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R2D2 — a symmetric measurement of reactor neutrinos free of systematical errors

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Abstract: We discuss a symmetric setup for a reactor neutrino oscillation experiment consisting of two reactors separated by about 1 km, and two symmetrically placed detectors, one close to each reactor. We show that such a configuration allows a determination of $\sin^2 2\theta_{13}$ which is essentially free of systematical errors, if it is possible to separate the contributions of the two reactors in each detector sufficiently. This can be achieved either by considering data when in an alternating way only one reactor is running or by directional sensitivity obtained from the neutron displacement in the detector.

Keywords: Solar and Atmospheric Neutrinos, Neutrino Physics.

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1. Introduction

In the previous several years large progress has been obtained in neutrino physics, and quite a clear picture is emerging for the mass and mixing parameters relevant for neutrino oscillations (see ref. [1] for a recent review). One of the remaining questions is the value of the mixing angle θ_{13}, where present data give only the upper bound $\sin^2 2\theta_{13} \leq 0.086$ at 90% CL [1], and it is a main objective of the next generation of oscillation experiments to pin down the value of θ_{13} (see ref. [2] for an overview and references). The current bound on $\sin^2 2\theta_{13}$ is dominated by the reactor neutrino experiments CHOOZ [3] and Palo Verde [4], which have been looking for the disappearance of the electron anti-neutrinos produced by nuclear reactors with a detector located about 1 km away from the reactor core. The sensitivity of these experiments is limited by the systematical uncertainties related to the neutrino flux produced by the reactor, which typically are of the order of 2%.

Recently it has been realized that the sensitivity of reactor neutrino experiments can be significantly improved if in addition to the "far detector" a "near detector" is put at a distance $\lesssim 300$ m from the reactor [5]–[7]. Many sites around the world are under discussion, among them the Double-Chooz proposal [8, 9] at the original CHOOZ site in France, the KASKA project in Japan [6] at the Kashiwazaki-Kariwa reactor complex, a site in China at the Daya-Bay reactor complex [10] (see also ref. [11]), and several sites in the US [12], e.g., at the Braidwood reactor (see ref. [13] for an overview). With such a one-reactor-two-detector setup (R1D2) the initial neutrino flux before oscillations can be determined to a very good accuracy by the near detector. The uncertainties associated to the neutrino flux are eliminated by the comparison of the near and far spectra, and sensitivities of the order of 10^{-2} for $\sin^2 2\theta_{13}$ can be achieved. To reach this aim it is necessary to reduce the uncertainties associated with the detectors below the one percent level, since the performance depends crucially on the relative normalization of the two detectors (see ref. [7] for a detailed discussion).

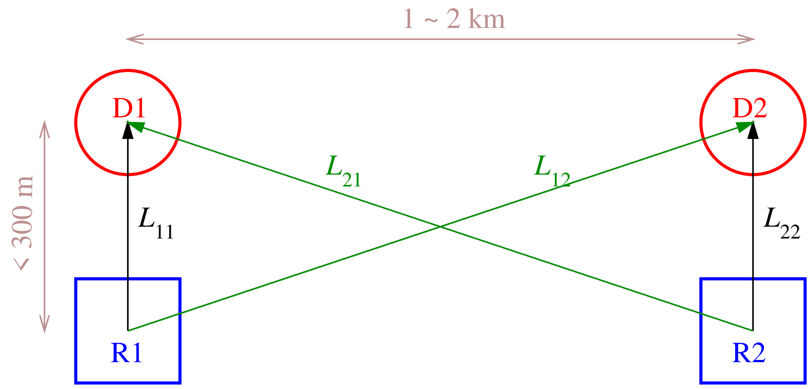

Figure 1: Geometry of the symmetric reactor neutrino experiment. The two reactor cores are labeled R1 and R2, and the two detectors are labeled D1 and D2.

