The parabolic component of the fission reaction energy, again using our empirical surface, is approximately

$$Q_{ef} = -2J\left(\frac{A^*}{2}\right)\theta'^2 = -\frac{100}{A^*}\left(\frac{100D^*}{A^*+400}\right)^2 = -\frac{1}{A^*}\left(\frac{D^*}{A^*+4}\right)^2 \tag{9-35}$$

For U^{236} this is -28.2 mMU, or -26.4 Mev.

Since the parabolic energy of the initial nuclide is negligible, one-half the magnitude of the above parabolic component can be identified with each of the nuclides formed in symmetrical fission. This is quite a substantial amount of energy, and in consequence we might conjecture that decay by neutron emission is also a possibility for the products of fission. This possibility may be readily investigated by calculating the neutron binding energy for a typical fission product, using the empirical equations developed in the preceding chapter. According to these equations the binding energy of the last neutron in a nucleus with coordinates A' and D' is given approximately by

$$B_n(A',D') = (10.072 - 2A') - (b' - b'')A'^{-1} - (\theta'^2 - \theta''^2)(4A')^{-1} + B_{ns} \quad \text{mMU} \tag{9-36}$$

where $\theta' = D' - D_m(A')$ and θ'' and b'' refer to the nuclide which is formed when a neutron is pulled out of the (A',D') nuclide. When consideration is given to the slope of the line of beta stability, we find that, for a medium-weight nuclide, $\theta'' \approx \theta' - 0.75$. Consequently, when θ' is large, we can let

$$\theta''^2 \approx \theta'^2 - 2 \times 0.75\theta'$$

or

$$-(\theta'^2 - \theta''^2)(4A')^{-1} \approx 1.5\theta'(4A')^{-1} \tag{9-37}$$

For the symmetrical products of U^{236} ($A' = 118$) this parabolic energy is equal to $(1.5 \times 8.2)/(4 \times 1.18) = 2.5$ mMU $= 2.3$ Mev. Considering the first and third terms in Eq. (9-36) but ignoring the pairing and shell energies, we find that the binding energy of the last neutron in a typical fission product is of the order of 6.0 mMU, or 5.6 Mev. Accordingly the medium-weight substances formed in fission cannot spontaneously emit neutrons unless they have an excitation energy greater than about 6 mMU. Since the nuclear fragments actually carry away an appreciable fraction of the fission energy as internal excitation energy, these fragments are actually energetically capable of emitting neutrons. These so-called "prompt" neutrons are emitted almost instantaneously ($\sim 10^{-12}$ sec) after the fission process. Experiment indicates that there are about two or three instantaneous neutrons emitted per fission.

The beta decay energies of fission products are large because in a β-decay process the change in θ is -2, and hence the corresponding differences in the parabolic energies are large. Should a fission product decay by beta emission to a highly excited state of the daughter nucleus, the excitation energy of the daughter may be greater than its neutron binding energy, and a neutron may be ejected. The delayed neutrons which have been observed emanating from fission products are thought to arise in this manner.

9-10. Activation Energy. Although all nuclei having $A \geq 90$ are energetically unstable relative to decay by fission, nevertheless the probability for the spontaneous fission of naturally occurring heavy nuclei in their ground states is very small. For example, the half-life of U^{238} relative to spontaneous fission is about 10^{17} years. Apparently there exists a highly effective barrier against fission which holds any naturally occurring nucleus in a metastable state of equilibrium. The probability of penetrating this barrier is relatively small unless the nucleus has an excitation energy (W^*) which is almost equal to or greater than an activation energy (W^a), which represents the difference between the height of the barrier and the ground-state energy of the nucleus. In Fig. 9-6 we indicate the hypothetical potential energy of a nucleus as a function of the distance between the centers of two virtual or actual fission fragments. This figure indicates the physical significance of the statement that the original nucleus is in a metastable state of equilibrium.

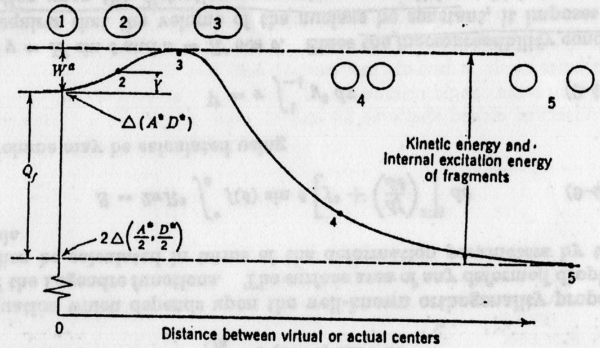

FIG. 9-6. Schematic diagram of the potential energy between two equal fission fragments.

The activation energy W^a by definition is the classical energy required to bring the nucleus to the condition of unstable equilibrium from which it will spontaneously dissociate into two parts. For very heavy naturally occurring nuclei ($A \sim 230$), activation energies are of the order of 4 to 6 Mev, that is, of the same order as the excitation energies acquired