Nuclear Reactions

Thornton and Rex, Ch. 13

Reaction Kinematics

Consider a general reaction,
A (x , y) B or $A + x \rightarrow y + B$
with target A at rest.

Ex. $^{9}Be_{4} + {}^{4}\alpha_{2} \rightarrow {}^{1}n_{0} + {}^{12}C_{6}$
or equivalently,
$^{9}Be_{4}\ (\alpha,n)\ ^{12}C_{6}$

Conservation of energy gives:

$$M_A c^2 + m_x c^2 + K_x = m_y c^2 + K_y + M_B c^2 + K_B$$

The difference between final and initial kinetic energies is called the Q-value.

$$Q = K_y + K_B - K_x$$
$$= M_A c^2 + m_x c^2 - (m_y c^2 + M_B c^2)$$

If Energy is released, $Q > 0$

$\Rightarrow$ Exothermic

If Energy is converted to mass, $Q < 0$

$\Rightarrow$ Endothermic

Two of the most important exothermic reactions are Fission and Fusion.

Nuclear masses are usually measured in atomic mass units (roughly the mass of a proton or a neutron) but actually defined as $\frac{1}{12}$ th of the mass of a Carbon atom

$1\ u = 1.66054\text{E-}27\ kg = 931.49\ MeV/c^2$

Neutron Activation

Neutrons - uncharged, can penetrate close to the nucleus, can induce reactions (Neutron Activation).

1930's - Enrico Fermi bombarded elements from Hydrogen to Uranium with neutrons. On Uranium, Fermi was unable to identify the final products of the reactions. He expected elements heavier than Uranium, such as in the expected process:

$$^{238}U_{92} + {}^{1}n_{0} \rightarrow {}^{239}U_{92} \rightarrow {}^{239}Np_{93} + {}^{0}e_{-1} + \bar{\nu}$$

IN ORDER TO UNDERSTAND WHAT IS PRODUCED WHEN URANIUM IS BOMBARDED WITH NEUTRONS, THE RESULTING ELEMENTS HAVE TO BE EXTRACTED BY CHEMICAL MEANS.

IN THE YEARS 1935 - 1938 IT BECAME INCREASINGLY OBVIOUS THAT SOMETHING STRANGE AND IMPORTANT WAS GOING ON. NONE OF THE EXPECTED ELEMENTS WERE OBSERVED.

ONE OF THE LEADING RESEARCHERS, AN AUSTRIAN PHYSICIST, LISE MEITNER (WHO WAS JEWISH) HAD TO FLEE FROM THE BERLIN INSTITUTE WHEN GERMANY TOOK OVER HER NATIVE COUNTRY IN 1938. SHE TOOK REFUGE IN NEUTRAL SWEDEN.

THE SENIOR MEMBER OF HER GROUP, OTTO HAHN (WHO HAD WORKED WITH RUTHERFORD AT McGILL 35 YEARS EARLIER) AND A CHEMIST, FRITZ STRASSMANN, EVENTUALLY IDENTIFIED ONE OF THE PRODUCT NUCLEI AS BARIUM ($^{141}Ba_{56}$), AN ELEMENT <u>MUCH</u> LIGHTER THAN URANIUM.

HAHN COMMUNICATED THIS AMAZING DISCOVERY TO MEITNER. DURING THE CHRISTMAS VACATION OF 1938 SHE AND HER NEPHEW OTTO FRISCH (WHO WAS ALSO A REFUGEE FROM NAZI GERMANY, WORKING AT NIELS BOHR'S INSTITUTE IN COPENHAGEN) PONDERED THE POSSIBLE MEANING OF THE REACTION.

THEY SUDDENLY REALIZED THAT IT WAS EVIDENCE OF AN ENTIRELY NEW TYPE OF NUCLEAR REACTION WHICH THEY NAMED <u>NUCLEAR FISSION</u>.

