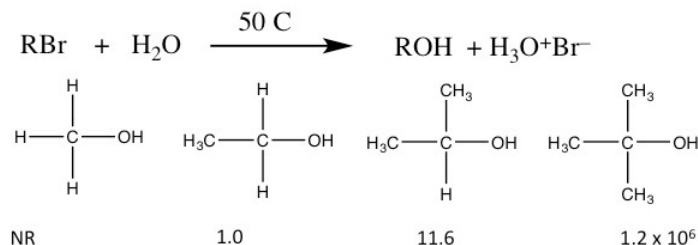


4.2: The $\text{S}_{\text{N}}1$ Reaction

If you have already taken a laboratory course in chemistry, you have no doubt observed that you do not get a 100% yield for a particular reaction and often more than one product is generated. This is not (generally) a case of faulty experimental technique, but rather reflects the complexity of reaction systems. Given our experience using evidence to support proposed reaction mechanisms, let us take a look at another set of conditions for nucleophilic substitutions. Consider the reaction:



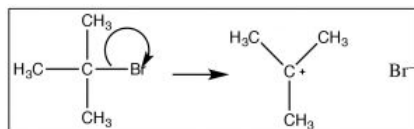
Relative Rates of $\text{S}_{\text{N}}1$ Reactions

In this scenario, water is both the nucleophile and the solvent. Water is not a very strong nucleophile and it is a protic solvent. Under these conditions, a nucleophilic substitution takes place, but this reaction differs in several empirically observable ways from the $\text{S}_{\text{N}}2$ reactions discussed earlier.

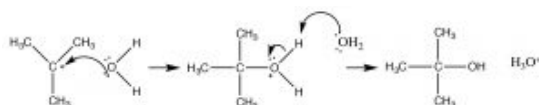
1. The rate of reaction depends *only* on the *substrate*. The reactivity of the nucleophile is irrelevant. The rate equation for these reactions is: $\text{rate} = k[\text{RBr}]$. The reaction is first order, and is therefore named as an $\text{S}_{\text{N}}1$ reaction (Substitution, Nucleophilic, First Order).
2. The relative rates of reaction for substrates are reversed from the $\text{S}_{\text{N}}2$ reaction. That is, reaction rate is higher for the tertiary and lowest for the primary form.
3. When a chiral center undergoes an $\text{S}_{\text{N}}1$ reaction, the product contains a mixture of *both possible enantiomers*, rather than the inversion of configuration found with $\text{S}_{\text{N}}2$ reactions..
4. The reaction is accelerated by polar *protic* solvents (which slow $\text{S}_{\text{N}}2$ reactions).

How can we explain these behaviors? Our assumption is that a different reaction mechanism is involved; compared to the $\text{S}_{\text{N}}2$ reactions we have been considering. What might that mechanism be?

Given that the observed reaction rate is dependent only on the substrate concentration (1) we can assume that *only the substrate molecule is involved in the rate-determining step*. So how does the reaction begin? We must assume that the reaction involves bond-breaking (since there is nothing else that can happen if there is only one molecule in the rate-determining step. Since bond breaking requires energy, thermal collisions with solvent molecules must drive this bond breaking event. However, we also know that the the solvent molecule does not take part in this step of the reaction (because it is not in the rate law). One possibility is that the bond to the leaving group breaks, resulting in a positively charged carbon (a *carbocation*) and the leaving group anion \rightarrow . This is the first instance we have seen of a *carbocation*. The formation of this carbocation requires energy (since the bond is breaking), and we can infer that it has a high activation energy. Carbocations themselves are high-energy species that are very reactive. However, they are different from transition states in that it is possible to generate and detect a carbocation—it usually has a short lifetime—but we can detect its presence by spectroscopic methods. This is different from a transition state, which is the highest-energy species on the reaction energy profile. Transition states exist for only one molecular vibration and have lifetimes on the order femtoseconds.

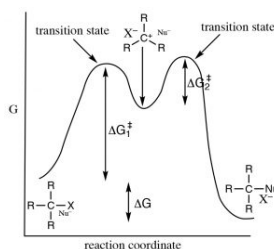


We might expect that such a carbocation would rapidly react with any potential nucleophile present, which in this case is the solvent water molecule.



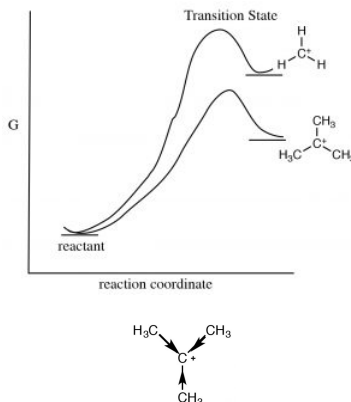
Although water is a poor nucleophile, it will react with the highly reactive carbocation to give the intermediate protonated form. This is followed by a proton transfer to another water (solvent) molecule to form the final product.

Such a mechanism satisfies our experimental observations. It has a slow (rate limiting, high activation, energy requiring) first step, and a faster (lower activation energy) second step. Because of the differences in the activation energies of the two steps, only the first step is involved in determining the overall reaction rate. To figure out which is the rate determining step we can see that ΔG^\ddagger for step 1 is larger than ΔG^\ddagger for step 2.

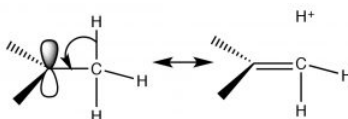


Why does the structure of the substrate matter?