In the present note we discuss a reactor neutrino measurement consisting of two reactors separated about one kilometer, and two symmetrically placed detectors, one close to each reactor. This setup is called R2D2 and it is illustrated in figure 1. Such configurations could be realized, e.g., at the Kashiwazaki-Kariwa complex in Japan or at the Daya-Bay complex in China.[1] A crucial element is the assumption that it is possible to separate events from the two reactors within the detectors. This could be achieved by periods where successively one of the two reactors is off or with both reactors on by sufficient statistical directional sensitivity obtained from the measurement of the neutron displacement [14, 15] in the detector. We will show in the following that the measurement of $\sin^2 2\theta_{13}$ becomes in this case essentially free of systematical uncertainties, and the $\sin^2 2\theta_{13}$ sensitivity is limited only by statistics. The reason for this is that all uncertainties associated to the produced neutrino flux cancel by the comparison of the two detectors, and the uncertainties associated to the detectors cancel since each detector acts simultaneously as near and far detector. Therefore, such a setup leads to a very efficient "self-calibration" and it turns out that in the ideal case indeed *no* external information on flux and detector normalization is necessary.

Let us mention that a similar effect could be achieved in principle at a one-reactor experiment if near and far detectors are exchanged. Movable detectors are discussed for some proposals in the US, see refs. [12, 13]. However, the R2D2 configuration provides a very elegant way to benefit from such kind of cross-calibration without the need to move detectors, which might introduce additional systematical effects. We also note that in a recent paper [16] a general multi-reactor-multi-detector experiment has been considered, which includes in principle also the R2D2 configuration. However, in that analysis, for the near detector(s) the events induced by far reactors have been neglected, and therefore the effects discussed in the present note are not covered.

The outline of the paper is as follows. In section 2 we present analytical considerations to illustrate how systematic effects associated to the detectors cancel in the R2D2 setup, whereas in section 3 we show the results of more realistic numerical investigations, including

[1] In the case of Kashiwazaki-Kariwa there are actually two reactor groups consisting of 3 and 4 blocks. In this work we always consider the idealized situation of only two separated reactor cores.

several types of systematics and backgrounds. In section 4 we comment on the possibility to use the neutron displacement to separate the two reactor contributions and on how the performance of R2D2 is affected if it is not possible to separate the events from the two reactors perfectly. We finish the work with concluding remarks in section 5.

2. Analytical estimates

To illustrate how systematic effects associated to the detectors cancel in the R2D2 setup we consider in the following a total rate measurement, taking into account only the (individual) normalization errors $\sigma_1 = \sigma_2 \equiv \sigma_{\rm det}$ of the two detectors. It is straight forward to include in this calculation more systematics like flux uncertainties or energy calibration, which we omit in this section for the sake of clarity. In this simplified case the χ^2 to estimate the sensitivity to $\sin^2 2\theta_{13}$ is given by

$$\chi^2_{\rm R2D2} = \sum_{r,d=1,2} \frac{[(1+a_d)T_{rd} - O_{rd}]^2}{O_{rd}} + \sum_{d=1,2} \left(\frac{a_d}{\sigma_{\rm det}}\right)^2 , \tag{2.1}$$

where d denotes the detector and r the reactor. The theoretical prediction in the case of oscillations T_{rd} and the "observed" number of events O_{rd} are given by

$$T_{rd} = N_{rd}(1 - \sin^2 2\theta_{13} \langle \sin^2 \phi \rangle_{rd}) \tag{2.2}$$

$$O_{rd} = N_{rd} , \tag{2.3}$$

where N_{rd} denotes the number of events in detector d from reactor r without oscillations, and $\langle \sin^2 \phi \rangle_{rd}$ is the averaged oscillation phase with $\phi = \Delta m^2_{31} L_{rd}/(4E_\nu)$. Up to leading order in the small quantities a_d and $\sin^2 2\theta_{13}$ eq. (2.1) becomes

$$\chi^2_{\rm R2D2} = \sum_{r,d=1,2} N_{rd} \left(a_d - \sin^2 2\theta_{13} \langle \sin^2 \phi \rangle_{rd}\right)^2 + \sum_{d=1,2} \left(\frac{a_d}{\sigma_{\rm det}}\right)^2 . \tag{2.4}$$

