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MEASUREMENTS OF PARITY VIOLATION IN NEUTRON-NUCLEUS REACTIONS

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Introduction

In this talk I describe a new generation of experiments studying the weak interaction between nucleons. Measurements of the effect of this interaction are few in number and the significance of the observed effects are generally small. It is well known that the weak interaction violates parity. This was first experimentally established by C. S. Wu through measurement of an asymmetry of electrons emitted in the beta-decay of polarized ^{60}Co. The measured asymmetry was large because beta decay is a weak interaction process. For a process in which the strong interaction can contribute, we expect much smaller asymmetries, of order 10^{-7}.

In the work I will describe here we study the effects of the weak interaction through the signal of the parity violation associated with that interaction. There are two basic classes of experiment used to detect parity violation. The first relies on the measurement of a cross section or width that would vanish if parity were conserved. One example of this type of experiment in nuclear physics is the decay of an unnatural parity state to a 0^+ nucleus and an α-particle. Such measurements have been made for two nuclei: $^{16}O(2^-) \Rightarrow^{12} C(g.s.) + \alpha$ (Ref. 1) and $^{20}Ne(1^+) \Rightarrow^{16} O(g.s.) + \alpha$ (Ref 2). Parity-violating widths as small as $10^{-10}eV$ have been measured in these experiments. The interpretation of these results requires a detailed knowledge of the nuclear structure which is generally not available.

The second class of experiments involves a measurement of pseudo-scalar observables which are odd under parity inversion. These involve correlations between spin and linear angular momenta, for example circular polarization of γ-rays ($\sigma_\gamma \cdot k_\gamma$) or longitudinal analyzing power ($\sigma_p \cdot k_p$). One set of such measurements has involved measuring γ decays from parity-mixed doublets in light nuclei. The observable is the γ-ray circular polarization P_γ or, if the excited state has been produced with polarization, the γ-ray asymmetry A_γ. Measurements of P_γ in ^{18}F yielded a results[3] consistent with zero, as did experiments in ^{21}Ne (Ref. 4). The Seattle group was able[5] to produce the 110 keV level of ^{19}F in a polarized state and subsequently measured an asymmetry of the decay γ rays. The nuclear structure of the levels involved must be known in order to relate these measurements to the underlying interaction. In the case of ^{18}F and ^{19}F the nuclear matrix elements are calibrated by beta decay of the mirror nuclei.

Another member of the second class of experiments is the measurement of longitudinal analyzing powers. Such measurements have been made in the $p + p$ system at a number of incident proton energies (Ref. 6-8). The control of systematic errors in these experiments at the level of 10^{-7} is very difficult. In some cases corrections are made to the data that are as large as the remaining effects. The most significant measurement of a non-zero, parity-violating analyzing power[7] was made at $E_p = 45$ MeV and is $A_L = (-1.5 \pm 0.22)10^{-7}$.

In contrast to the 10^{-7} asymmetries measured in pp scattering, very large asymmetries have been measured in $n + A$ at low energies. Alfimenkov, et al.[9] measured transmission of a polarized epithermal neutron beam through a number of samples. They saw very large asymmetries for certain compound nucleus levels. The largest of these was $P_T = 7.3\%$ for a resonance at 0.73 eV in ^{139}La. This is an amazingly large effect of the parity-violating weak interaction in nuclear physics. Before I describe the subsequent work which has utilized the compound nucleus as an amplifier for the weak interaction, I will present a brief review of the physics of the compound nucleus.

Compound Nucleus Physics

An epithermal neutron incident on a nucleus will excite states at an excitation energy of 6 to 8 MeV in the compound nucleus. At this excitation energy the level spacings are of order 10's of eV as compared to 100's of keV near the ground state. Two processes can occur: potential scattering, in which the neutron is scattered from the overall nuclear potential, and resonance scattering, in which the neutron excites a specific state in the compound nucleus. The potential scattering appears as a more or less energy independent *background* underlying the compound nucleus resonances.

The scattering is characterized by the orbital angular momentum of the neutron, $l = 0$ (s-wave) or $l = 1$ (p-wave). At energies below a few hundred eV the s-wave partial width is much greater than the p-wave width. For reactions on spin 0 targets, the s-waves result in compound nuclear states with angular momentum $J = 1/2$; the p-waves can couple to form either $J = 1/2$ or $J = 3/2$.