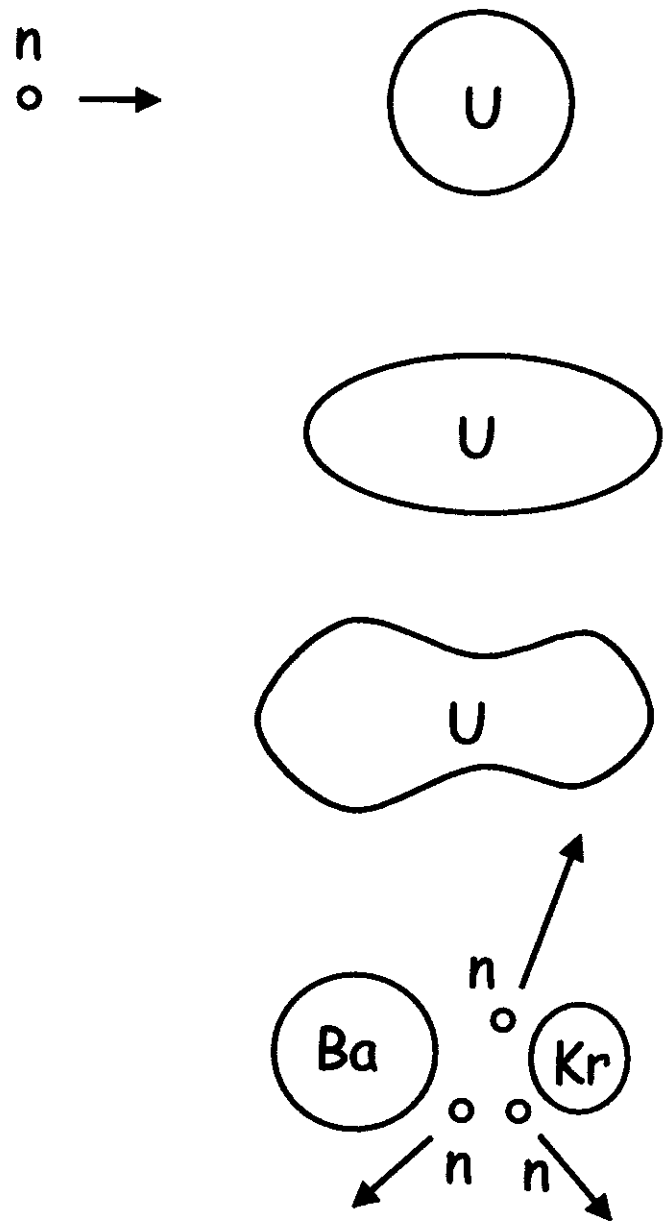
THEY EXPLAINED THE PROCESS AS THE URANIUM NUCLEUS BEING LIKE A BALLOON CLOSE TO BURSTING.

(THE COULOMB REPULSION OF THE 92 POSITIVE PROTONS ALL BEING CRAMMED TOGETHER IN A NUCLEUS MUST BE ENORMOUS.)

THE ENERGY OF THE NEUTRON IS ENOUGH TO "POP" THE BALLOON INTO ROUGHLY EQUAL FRAGMENTS.

NIELS BOHR HAD RECENTLY PICTURED THE NUCLEUS AS BEING SIMILAR TO A DROP OF WATER WITH THE NUCLEAR FORCE BEHAVING LIKE THE LIQUID SURFACE TENSION.