To minimize eq. (2.4) with respect to a_1 and a_2 we calculate

$$\frac{\partial \chi^2_{\rm R2D2}}{\partial a_d} = 2 \sum_{r=1,2} N_{rd} \left(a_d - \sin^2 2\theta_{13} \langle \sin^2 \phi \rangle_{rd}\right) + 2\,\frac{a_d}{\sigma^2_{\rm det}} = 0 , \tag{2.5}$$

which gives

$$a_d = \sin^2 2\theta_{13} \frac{\sum_{r=1,2} N_{rd} \langle \sin^2 \phi \rangle_{rd}}{\sum_{r=1,2} N_{rd} + 1/\sigma^2_{\rm det}} . \tag{2.6}$$

For simplicity let us assume complete symmetry between the detectors and reactors. Then we can identify the indices (compare figure 1)

$$\begin{aligned} (r,d) &= (1,1) = (2,2) = N , \\ (r,d) &= (1,2) = (2,1) = F , \end{aligned} \tag{2.7}$$

and hence, $N_{11} = N_{22} = N_N$ and $N_{12} = N_{21} = N_F$. Furthermore, we assume no oscillations for the "near" baseline, i.e., $\langle \sin^2\phi\rangle_N = 0$, and the oscillation maximum at the "far" baseline i.e., $\langle \sin^2\phi\rangle_F \sim 1$. Then eq. (2.6) becomes

$$a_1 = a_2 \approx \sin^2 2\theta_{13} \frac{N_F \langle \sin^2\phi\rangle_F}{N_N + N_F + 1/\sigma^2_{\rm det}} \approx \sin^2 2\theta_{13} \langle \sin^2\phi\rangle_F \frac{N_F}{N_N}, \tag{2.8}$$

where we have used $N_N \gg N_F + 1/\sigma^2_{\rm det}$. For the kind of setup under consideration one finds $\langle \sin^2\phi\rangle_F N_F/N_N = \langle \sin^2\phi\rangle_F (L_N/L_F)^2 \sim 10^{-2}$. Hence, we conclude from eq. (2.8) that the systematic pulls a_1 and a_2 are very close to zero. Indeed, substituting eq. (2.8) into eq. (2.4) we find

$$\chi^2_{\rm R2D2} = 2N_F \left(\sin^2 2\theta_{13} \langle \sin^2\phi\rangle_F\right)^2 \left[1 - \mathcal{O}\left(\frac{N_F}{N_N}\right)\right], \tag{2.9}$$

which gives the 1σ error on $\sin^2 2\theta_{13}$ of

$$\sigma_{\rm R2D2}(\sin^2 2\theta_{13}) = \frac{1}{\sqrt{2N_F}\,\langle \sin^2\phi\rangle_F} \left[1 + \mathcal{O}\left(\frac{N_F}{N_N}\right)\right]. \tag{2.10}$$

The leading order term corresponds to the case $a_1 = a_2 = 0$ in eq. (2.4), where the error on $\sin^2 2\theta_{13}$ is essentially given by the statistical error $1/\sqrt{2N_F}$. Note that the result in eq. (2.10) is independent of the value of $\sigma_{\rm det}$, which means that within this framework *no* external information is needed on the detector normalization.

Let us now compare this result with the traditional R1D2 setup with only one reactor. By dropping the reactor index r and taking into account a factor of two in the number of events to obtain the same statistics a similar calculation leads to

$$\sigma_{\rm R1D2}(\sin^2 2\theta_{13}) = \sqrt{\frac{1 + 2N_F\sigma^2_{\rm det}}{2N_F}}\,\frac{1}{\langle \sin^2\phi\rangle_F}. \tag{2.11}$$

Eq. (2.11) gives the same result as eq. (2.10) in the statistics dominated regime $N_F\sigma^2_{\rm det} \ll 1$. However, once the statistical and systematical errors become comparable, i.e., $1/\sqrt{2N_F} \sim \sigma_{\rm det}$ the 1σ error on $\sin^2 2\theta_{13}$ from the R1D2 setup becomes larger than the one from R2D2. Eventually, in this simple analysis based only on the total number of events, for infinite statistics the one-reactor setup is limited by the systematical error: $\sigma_{\rm R1D2}(\sin^2 2\theta_{13}) \to \sigma_{\rm det}/\langle \sin^2\phi\rangle_F$ for $N_F \to \infty$, whereas R2D2 gives infinite precision: $\sigma_{\rm R2D2}(\sin^2 2\theta_{13}) \to 0$.

