of $\tilde{a}$ on the *fitting regions* of the proton spectra; a 28% variation in the width of the region changed $\tilde{a}$ by less than $\pm 0.00055$. We examined the dependence of our results on the form of the detector response function by re-analysing the data with a single-tail response function; by re-analyzing the data assuming that a weak Gamow-Teller peak lay under the tail of the $^{32}$Ar superallowed peak; and by simultaneously fitting the $^{33}$Ar and $^{32}$Ar superallowed peaks using a common response function. From these tests we inferred a *line-shape* systematic error of $\delta \tilde{a} = \pm 0.0016$.

Figure 5 compares our results to previous constraints on scalar couplings. For scalar interactions with $\tilde{C}_S = -\tilde{C}_S'$ so that $b = 0$, our data yield the $1\sigma$ constraint $|\tilde{C}_S|^2 \leq 3.6 \times 10^{-3}$. The corresponding lower limit on the mass of scalar particles with gauge coupling strength is $M_S = |\tilde{C}_S|^{-1/2} M_W \geq 4.1 M_W$. We note that data from neutron $\beta$ decay by itself does not place stringent constraints on scalar couplings because the measurement on the correlation coefficient is not very accurate ($\delta a/a \approx 5\%$) and neutron decay is sensitive to both scalar and tensor couplings. Moreover, because of the larger value of $< m/E >$ (*i.e.* the lower endpoint energy), the circle generated by the equivalent of Eq. 5 has a large radius which weakens the neutron constraints. Even when supplemented by other data on the GT Fierz interference *etc.*, the neutron constraints are not as tight as those from the present work and limits on Fierz interference in $0^+ \rightarrow 0^+$ transitions.

### 3. Isospin mixing Corrections to $0^+ \rightarrow 0^+$ $Ft$ values and $|V_{ud}|$

Taken at face value, the $V_{ud}$ matrix element extracted from the $Ft$ values of nine $0^+ \rightarrow 0^+$ $\beta$-decay transitions implies non-unitarity of the Kobayashi-Maskawa matrix \[7\]. Because of the importance and unexpected nature of this conclusion, it is worth reexamining whether any systematic effect could affect the $Ft$ values. One possibility concerns the corrections for isospin-symmetry violation in the parent and daughter nuclear wave functions. These corrections are usually
Figure 5. Comparison of our constraints on scalar couplings with previous work. The light shaded area represents constraints from neutron β decay alone: i.e. from measurements of $a$, $A$, $B$, and $t_{1/2}$ [12]. A slightly darker area shows how these constraints improve when combined with measurements of the polarization of β’s from $^{14}$O and $^{10}$C [13]. The darker shaded area shows the result of adding to the previous the constraints on Fierz terms from $^{22}$Na [14] and the measurement of $a$ in $^{6}$He [15]. The darkest shaded area shows constraints from our results. The narrow area looking like a line at $-45^\circ$ is from constraints on Fierz terms from $0^+ \rightarrow 0^+$ transitions.

separated into ‘configuration mixing’ and ‘nucleon overlap’ parts; the latter being dominant ($\approx$ four times the former). Although several authors [18,19,20] have performed independent calculations that agree reasonably well it would be valu-
able to check these calculations on additional transitions in neighboring nuclei.

The cases we present below provide a good opportunity to check the calculated corrections; the ‘nucleon overlap’ corrections are enhanced over those in the nine standard cases because the nuclei lie farther from the valley of stability.

3.1. Isospin Mixing in the Fermi decay of $^{32}$Ar

The isospin-mixing correction in $^{32}$Ar was calculated by B.A. Brown [21] using the SKX Skyrme interaction [22]. This calculation yields $2.0 \pm 0.4\%$ where the uncertainty is based on previous comparisons of similar calculations to measurements. The large size of the correction is due to the looser binding of the $d_3^2$ and $s_{1/2}$ proton states compared to the neutron states. For comparison, the average correction for the nine standard cases is $\approx 0.41\%$, while the correction for the neighboring decay of $^{34}$Cl is $\approx 0.61\%$.

In $^{32}$Ar decay there is no mixing with GT transitions so that one can check the isospin-mixing correction simply by determining the half-life of the parent, and the branching ratio and endpoint of the superallowed transition. One can thus extract the $Ft$ value and compare with the prediction. Furthermore, if some Fermi strength is diverted into narrow $J^\pi = 0^+; T = 1$ levels in the $^{32}$Cl daughter, it may be possible to identify these transitions because they will have $a = +1$ instead of $a = -1/3$.

We expect to determine the $^{32}$Ar half life to $\approx 0.2\%$ from our ISOLDE experiment (our preliminary value is $t_{1/2} = 100.74 \pm 0.18$ ms) and we hope to determine the branching ratio with high precision at an upcoming experiment at MSU [23].

The extraction of the $^{32}$Ar mass from the IMME presented in section 2 yields the endpoint to $\approx 2.2$ keV, which allows to calculate the phase space factor to $\approx 0.3\%$. The $^{32}$Ar mass could also be measured at ISOLTRAP [24] but due to the short $^{32}$Ar half-life it is not clear that one could get enough intensity to determine the endpoint to within a few keV. All of the above indicates that one could extract the $Ft$ value to $\approx 0.41\%$.