Fission



Comments on Fission

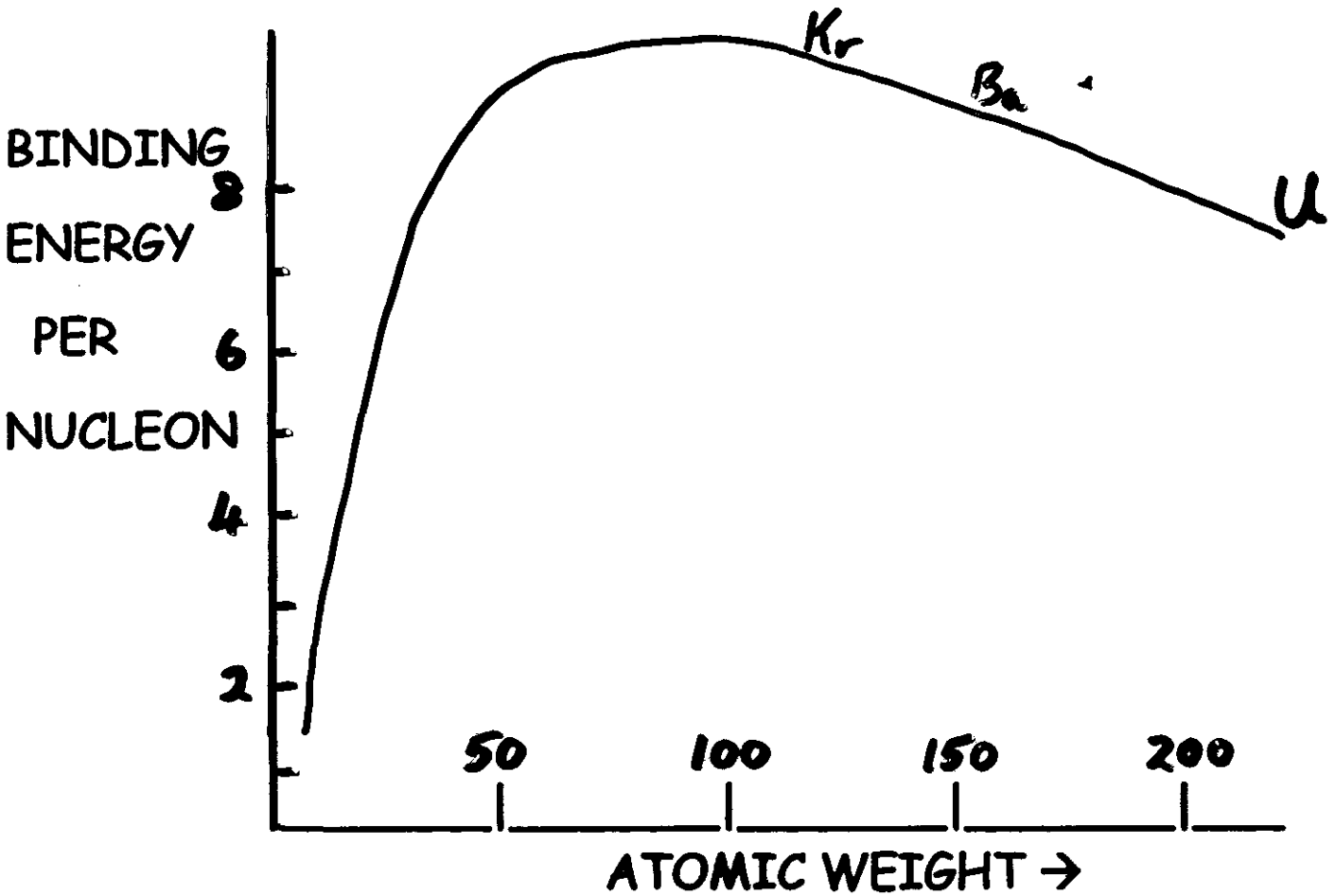
- The observed reaction is one of many possible reactions:

$$^{235}U_{92} + {}^{1}n_0 \rightarrow {}^{141}Ba_{56} + {}^{92}Kr_{36} + 3\ {}^{1}n_0$$

- $^{235}U_{92}$ undergoes fission. $^{238}U_{92}$ does not. Uranium ore contains 99.3% U-238 and only 0.7% U-235.

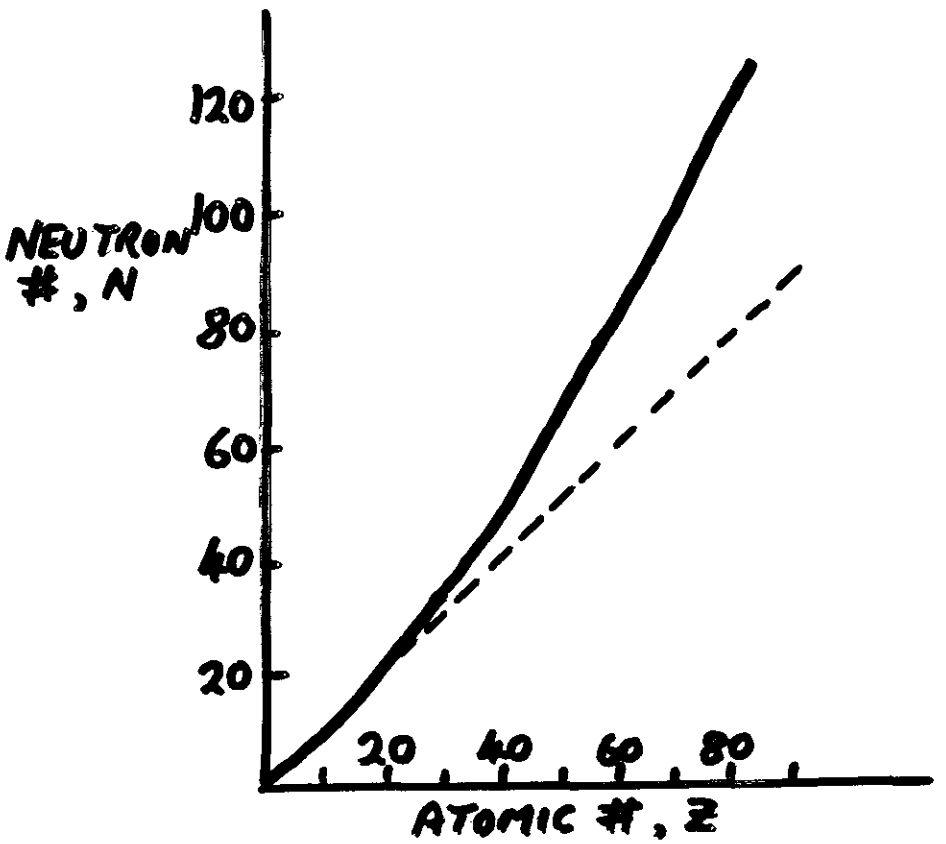
- Fission occurs more easily if the neutron is slow (allowing more time for the reaction to occur.)