3. Numerical calculations

In this section we present more realistic numerical calculations to confirm the analytical estimates of the previous section. We assume two identical reactors and two identical detectors and adopt typical values for the baselines: $L_{11} = L_{22} = 300\,\mathrm{m}$ and $L_{12} = L_{21} = 1.3\,\mathrm{km}$ (compare figure 1). However, we remark that minor deviations from such a perfect symmetry do not change the qualitative behaviour of our results. To demonstrate the maximum potential of the R2D2 configuration we assume in this section a *perfect*

Label	Type of systematical effect
(S1)	2% error on the neutrino flux normalizations (uncorrelated between the reactors), 0.6% error on the detector fiducial masses (uncorrelated between the detectors), energy scale uncertainty of 0.5% for each detector.
(S2)	Four different backgrounds of known shape (in total 2.2% of the events from the far reactor), with a normalization uncertainty of 100% for each component, uncorrelated between the two detectors (see ref. [2] for details).
(S3)	Flat background (2% of the events from the far reactor) with a bin-to-bin uncorrelated uncertainty of 50%.
(S4)	Experimental error completely uncorrelated between bins, detectors, and reactors.

Table 1: Systematical effects and backgrounds considered in the numerical calculations.

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separation of the events from the two reactors. We will comment on how deviations from this idealized situation affect the performance later in section 4. Following refs. [7, 2, 17] we perform a χ^2 analysis taking into account full spectral information (15 bins in positron energy) and various systematical effects, which are listed in table 1.[2]

The results of our analysis are summarized in figure 2. We show the sensitivity to $\sin^2 2\theta_{13}$ for the R2D2 setup as a function of the total number of far detector events, i.e., $N_{12} + N_{21}$.[3] To compare this luminosity scaling with the one of the traditional R1D2 setup we consider for the same configuration only events from one reactor and rescale the event numbers by a factor of 2 to obtain the same statistics as for R2D2. Panel (a) of figure 2 confirms the result of the previous section: In the case of the R2D2 setup the sensitivity to $\sin^2 2\theta_{13}$ scales simply with the square root of the number of events. The normalization uncertainties of fluxes and detectors cancel thanks to the symmetric cross-calibration implied by the experimental configuration. We have verified that even if both reactor fluxes and both detector normalizations are treated as free parameters in the fit the result is practically unchanged. In contrast, in the case of R1D2 we observe the well known effect of the worsening of the sensitivity caused by the detector uncertainties [7].

In panels (b) and (c) of figure 2 we have investigated the impact of the backgrounds (S2) and (S3) described in table 1. One observes that the sensitivity of the symmetric reactor experiment is hardly affected by backgrounds, whereas in the case of the one-reactor configuration they may lead to a significant worsening of the performance, especially for high statistics. The reason is again, that for R2D2 the background can affect a given detector only in the same way for the events from the near reactor and the far reactor. Hence, it is impossible to mimic the effect of oscillations by the background. Note that this is also true if the magnitude and/or the shape of the backgrounds in the two detectors are

[2]We do not include the spectral shape uncertainty of the initial neutrino flux, since it was shown in ref. [17] that for these type of experiments it has a very small impact on the sensitivity.

[3]At the baseline of 1.3 km roughly 130 events are obtained per ton detector mass, GW thermal reactor power, and years of data taking time.

