The Delayed Neutron Emission which Accompanies Fission of Uranium and Thorium

In our previous letter[1] we suggested that the delayed neutrons produced by neutron bombardment of uranium might originate either in direct neutron emission (by one of the disintegration products), or in a photodisintegration process. Further evidence has now been obtained which indicates that direct neutron emission is responsible for the delayed neutrons which we observed.

All elements except uranium, carbon, and hydrogen (in paraffin) were eliminated as a source of the delayed neutrons by changing the neutron detector from a boron-lined brass chamber to one of aluminum lined with lithium. The detecting apparatus was located at a distance from the bombarding position at the high voltage target. Furthermore, cloud-chamber photographs of hydrogen recoils from the delayed neutrons showed no appreciable diminution in the number of recoils when one inch of lead was interposed between the chamber and the activated uranium, although the gamma-ray intensity was greatly decreased. The remaining possibility of photodisintegration in the uranium itself was eliminated by surrounding a small amount of the activated uranium with a large quantity of normal uranium. No observable increase in the number of delayed neutrons was produced by the additional uranium.

In comparing the periods of the delayed neutrons and gamma-rays from uranium several longer periods were observed for the gamma-rays but not for the neutrons. The complexity of the gamma-ray decay makes it difficult to determine any of the periods accurately, but there seems to be evidence for at least three periods considerably longer than the short period previously reported.

It was found that the delayed neutrons and all the gamma-ray periods were produced by both thermal and high energy neutrons but not by the medium energy neutrons from carbon. These conditions are the same as for the uranium fission process.

The cross section for the production of delayed neutrons by lithium-neutron bombardment of uranium (high energy neutrons) was measured by comparing the number of delayed neutrons with the number observed from a calibrated radon-beryllium source. By neglecting the asymmetry of the lithium-neutron source and using the yield curves of Amaldi, Hafstad, and Tuve,[2] the cross section was found to be about 4×10^{-26} cm^2 which is roughly one-half the reported cross section for fission when fast radon-beryllium neutrons are used.[3] This large cross section is further evidence that the 15-sec. gamma-rays cannot be the cause of the neutrons.

Cloud-chamber observations of the recoils from the delayed neutrons indicated that their energy is less than one million electron volts and probably near one-half million electron volts.

Delayed neutrons were also observed from thorium nitrate which had been activated by fast lithium neutrons. The intensity was roughly one-fourth of that observed from uranium. The period seemed to be roughly the same as that of the delayed neutrons from uranium.

We are greatly indebted to Professor J. R. Dunning for the radon-beryllium neutron source used in the cross section determination, and to Dr. F. Kracek for the loan of material which made the measurements on thorium possible.

R. B. Roberts
L. R. Hafstad
R. C. Meyer
P. Wang

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.,
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[2] E. Amaldi, L. R. Hafstad, and M. A. Tuve, Phys. Rev. **51**, 896–912 (1937).
[3] H. L. Anderson and others, Phys. Rev. **55**, 511–512 (1939).

The Determination of Force Fields from Scattering in the Classical Theory

Although mutual scattering of nuclei provides one of the most important sources of information on nuclear force fields, no systematic method has so far been developed for the determination of these fields from the observed angular distributions. In a recent conversation Dr. O. Klein suggested to me that a method devised by him[1] for the determination of the potential curves of diatomic molecules from their band spectra might be useful in this connection. A slightly modified form of this method proves, indeed, to be applicable to the scattering problem, but only insofar as the results are interpreted according to classical mechanics. In spite of this serious limitation, a brief account of the method should be of interest.

For scattering by a fixed force center with potential function $V(r)$, the effective potential U for the radial motion of particles with angular momentum L and mass m is $U=V(r)+L^2/2mr^2$, where r is distance from the force center. The angular deflection θ of such particles is determined by their energy E, and for present purposes is most conveniently measured by the "deflection parameter" $\rho=\pi/2-\theta/2$. It is readily shown that ρ can be expressed in the form

$$\rho(E)=-[L/(2m)^{\frac{1}{2}}]\int_{\infty}^{r_0} dr/r^2(E-U)^{\frac{1}{2}},$$

where r_0 is the distance of closest approach, for which $E=U$. If the equation of the potential function be taken in the form $f(U)=1/r$ so that $dr/r^2=-f'(U)dU$, the above relation may be written

$$\rho(E)=\frac{L}{(2m)^{\frac{1}{2}}}\int_0^E \frac{f'(U)dU}{(E-U)^{\frac{1}{2}}}.$$

This functional equation connecting $\rho(E)$ and $f(U)$ is of the Abelian type encountered by Klein and can be solved for $f(U)$ to give the equation of the potential curve in the form

$$\frac{1}{r}=f(U)=\frac{(2m)^{\frac{1}{2}}}{\pi L}\int_0^U \frac{\rho(E)dE}{(U-E)^{\frac{1}{2}}}.$$

The function $\rho(E)$ (angular deflection as a function of the energy for a fixed angular momentum) can, in principle, be determined from the scattering data in the follow-