REMEMBER THE CURVE OF BINDING ENERGY VS. ATOMIC WEIGHT



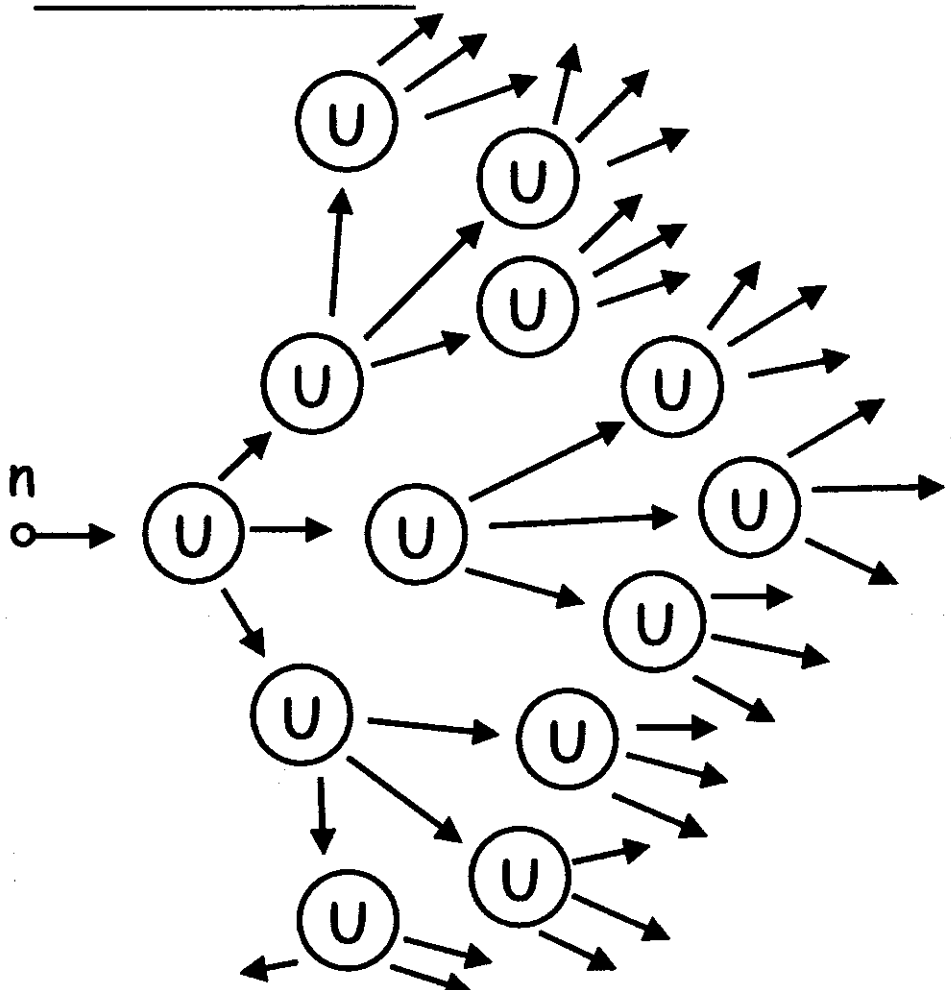
THIS SHOWS THAT NUCLEI THAT ARE LIGHTER THAN URANIUM ARE MORE STABLE (MORE TIGHTLY BOUND). SO THE MASS OF THE URANIUM IS GREATER THAN THE SUM OF ITS PARTS (BARIUM, KRYPTON AND THE THREE NEUTRONS), THIS MASS DIFFERENCE IS RELEASED AS KINETIC ENERGY OF THE FRAGMENTS (AND ALSO AS EM RADIATION IN THE FORM OF GAMMA RAYS). THE FISSION OF A U-235 NUCLEUS RELEASES APPROXIMATELY 200 MEV.