The formation of intermediate carbocation is the rate-determining step in such a reaction, and therefore it follows that the *structure of the carbocation has an impact on the activation energy* of the reaction, and therefore its rate. The more stable the carbocation, the lower the energy of the transition state leading to the carbocation.^[3] Factors that stabilize the carbocation will also stabilize the transition state and lower the activation energy.

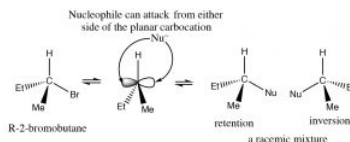


There are two mechanisms that can stabilize carbocations and both predict that, as the number of alkyl groups attached to the C^+ increase, so will its stability. One mechanism we have already encountered is induction. The alkyl groups attached to the central carbon, are polarizable and their electron density is attracted towards the positive charge of the central carbon thus delocalizing the positive charge over the alkyl groups. The more alkyl groups attached to the central carbon, the more pronounced this stabilization is. The second mechanism, known as hyperconjugation, also delocalizes the positive charge. In hyperconjugation, the electron density from any adjacent $C-H$ or $C-C$ bond can overlap with the empty p orbital on the sp^2 hybridized carbocation, forming a sort of π bond and, again, delocalizing the positive charge over the rest of the molecule. The more alkyl groups present (attached to the C^+), the more pronounced this effect will be.



Together, both induction and hyperconjugation explain why an S_N1 reaction proceeds faster with tertiary substrates. The tertiary carbocation is more stable (relative to secondary and primary carbocations) so that the reaction has a lower activation energy.

Why do chiral centers racemize?

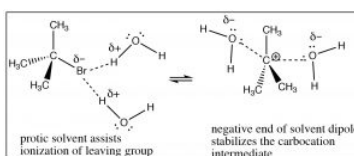


The answer to this question lies in the structure of the carbocation. It is a planar, sp^2 hybridized, symmetrical structure. Once formed, it can be attacked from either side by a nucleophile; in simple compounds which side the carbocation will be attacked on involves a random collision event, giving a mixture of enantiomers.

Why are S_N1 reactions accelerated by polar protic solvents?

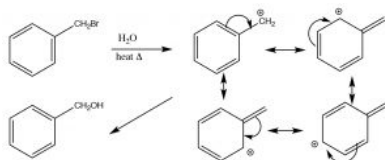
Remember a polar protic solvent (such as water or ethanol) contains a dipole: a partially positive and partially negative domain.

Attack at a chiral center gives a racemic mixture of products.

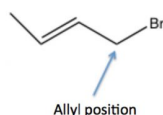


This solvent molecule dipole serves two functions: it can solvate the leaving group, in effect helping to remove it from the carbocation through interactions with the positive end of the solvent dipole and it can solvate the carbocation through interactions with the solvent dipole's negative domain. In essence, the solvent assists in the ionization of the leaving group, and it lowers the energy of the intermediate carbocation.

S_N1 reactions in resonance-stabilized systems:



As we have seen, S_N1 reactions tend to occur when a stabilized carbocation intermediate can be formed. In addition to those tertiary cations discussed earlier, which are stabilized by induction and hyperconjugation, there are also occasions when even primary carbocations can be formed if there is a way to stabilize them. For example, any primary carbon that can be conjugated with a pi system can be stabilized by resonance. For example, a benzylic (that is any carbon attached to a benzene ring) carbocation can be stabilized by delocalizing the positive charge into the benzene ring. This lowers the activation energy for the reaction and makes an S_N1 reaction possible.



A similar phenomenon can happen in substrates with leaving groups in the allylic position: that is, on the carbon next to a double bond, where the resulting carbocation can be resonance stabilized by delocalization onto the pi system of the double bond. We will discuss this phenomenon in more detail later (in Chapter 7).

S_N1 or S_N2 ?

Before we move on, let us review what we know about S_N1 and S_N2 reactions. While it may seem a little confusing, there are a number of factors that can help us predict what the potential mechanism for a reaction might be, and also to predict the product. As we move forward to more complex reaction systems, it will be important to remember that there is typically more than one pathway a reaction can take, but by understanding how reactions occur we can adjust conditions so that the product we want is the major product. The table below summarizes what we have discussed so far with regards to S_N1 and S_N2 reactions.

	S_N1	S_N2
Substrate	Tertiary > secondary > benzylic~allylic > primary > methyl	Methyl > primary > secondary > tertiary
Leaving Group	Good leaving groups increase rate by lowering the energy of the TS	Good leaving groups increase rate by lowering the energy of the TS Accelerated by strong nucleophiles
Nucleophile	Non-(Bronsted) basic nucleophiles, weak nucleophiles (strong bases promote elimination—see next section)	
Solvent	Polar (solvates carbocation) protic (helps pull off the leaving group and solvates it.	Polar aprotic—solvates the cation leaving the nucleophile unsolvated and more reactive.
Stereochemistry	Racemization results from attack at both sides of the planar carbocation	Inversion of configuration if reaction takes place at the chiral center

In practice, tertiary substrates only undergo S_N1 and methyl and primary only undergo S_N2 , it is the secondary substrates where the ambiguity lies, and for that we have to consider the other factors such as solvent and nucleophile strength. However, reactions that generate carbocations may also undergo other reaction pathways besides substitution.

This page titled [4.2: The \$S_N1\$ Reaction](#) is shared under a [CC BY-NC-SA 4.0](#) license and was authored, remixed, and/or curated by [Melanie M. Cooper & Michael W. Klymkowsky](#).