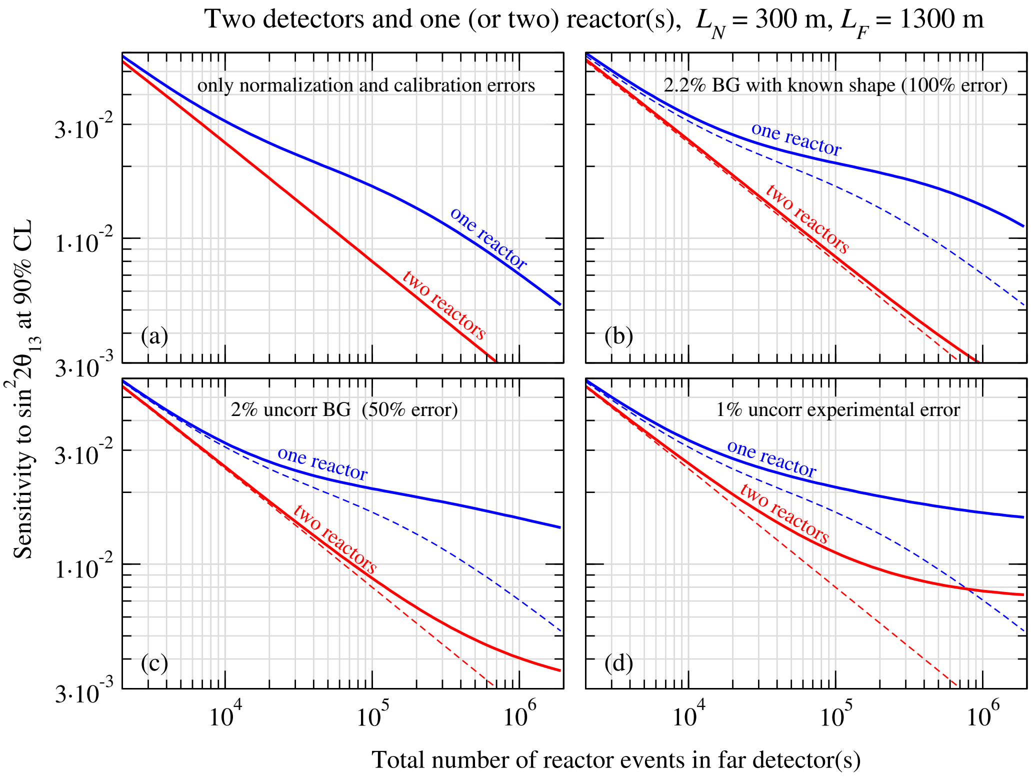

Figure 2: Comparison of the symmetric R2D2 reactor neutrino experiment setup ("two reactors") with the R1D2 configuration ("one reactor"). The luminosity scaling of the sensitivity to $\sin^2 2\theta_{13}$ is shown for different assumptions on backgrounds and systematic errors as described in table 1. In all panels flux and detector normalization errors, as well as the energy scale uncertainty (S1) are included. In panels (*b*), (*c*), (*d*) in addition the systematics (S2), (S3), (S4) are included, respectively. The dashed curves in the panels (*b*), (*c*), and (*d*) correspond to the curves shown in panel (*a*).

different. Only for very high luminosities a bin-to-bin uncorrelated background (S3) leads to some worsening of the sensitivity also for the R2D2 configuration.

Finally we have considered the impact of a completely uncorrelated error (S4) in panel (*d*) of figure 2. As expected in that case the $1/\sqrt{N}$-scaling is prevented also for the R2D2 setup. However, we want to stress that such an error corresponds to the worst case situation and realistically one expect such an error to be much less than 1%. It is hard to imagine a physical effect which can lead to an error which is uncorrelated between the detectors as well as between the reactors.[4] In the case where the separation of the events from the two reactors is done only by using data when one of the reactors is shut down time dependent effects in the detector or the backgrounds could introduce some uncorrelated errors, since data taken at different times are compared. If the event separation

[4]Let us note that an error of this type is expected to be significantly smaller than a completely uncorrelated error in the case of R1D2, as considered e.g. in refs. [7, 8]. The reason is that contributions to this error related to the reactors *and* to the detectors are eliminated because of the self-calibration, similar as in the case of the errors (S1).

is done by the neutron displacement measurement a background varying with the (horizonal) direction could lead to such an error. Both of these effects are expected to be very small.

4. Neutron displacement and the statistical separation of events

A crucial assumption of the considerations presented in sections 2 and 3 is that it is possible to separate the contributions of the two reactors in the detectors. This separation can be done in an obvious way by just considering data only when one of the two reactors is switched off. However, in that case it will be very difficult to obtain a large number of events. Therefore we point out a second possibility to separate the events from simultaneously running reactors using the directional sensitivity, which is based on the displacement of the neutrons between production point and capture on the scintillator. This effect has been observed previously in the reactor experiments Gösgen [18], Bugey [19] and CHOOZ [14].