ANOTHER CURVE TO RECALL IS PLOT OF N VS. Z:-



NOTE THAT HEAVY NUCLEI ARE MORE RICH IN NEUTRONS. THUS WHEN $^{235}U_{92}$ DECAYS TO $^{141}Ba_{56}$ AND $^{92}Kr_{36}$ SOME EXTRA NEUTRONS ARE LIBERATED.

- Under the right conditions, the extra neutrons could cause <u>more</u> U-235 to fission. This would release even more neutrons, etc., resulting in a <u>chain reaction.</u>



(The idea of chain reaction was patented by Leo Szilard in 1933, before he had any idea what nuclei might participate!)

AFTER HIS AND MEITNER'S REALIZATION OF THE PROCESS OF NUCLEAR FISSION, FRISCH RETURNED TO COPENHAGEN AND COMMUNICATED THE NEWS TO NIELS BOHR, WHO WAS LEAVING FOR THE U.S. ON THE FOLLOWING DAY.

IN NEW YORK, IN MID-JANUARY 1939, BOHR TOLD ENRICO FERMI WHO HAD ARRIVED IN EXILE ON JANUARY 2. SOON GROUPS ALL OVER THE WORLD WERE INVESTIGATING THE FISSION OF URANIUM AND ITS POTENTIAL TO CAUSE A CHAIN REACTION.

THE WORSENING INTERNATIONAL SITUATION IN THE MONTHS BEFORE THE START OF THE SECOND WORLD WAR RESULTED IN MAJOR PROJECTS BEING SET UP IN SEVERAL COUNTRIES (U.S., BRITAIN, FRANCE, GERMANY AND JAPAN) IN ORDER TO PRODUCE THE FIRST NUCLEAR WEAPONS.

THE LARGEST EFFORT WAS THE MANHATTAN PROJECT IN THE UNITED STATES. THIS WAS STARTED AT COLUMBIA UNIVERSITY BY FERMI IN 1940. UNDER THE LEADERSHIP OF J. ROBERT OPPENHEIMER AT A SECRET LAB IN LOS ALAMOS, NM, THE PROJECT PRODUCED THE "ATOMIC" BOMBS THAT EXPLODED IN THE ALAMOGORDO DESERT IN NEW MEXICO (JULY 16, 1945) AND OVER HIROSHIMA (AUGUST 6, 1945) AND NAGASAKI (AUGUST 9, 1945).

THERE ARE TWO PARTICULAR TECHNICAL PROBLEMS THAT HAVE TO BE SOLVED IN ORDER TO ACHIEVE A CHAIN REACTION IN URANIUM.

FIRST THE DEVICE MUST CONTAIN A SUBSTANCE WHICH WILL SLOW NEUTRONS DOWN. FISSION OCCURS ONLY IF THE U-235 NUCLEUS CAPTURES A SLOW NEUTRON, BUT THE NEUTRONS EMITTED IN FISSION ARE FAST NEUTRONS. A NEUTRON "MODERATOR" IS AN ELEMENT WHOSE NUCLEI DON'T ABSORB NEUTRONS AND WHICH ARE RELATIVELY LIGHT SO THAT IN COLLISIONS WITH NEUTRONS THEY WILL ABSORB ENERGY EASILY AND THUS SLOW DOWN THE NEUTRONS. TYPICAL MODERATORS ARE WATER, HEAVY WATER (D_2O, WHERE DEUTERIUM, D, IS AN ISOTOPE OF HYDROGEN) OR CARBON (GRAPHITE).