3.2. Isospin Mixing in the Fermi decay of $^{33}$Ar

The theoretical isospin-mixing calculations can also be tested by studying the superallowed decays of the $A = 4n + 1$ nuclei. These are mixed Fermi/GT transitions so that one needs to determine the $B(F)/B(GT)$ ratios as well as the
half-lives, branching ratios and energy releases of the superallowed transitions. The $B(F)/B(GT)$ ratio can be obtained from the positron-neutrino correlation. As pointed out in Section 1 the $e-\nu$ correlation from mixed Fermi-GT transitions is not as useful for extracting information on scalar or tensor currents because one needs to know the relative amounts of each component. However, one can take the existing limits on scalar and tensor currents from other experiments and use the $e-\nu$ correlation to extract the $B(GT)/B(F)$ ratio. For simplicity, we here assume the scalar and tensor couplings to be zero.

We will soon gather the necessary information for the case of $^{33}$Ar. We will obtain the half-life of $^{33}$Ar and the absolute branching ratio of the superallowed transition from our experiment at MSU [23]. The endpoint can be extracted from the Isospin-Multiplet Mass Equation. Table 2 shows the mass excesses for the $T = 3/2$ quartet and the corresponding values of the IMME fit. Here we get:

$$\Delta(^{33}\text{Ar}) = 6060.6 \pm 2.6 \text{ keV}. \quad (10)$$

In addition there are plans to determine the $^{33}$Ar mass to $\approx 3$ keV using ISOLTRAP [24] (the mass of the daughter level is known to $\approx 1$ keV).

We obtain $a$ from the $^{33}$Ar delayed proton spectrum, a typical example of which is shown in Fig 6. Our fit to the ISOLDE data yields

$$a(^{33}\text{Ar}) = 0.944 \pm 0.002(\text{stat.}) \pm 0.003(\text{syst.}), \quad (11)$$

which implies $B(GT)/B(F) = 0.044 \pm 0.002$ [16]. Our result is in reasonably good agreement with the shell-model calculation of [25] which predicts
Figure 6. R-matrix fit to the $^{33}$Ar delayed proton spectrum. This spectrum contains roughly 1/10 of our data.

$B_{(GT)}/B_{(F)} = 0.055$, but in strong disagreement with the previous determination of Schardt and Riisager who obtained \[ a^{(33\text{Ar})} > 1.02 \pm 0.04 \] (2$\sigma$ error bars), which can be translated into an upper limit $B_{(GT)}/B_{(F)} < 0.015$ which is $\approx 4$ of their $\sigma$’s from our value.

We evaluated the systematic errors in $a$ following the same procedure we used for $^{32}$Ar. Using the endpoint deduced from the IMME and the masses of
Table 2, combined with the known $Q_p = 2276.5 \pm 1.0$ keV, and the derivatives \( \partial \tilde{a}/\partial \Delta = -9.1 \times 10^{-4} \text{ keV}^{-1} \); and \( \partial \tilde{a}/\partial Q_p = -8.5 \times 10^{-4} \text{ keV}^{-1} \), extracted by redoing the analysis with different values of \( \Delta \) and \( Q_p \), yields \( \delta \tilde{a} = 0.0023 \). Varying the width of the fitting region by 28\% yields variations of \( \delta \tilde{a} \approx 0.0004 \). Simultaneously fitting the $^{32}$Ar and $^{33}$Ar data with a common detector response function yields \( \delta \tilde{a} \approx 0.002 \). These three uncertainties were combined in quadratures to give the total systematic error shown in Eq. [1].

The discrepancy between our result in Eq. [1] and that of Schardt and Risager in Eq. [12] is due primarily to differences in the analysis rather than disagreement of the data itself. Dieter Schardt kindly made the raw data of Ref. [3] available to us and our analysis of their data gave a result essentially consistent with Eq. [1].

We now can show the potential value of measuring the \( \mathcal{F}t \) value for the superallowed transition by imagining that the total strength \( B(F) + B(GT) \) has been determined to \( \approx 0.3\% \). Combining this with our positron-neutrino correlation measurement would yield \( B(F) \) to \( \approx 0.5\% \). The predicted [21] isospin-mixing correction for $^{33}$Ar is \( \approx 1.2\% \). For comparison, the correction in $^{34}$Cl is \( \approx 0.6\% \). The fact that the correction is enhanced, as in $^{32}$Ar, makes it easier to measure. So these measurements could check whether the calculated corrections are accurate to within \( \approx 50\% \). It should be noted that larger discrepancies (corrections should be \( \approx 0.7\% \) as opposed to \( \approx 0.4\% \) [20]) would be needed to explain away the apparent non-unitarity of the Kobayashi-Maskawa matrix.

Acknowledgments
We thank D. Forkel-Wirth for help setting up our apparatus at CERN. This work was supported in part by the USA National Science Foundation and the Warren Foundation (at the University of Notre Dame) and by the Department of Energy (at the University of Washington).
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