After the production of the neutron in the reaction $\bar{\nu}_e + p \to e^+ + n$ it is moderated to thermal energies by scattering on hydrogen. This is a non-isotropic process which preserves some memory of the initial direction and leads to an average displacement of about 1.5 cm along the direction of the incoming neutrino. Once the thermal energy is reached isotropic diffusion takes place before the neutron capture, which does not alter the average displacement, but leads to a smearing of the individual capture locations. The details of this process depend also on the Gd loading of the scintillator. Finally one obtains a 3-dimensional gaussian distribution of neutron capture locations, with a mean shifted from the interaction vertex by approximately 1.5 cm along the neutrino direction. The width of the distribution is determined by the smearing from the diffusion process and the spatial detector resolution, and a typically value for the width is 6 cm [20] (see also ref. [15]). Although the width of the gaussian distribution is several times larger than the signal the large number of events allows a rather precise determination of the average neutron displacement.[5] For example with the 2700 events in CHOOZ a precision of (1.9 ± 0.4) cm has been obtained for the neutron displacement [14].

This result suggests that it might be possible to use this effect to separate the two reactor contributions in the case of the R2D2 experiment. Assuming an angle of 180° between the two reactors it is necessary to identify two overlapping gaussian distributions, shifted by ± 1.5 cm and with widths of $\sim$ 6 cm. Hence it is impossible to determine the source reactor for a single event, however on a statistical basis the number of events from the two reactors could be determined by fitting the normalizations of the two distributions to the data. Although there is a large overlap of the two gaussian distributions the large number of events imply very small statistical errors, and it seems possible to separate the two reactor contributions with sufficient precision. Moreover, also in this case the accuracy benefits from the cross-calibration offered by the geometrical configuration.

[5] Recall that if N events are observed from a gaussian distribution with standard deviation σ the error on the mean is given by $\sigma/\sqrt{N}$.

The obtainable accuracy in the event separation based on this method may very well reach the percent level. To illustrate this claim we assume that the neutron displacement is 1.5 cm and the corresponding width of the gaussian distribution is 6 cm [20, 15]. Next we take the distance to the far reactor to be 1.3 km, whereas the distance to the near reactor is taken to be 300 m. The reactors and detectors are aligned such that the angle between the direction to the near and far reactor in each detector is 180°. Now we simulate data with the correct angular distributions and try to determine the number of events from the far reactor in one detector by fitting the simulated data. Based on a sample of 10^5 events from the far reactor we find with above assumptions that the far reactor events can be measured with an accuracy of 3% at 1σ.

A detailed investigation of this possibility goes beyond the scope of the present work and will be covered elsewhere [21]. In the following we want to estimate the impact of a non-perfect separation of the two reactor contributions on the sensitivity to $\sin^2 2\theta_{13}$. Therefore we define the parameter s as the fraction of miss-identified events, which is given from the statistical precision of a fit to the directional information as outlined above. We perform the same χ^2 analysis as in section 3 but we replace the event numbers

$$N_{1d} \to (1-s)N_{1d} + sN_{2d}\,, \tag{4.1}$$
$$N_{2d} \to (1-s)N_{2d} + sN_{1d} \tag{4.2}$$

in each energy bin for the two detectors $d = 1, 2$. Hence, $s = 0$ (as well as $s = 1$) corresponds to perfect separation and the results of section 3 are recovered, whereas $s = 0.5$ corresponds to the case where no distinction of the reactors is possible. In figure 3 we compare the luminosity scaling of the $\sin^2 2\theta_{13}$ sensitivity of the R2D2 setup for various values of s. It becomes clear that one has to achieve $s \lesssim 0.05$ in order to maintain the sensitivity. Note however, that for luminosities $\gtrsim 5 \times 10^4$ R2D2 is still better than the one-reactor setup R1D2 even for $s = 0.1$.

In order to understand these results we note that in the case of non-perfect event separation the spectral analysis is very important. The energy distortion due to oscillations is present only in the events from the far reactor, and hence it provides a unique signal, which leads to a non-trivial sensitivity to $\sin^2 2\theta_{13}$ even if no distinction of the two reactors is possible (see figure 3). Consequently the results shown in figure 3 depend to some extent on the details of the spectral analysis, e.g., number of bins or energy resolution. We add however, that the main conclusions drawn from this figure are stable, and do not change also in the presence of additional systematical effects and/or backgrounds. The investigation of higher order effects like an energy dependent event separation s or an uncertainty on s is beyond the scope of the present note.