We can see that the compound nucleus is a system of a closely spaced levels, of both positive and negative parity. What happens in the presence of a parity non-conserving weak interaction? The positive and negative parity levels will be mixed; the mixing can be described in perturbation theory since the weak interaction causing the mixing is much weaker than the strong interaction which formed the initial eigenstates. The mixing amplitude is proportional to the matrix element of the weak interaction between s and p states divided by the energy difference between the two states. The effect thus becomes larger when the level spacing decreases.

Bunakov and Gudkov[10] have derived an expression for the cross section asymmetry P introduced by the parity-violating mixing of s- and p-wave levels. Their expression is:

$$P = 2\frac{\langle \phi_s \mid H_w \mid \phi_p \rangle}{(E_p - E_s)} \frac{\gamma_s^n}{\gamma_p^n}. \tag{1}$$

Here E_p and E_s are the energies of the p- and s-wave states, H_w is the weak Hamiltonian, and γ_s^n and γ_p^n are the s- and p-wave partial width amplitudes. The energy denominator results in a *dynamical* enhancement, which is of order 10^3 times larger for these compound nuclear states than for single particle states near the ground state. The ratio of partial width amplitudes γ_s^n/γ_p^n is of order 100. This is the so-called *structural* enhancement. The combination of these two effects results in enhancements of order 10^5 larger than are found in parity-mixing of low-lying single-particle levels.

From the above discussion, we see that there are very large, several percent, effects due to parity violation in the compound nucleus. I have presented arguments that make the magnitude of these effects plausible. Experimentally, the parity violation is measured by looking at pseudo-scalar observables. The vectors available to form pseudo-scalar products are the neutron momentum k_n, the neutron spin σ_n, the target spin I_t, the photon spin σ_γ, and the photon momentum k_γ. Using these one can measure neutron spin rotation, neutron helicity $(\sigma_n \cdot k_n)$ dependence of both total cross section and capture cross section, $(\sigma_n \cdot k_\gamma)$ dependence of the capture cross section, and circular polarization of capture γ-rays. In this paper I will discuss only neutron helicity dependence measured for the total cross section and for the neutron capture cross section.

TRIPLE Measurements at LANSCE

The schematic layout of a transmission measurement of the helicity dependence of the total cross section is shown in Fig. 1. The elements of the experiment are an intense source of neutrons, a spin filter to polarize the neutron beam, a spin flipper to periodically reverse the neutron spin, a target, and a detector to count the neutrons that are transmitted through the target. The signal of parity violation is simply a difference in counting rate between neutrons with spin parallel and anti-parallel to the beam direction.

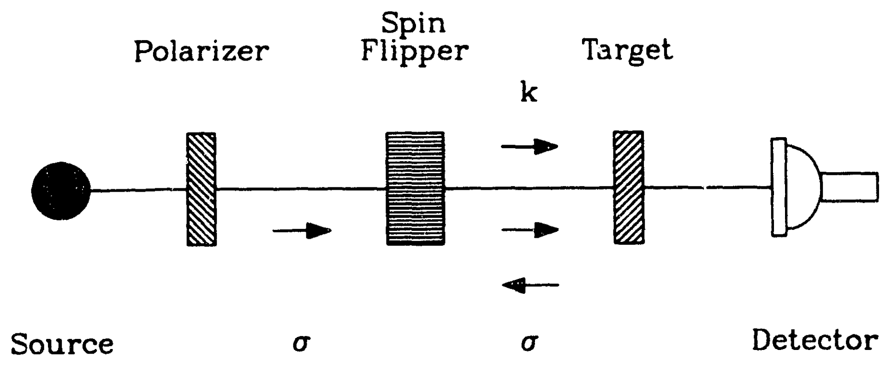

Fig. 1. Schematic Layout of a Transmission Experiment.

The TRIPLE group is carrying out transmission measurements at the Los Alamos Neutron Scattering Center (LANSCE). At LANSCE a proton storage ring is used to compress the 500 μsec beam pulse from the LAMPF accelerator into a pulse of about 250 nsec. The beam extracted from the PSR strikes a tungsten neutron production target that is surrounded by moderating material to produce a flux of low energy neutrons. The shielding around the production target is penetrated by well-collimated neutron flight paths. Our experiment is located on a flight path extending to a detector located at 60m. The long flight path is necessary to obtain sufficient energy resolution to resolve states up to a few hundred electron volts.