SECOND THE SAMPLE MUST BE ENRICHED TO CONTAIN ENOUGH U-235 RELATIVE TO U-238 SO THAT SUCCESSIVE FISSIONS ARE ACHIEVED (U-238 ABSORBS SLOW NEUTRONS WITHOUT FISSIONING). THIS ENRICHMENT WAS A MAJOR TECHNICAL CHALLENGE OF THE MANHATTAN PROJECT AND WAS ACHIEVED BOTH BY GAS DIFFUSION TECHNIQUES AT OAK RIDGE, TENN., AND BY EM SEPARATION USING "CALUTRONS" INVENTED AT BERKELEY.

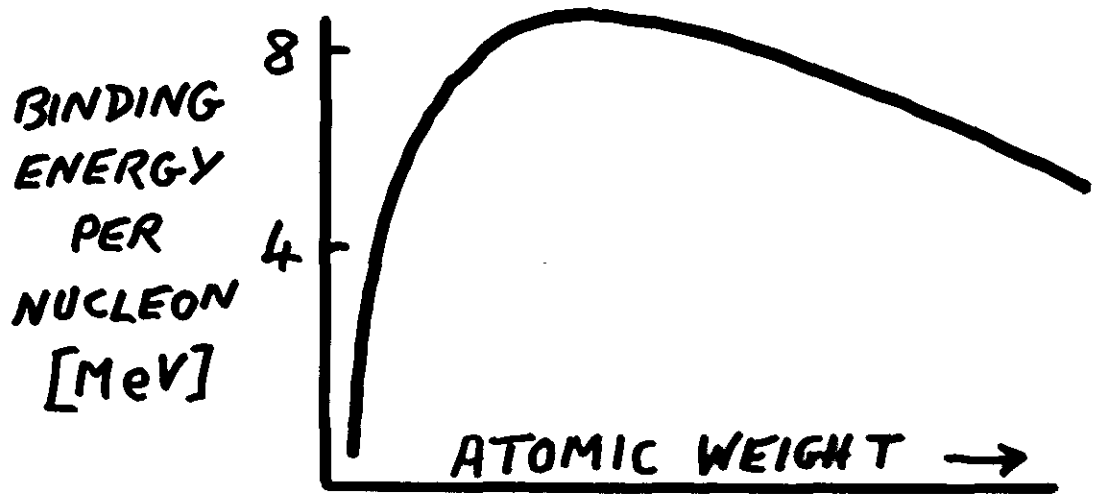
AN ADDITIONAL TECHNICAL PROBLEM MUST BE OVERCOME IF ONE WANTS TO ACHIEVE CONTROLLED NUCLEAR FISSION, FOR EXAMPLE FOR POWER GENERATION.

A VARIABLE AMOUNT OF AN ADDITIONAL MATERIAL (USUALLY IN THE FORM OF MOVEABLE RODS) MUST BE INSERTED INTO THE URANIUM MATERIAL. THESE RODS WOULD CONTAIN A MATERIAL THAT WOULD BE HIGHLY EFFICIENT IN CAPTURING NEUTRONS. CADMIUM IS AN EXAMPLE OF SUCH A MATERIAL. IF THE URANIUM PILE CONTAINS CADMIUM RODS NEUTRONS WOULD BE ABSORBED AND A CHAIN REACTION WOULD BE IMPOSSIBLE. AS THE RODS ARE WITHDRAWN THE CREATION OF NEUTRONS FROM FISSION STARTS TO EXCEED THE ABSORBING POWER OF THE CADMIUM AND A CONTROLLED CHAIN REACTION OCCURS. IF TOO MUCH HEAT IS GENERATED, THE CADMIUM RODS ARE AGAIN INSERTED.

THE FIRST SELF-SUSTAINING NUCLEAR REACTOR, USING GRAPHITE AS A MODERATOR, WAS BUILT UNDER THE STANDS OF THE FOOTBALL STADIUM (STAGG FIELD) AT THE UNIVERSITY OF CHICAGO BY ENRICO FERMI ON DECEMBER 2, 1942.

FUSION

RECALLING ONCE AGAIN THE CURVE OF BINDING ENERGY VS ATOMIC WEIGHT:-



WE CAN SEE THAT LARGE AMOUNTS OF ENERGY WILL ALSO BE LIBERATED IN THE TRANSITION FROM THE LOWEST END OF THE CURVE TO HIGHER VALUES OF ATOMIC WEIGHT.

FOR EXAMPLE, IN THE REACTION

$$^{2}D_{1} + {}^{3}T_{1} \rightarrow {}^{4}He_{2} + {}^{1}n_{0}$$

ABOUT 17.6 MEV ARE RELEASED.