5. Concluding remarks

In this note we have pointed out that a reactor neutrino measurement with a configuration consisting of two separated reactors and two symmetrically placed nearby detectors (R2D2) allows a determination of $\sin^2 2\theta_{13}$ essentially free of systematical errors. The

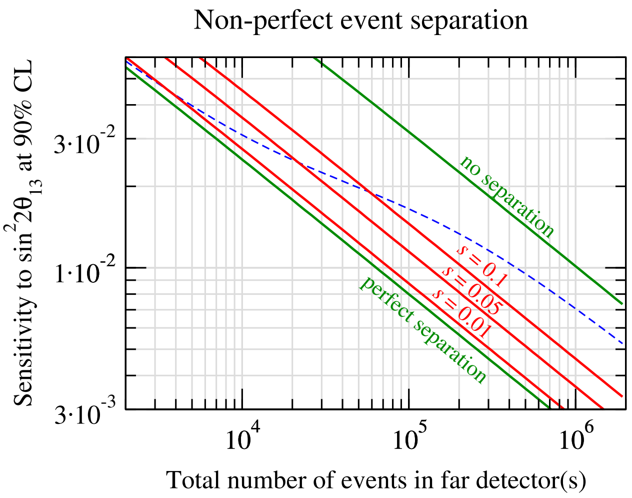

Figure 3: Luminosity scaling of the $\sin^2 2\theta_{13}$ sensitivity of the R2D2 setup in the case of non-perfect separation of the two reactor contributions. The same setup as in figure 2(a) has been adopted. The sensitivity is shown for various values of the fraction of miss-identified events s (see eq. (4.2)). The dashed curve corresponds to the one-reactor setup R1D2.

cross-calibration which becomes possible in such a configuration eliminates uncertainties associated to the initial neutrino fluxes as well as detector effects. In addition the impact of backgrounds is very small. In the specific cases of the KASKA proposal in Japan or the Daya-Bay project in China a configuration similar to the R2D2 setup seems in principle possible, since these reactor complexes consist of two groups of cores, separated by a distance of the order of 1 km, and a near detector has to be located close to each of the two blocks. Hence, in addition to the data from the far detector ("far" from all the reactors) also the data from the two near detectors on their own could provide very valuable information on $\sin^2 2\theta_{13}$, with a very small impact of systematical uncertainties.

An important condition for the cancellation of errors is the ability to separate events from the two reactors within each detector. An obvious way to achieve this would be a scenario, where only one reactor would be running in an alternating way at a given time. This is probably not realistic for commercial power reactors, but it might be realized in cases where a new reactor complex is added to an existing one at the right distance. The two detectors could measure initially with the first reactor on. Later, when the second complex is turned on, a (shorter) period where the first complex is off could be used to obtain the cross-calibration.

We are aware of the fact that it might be difficult to achieve large statistics data samples for an R2D2 experiment if data taking is limited to the periods when only one reactor is running. We discussed therefore the possibility to separate the events from two simultaneously running reactors by directional sensitivity from the measurement of the neutron displacement. Scaling the results obtained in the CHOOZ experiment to the much higher event numbers of the setups under consideration we conclude that such a separation might be possible on a statistical basis. We have estimated that the distinction of the events has to be better than 1% to 5% in order to maintain the self-calibration.

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We would also like to point out that our results do not rely on a *perfect* symmetrical configuration. The essential point is that both detectors act simultaneously as near and far detectors, while a certain stability exists against asymmetries in the size of the reactors and detectors, in baselines, and in backgrounds. This implies in particular that one needs not rely on identical reactors and the same overburden for the two detectors.

In conclusion, we have demonstrated that the method discussed here has the potential to significantly reduce the impact of systematical uncertainties for future reactor neutrino experiments. We believe that it is worth to pursue further studies to establish its experimental feasibility, including a more detailed investigation of the potential of the directional sensitivity of the detectors.

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