The neutron beam is polarized by taking advantage of the fact that the singlet np cross section is much larger than the triplet cross section over a large energy range. When the unpolarized neutron beam passes through a sample of polarized protons one spin state is selectively attenuated. The protons are polarized by the technique of dynamic nuclear polarization using a pumped ^{4}He refrigerator operated at 1.2 K in a 2 Tesla magnetic field. The protons are present as water of hydration in crystals of Lanthanum magnesium nitrate (LMN). Neutron polarizations of about 40 % with 20 % transmission are obtained in this way.

The relative polarization is monitored run by run using standard NMR techniques. The absolute magnitude of the neutron beam polarization is required to extract the parity-violating asymmetry P from the data. We perform this calibration using the large asymmetry for the 0.73 eV resonance in ^{139}La. We have measured this asymmetry independent of neutron beam polarization by replacing the spin filter with a second Lanthanum sample. The parity violation in the 0.73 eV resonance is used to both polarize and analyze the beam. Using this technique we measured[11] the asymmetry for the 0.73 eV resonance to be $P = 9.7 \pm 0.3\%$.

The original work of Alfimenkov, et al.[9] measured parity violation in a number of nuclei near Mass 100 (^{81}Br, ^{111}Cd, ^{117}Sn, ^{139}La). We have recently repeated the measurement on ^{117}Sn, using the capture technique for the first time[12] at LANSCE. In this method the neutron helicity dependence is measured for γ-rays emitted in neutron capture. The γ-ray detector consisted of two 15 by 15 by 15 cm^3 BaF_2 crystals which covered about 25 % of 2π. Neutron time of flight spectra were obtained for all gamma rays between 1 MeV and 9 MeV. Spectra corresponding to both the difference and sum of counts in the two helicity states are plotted in Fig. 2. The curves plotted are the fits using a line shape whose parameters are fitted to the sum spectrum. The extracted asymmetry was $P = 1.1 \pm 0.2\%$; this asymmetry has not been corrected for the effect of multiple scattering in the target.

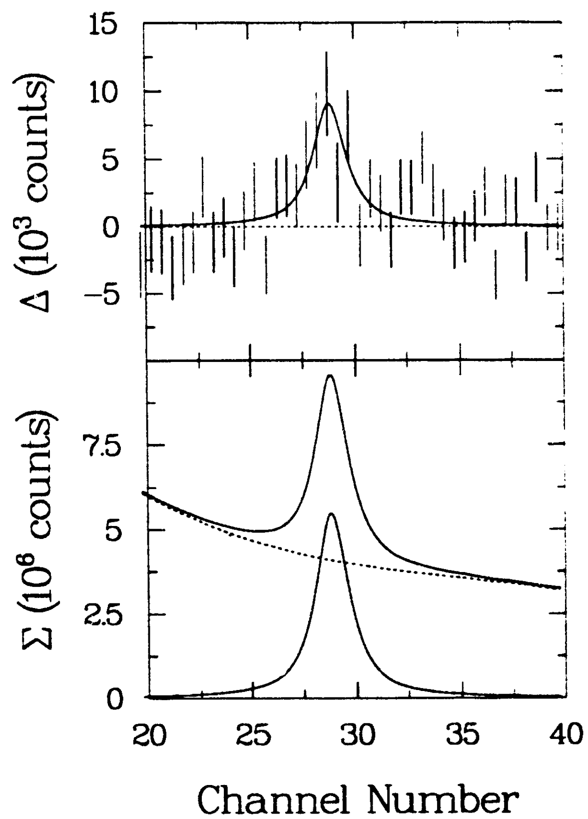

Fig. 2. Spectra for the sum and difference of the two helicity states in capture on ^{117}Sn.