[DEUTERIUM, D, AND TRITIUM, T, ARE ISOTOPES OF HYDROGEN CONTAINING 1 AND 2 NEUTRONS RESPECTIVELY.]

THIS, AND SIMILAR FUSION REACTIONS, ARE BELIEVED TO BE THE SOURCE OF ENERGY FOR THE SUN (AND ALL OF THE STARS!).
[BEFORE THE END OF THE 19TH CENTURY, IT WAS REALIZED THAT THE SUN WAS NOT A BALL OF FIRE, AT LEAST NOT IN THE USUAL SENSE. SPECTROSCOPIC DATA SHOWED NO SIGN OF CO OR CO_2 BUT LOTS OF HELIUM!]

THE FUSION "CYCLE" (A SERIES OF NUCLEAR TRANSFORMATIONS) WAS DESCRIBED BY THE GERMAN/AMERICAN PHYSICIST HANS BETHE (NOW AT CORNELL) IN 1938. THE WHOLE CYCLE, DURING WHICH 4 PROTONS COMBINE TO FORM A HELIUM NUCLEUS, LIBERATES 26.7 MEV.

SINCE 1948 THERE HAS BEEN A CONCERTED EFFORT TO PRODUCE A CONTROLLED FUSION REACTION ON EARTH. THE PROBLEM IS THAT THE TWO NUCLEI REPEL EACH OTHER WITH THE COULOMB FORCE AND SO ENERGY MUST BE GIVEN TO THEM TO BRING THEM WITHIN THE RANGE OF THE STRONG FORCE. IN THE SUN THIS ENERGY IS PROVIDED BY HEAT (TEMPERATURES OF 20 MILLION DEGREES).

ON EARTH THE MAIN EFFORT HAS BEEN TO USE A HOT, IONIZED GAS CALLED A PLASMA. THE NUCLEI ARE KEPT AT HIGH ENERGY AND COMPRESSED TOGETHER BY LARGE ELECTRIC AND MAGNETIC FIELDS. THE MAGNETS ARE USUALLY IN THE FORM OF A TOROID (OR DONUT SHAPE), CALLED A *TOKAMAK* (THEY WERE INVENTED IN RUSSIA). PROGRESS HAS BEEN MADE BUT VERY SLOWLY. EXPERIMENTS WITH TOKAMAKS (ESP. AT PRINCETON AND OAK RIDGE IN THE U.S. AND AT CULHAM IN ENGLAND) ARE STARTING TO UNDERSTAND THE PROPER COMBINATIONS OF PLASMA DENSITY AND TEMPERATURE, BUT NONE HAS YET PRODUCED MORE ENERGY FROM FUSION THAN WAS REQUIRED TO PRODUCE AND CONTAIN THE PLASMA.

ANOTHER SCHEME IS TO USE POWERFUL LASERS TO IRRADIATE TINY PELLETS OF DEUTERIUM AND TRITIUM FROM ALL SIDES RESULTING IN THEIR VAPORIZATION AND COMPRESSION, AGAIN PRODUCING FUSION.

ESTIMATES FOR THE COMMERCIAL EXPLOITATION OF FUSION REACTORS RANGE FROM 30 TO 50 YEARS.

A FEW YEARS AGO THERE WAS MUCH EXCITEMENT IN THE POPULAR PRESS ABOUT THE CONCEPT OF "COLD FUSION". SOME PEOPLE BELIEVED THAT DEUTERIUM ATOMS COULD BE BROUGHT CLOSE TOGETHER INSIDE A PALLADIUM ELECTRODE. WHILE IT APPEARS POSSIBLE THAT THERE ARE SOME ANOMALOUS CHEMICAL REACTIONS INVOLVING PALLADIUM AND HYDROGEN, THERE IS NO EVIDENCE THAT EITHER FUSION OR ENERGY PRODUCTION IS TAKING PLACE.

UNCONTROLLED NUCLEAR FUSION HAS BEEN ACCOMPLISHED! THE TEMPERATURE IN AN ATOMIC BOMB (FISSION) DURING THE FIRST FEW NANOSECONDS REACHES THE VALUE NEEDED FOR SPONTANEOUS FUSION. IF ONE SURROUNDS AN ATOMIC BOMB WITH ISOTOPES OF HYDROGEN THEN IT CAN BE MADE TO LIBERATE FUSION ENERGY

⇒THE HYDROGEN BOMB