The large neutron flux at LANSCE has enabled us to perform measurements over a large range of neutron energies. For samples that are available in sufficient quantity, 0.5-1.0 Kg, transmission measurements are the most efficient. Using the transmission technique we looked at many (17) p-wave resonances[13] for the first time in ^{238}U. Transmission and raw asymmetry (uncorrected for beam polarization) spectra are shown in Fig. 3. A number of strong s-wave and weaker p-wave resonances can be seen in this figure. The large asymmetry for the p-wave resonance at 63.5 eV stands out in this plot. We analyzed the data to extract the parity-violating asymmetry for 17 p-wave resonances in ^{238}U. In this set of data there was one very significant effect, $A = 2.5 \pm 0.4\%$ for the 63.5 eV resonance, and five barely significant ($\sim 2\sigma$) effects. Remember, in ^{238}U the p-wave resonances can have either $J = 1/2$ or $3/2$; only the $J = 1/2$ states can exhibit parity violation. One third of the resonances should be $J = 1/2$ and two thirds should be $J = 3/2$. We therefore expect to see parity violation in at most one third of the p-wave resonances; that is about what we have seen (5 of 17). Unfortunately, 2σ effects are not very convincing.

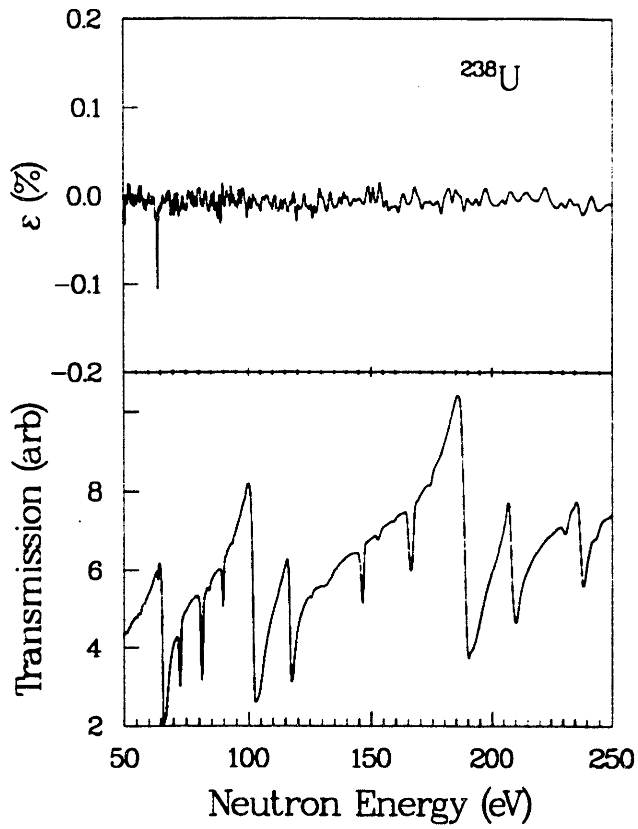

Fig. 3. Raw asymmetry and transmission spectra for ^{238}U.

Measurements made last summer[14] on ^{232}Th were much more satisfying in this regard. Spectra of raw asymmetry and transmission for a limited region of the ^{232}Th spectrum are plotted in Fig. 4. Twenty-three p-waves were analyzed in ^{232}Th; the results are plotted in Fig. 5. There are six effects of significance greater than 2.5 σ, including two whose magnitude was near 10 % , the largest since ^{139}La. It is interesting to note that these six effects in ^{232}Th represent more significant cases of parity violation than in **all** the existing data on A_L and parity mixing in light nuclei.

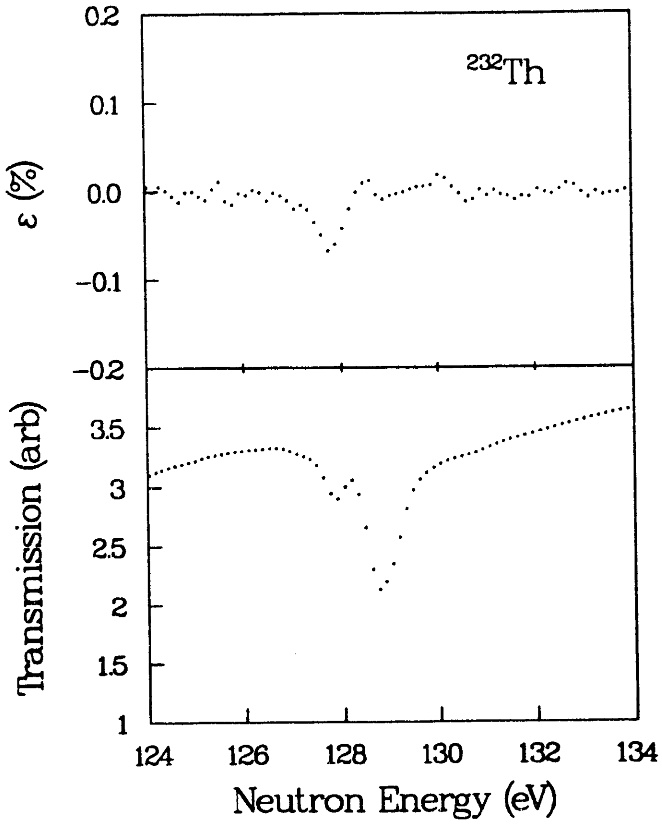

Fig. 4. Raw asymmetry and transmission spectra for ^{232}Th.

It seems that parity violation is ubiquitous in the compound nucleus; each $J = 1/2$ p-wave resonance exhibits parity violation. Although this is in itself interesting, we would like to be able to relate the measured parity violation to the matrix elements of the under-lying weak interaction. An examination of Eqn. 1 shows that this is straightforward in the case of two-state mixing if the parameters E_s, E_p, γ_s, and γ_p are known. In general, however, there are contributions from mixing with a number of s-waves. When there are contributions from many levels the parity violating asymmetry P$_i$ in the ith p-wave is given by:

$$P_i = \sum_j A_{ij} V_{ij}, \tag{2}$$

where

$$A_{ij} = \frac{2}{(E_p - E_s)} \frac{\gamma^n_{sj}}{\gamma^n_{pj}}$$

The subscripts i and j refer to the i^{th} p-wave and the j^{th} s-wave. The measured P_i are therefore linear combinations of many matrix elements V_{ij} and we cannot extract the matrix element between two specific levels.

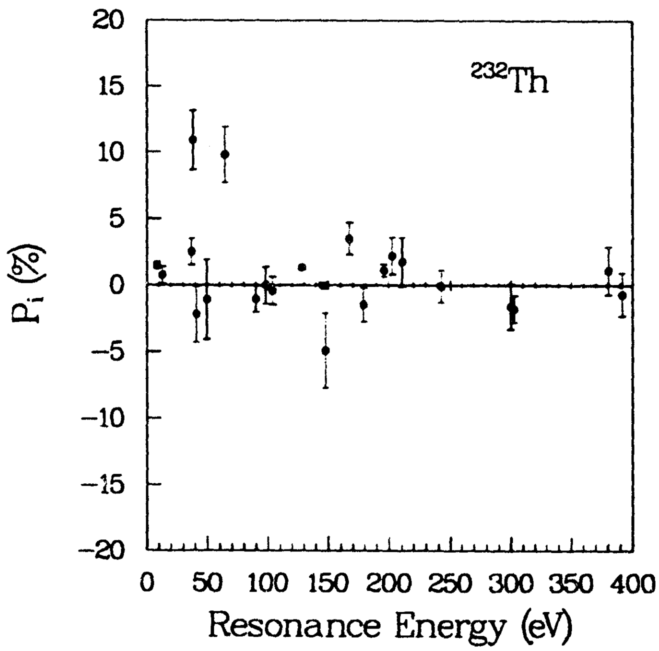

Fig. 5. The values of P_i extracted for 23 p-wave resonances analyzed in ^{232}Th.

The statistical nature of the wave functions involved allows us to extract the root-mean-square (rms) value of V_{ij} for all the levels in a given nucleus. The individual matrix elements can be treated as Gaussian random variables having mean zero and variance M^2. It can be shown[13] that the P_i, normalized by the sum of A_{ij}, are Gaussian variables drawn from the same distribution as V_{ij}. The distribution of measured parity-violating asymmetries can therefore be used to estimate M, the rms parity-violating matrix element. We have performed a maximum likelihood analysis to extract an estimate of M from both the Thorium and Uranium data sets. The result is $M = 0.58^{+0.50}_{-0.25}$ meV (Ref. 13) for ^{238}U and $M = 1.39^{+0.55}_{-0.38}$ meV (Ref. 14) for ^{232}Th.

Johnson, Bowman, and Yoo have worked[15] out the relationship between M and the parameters of the meson theoretical interaction of Desplanques, Donoghue, and Holstein (Ref. 16). It turns out that M depends mostly on the isoscalar ρ-coupling (h_ρ^0) and the isovector π-coupling (f_π^1). The limits placed on these parameters from our data overlap the DDH "reasonable" values. We are quite encouraged by these initial attempts to relate M to the underlying weak NN interaction.

The large enhancements of parity violation in the compound nucleus allow us to study the *systematics* of the weak interaction between nucleons in a way previously impossible. Figure 6 demonstrates why such a study is important. Here I have plotted the value of the parity-violating asymmetry divided by its uncertainty for all known cases of parity violation in the compound nucleus. This includes our own data on ^{139}La, ^{238}U, and ^{232}Th as well as the data of Alfimenkov, et al.[9] for ^{81}Br, ^{111}Cd, and ^{117}Sn. It is very surprising that 10 out of 11 effects greater than 2.5 σ are positive! This contradicts our earlier assumption about the randomness of the P_i.

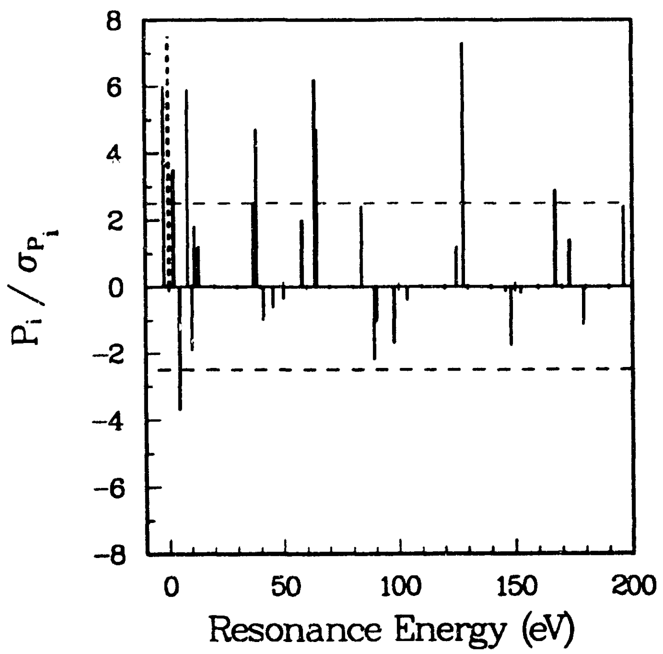

Fig. 6. Asymmetry divided by its error for parity violation in the compound nucleus. The dashed line is the value for ^{139}La, which has been divided by 2.

An examination of Eqn. 2 for P_i shows that to get a non-random sign for the P_i requires a correlation between the signs of: the PNC matrix elements V_{ij}, the partial width amplitudes γ_{sj} and γ_{pi}, and the energy denominator $(E_{sj} - E_{pi})$. All of these quantities are expected to have randomly distributed signs.[14]

The origin of the observed sign correlation is not yet understood. However, we know that sign and amplitude correlations are common when a symmetry-violating potential produces mixing of nuclear levels. One such example occurs for isospin mixing induced by the Coulomb interaction. The (π, π') reaction has been used[17] to study isospin mixing between doublets of 4^- states. The sign of the mixing is such that the lower state becomes a proton-like state and the upper state becomes neutron-like.

A second example is the asymmetric fine structure[18] measured for the Isobaric Analogue State (IAS) in medium heavy nuclei. In one picture this structure has been understood as due to an isospin-violating mixing between the IAS and the surrounding compound nuclear levels. The asymmetric structure comes about because the mixing occurs through a special "doorway" state. Auerbach has argued[19] by analogy with the IAS that a model describing the parity mixing of compound nuclear states through a "doorway" state could introduce sign correlation such as we have measured.

Summary

Large ($\sim 10^5$) enhancements of parity violation have been observed in the compound nucleus system. Arguments based on a statistical description of the compound nuclear levels have been used to relate the observed asymmetries to the parity-violating amplitudes in the underlying nucleon-nucleon interaction. The initial results show agreement with theoretical predictions of these quantities. Our unique ability to make systematic measurements has identified new physics in the form of unexpected sign correlations. It has been suggested that this new physics arises because of "collective" effects that modify the statistical picture of this reaction.

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