Characteristics of Bismuth Fission with High Energy Particles

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March 22, 1948

IN a previous communication[1] the fission of elements from bismuth to tantalum with high energy particles was reported and some properties of the reaction were deduced from the nature of the fission products. It is now possible to characterize further the mechanism and to show that the reaction differs considerably from the slow neutron-induced fission of uranium.

In the present studies some of the longer-lived fission products from the irradiation of bismuth with 200-Mev deuterons were examined. The most abundant fission products are those from near-symmetrical cleavage with yields falling off for lower and higher mass numbers. Although the fission yield curve appears to be a single symmetrical peak, the line of symmetry is at a mass somewhat below 100, rather than at 105–106 as would result from the fission of a compound nucleus of Bi^{209} and a deuteron. Besides the appearance of only a single peak in the fission product yield curve, another important difference from the slow neutron-induced fission of uranium was noted. Considering those cleavages in the fission of bismuth in which a light and a heavy fragment are formed, the light fragment in general has a neutron excess while the complementary heavy fragment is either neutron deficient or, by inference, stable.

These observations can be explained in terms of the following description of the process. The fission reaction competes with other reactions only after about 12 neutrons have boiled off from the compound nucleus. As will be mentioned below, the yield data can best be explained if it is assumed that bismuth or polonium of mass numbers 197–199 are the isotopes responsible for most of the fissions. The second assumption necessary to explain the observations is that the light bismuth or polonium nucleus undergoes fission preserving the same neutron/proton ratio in both fragments as in the parent nucleus. It is seen that since the postulated parent nucleus has $n/p=1.36$, the primary fission products of mass number well below 100 will be β^--emitters, those in an intermediate range will be stable, while the heaviest fission products will decay by orbital electron capture or by positron emission.

Using these assumptions (which no doubt present an oversimplification) it is possible to calculate for each mass number the most abundant primary fission product. If it is further assumed that this particular isobar is produced in almost all of the fissions producing that mass number, it should be possible to draw a smooth curve through the fission yields for these products. Furthermore, an isotope whose n/p ratio differs appreciably from 1.36 should fall well below the curve.

A fission product yield curve has been constructed on the basis of measured yields of 25 fission products. The mechanism advanced seems to give an adequate description of the fission process since the predictions and measured yields agree rather well both for isotopes that should fall on the curve and those which should lie well below it. A few of the heavy fission products depart somewhat from predictions but with these there is considerable uncertainty in estimating counting efficiencies since the decay schemes (orbital electron capture) are not known.

The following is a list of bismuth fission products which were identified in the present studies (references are given for isotopes which only recently appeared in the literature or which have been hitherto unreported): Ca^{45}, Fe^{59}, Ni^{66},[2] Cu^{67},[3] Zn^{72}, As^{74}, As^{77}, Rb^{86}, Sr^{89}, Y^{90}, Y^{91}, Zr^{95}, Mo^{99}, Ru^{103}, Ru^{106}, Ag^{111}, Pd^{112}, Cd^{115} (44 days), Te^{119},[4] Sb^{122}, I^{124}, I^{125},[5,6] I^{126}, Ba^{133}, Ce^{139}.[7] Not all of these isotopes should nor do lie on the fission yield curve. For example, the most probable representative of mass number 74 should be Ga^{74} (not measured in these studies) and the measured yield for As^{74} was below the curve by a factor of 20. Similarly, the yield for Pd^{112} was 20-fold below the curve, in line with the prediction that the most abundant isobar of mass 112 should be Cd^{112} (stable). The smooth fission yield curve drawn partly through measured yields and partly through calculated points is symmetrical about mass number 98–99, which represent maximum yields, and drops off by a factor of 100 at mass numbers ~ 60 and ~ 138. A rough value of 0.2×10^{-24} cm^2 for the fission cross section was obtained by integrating the smooth curve. This figure is probably uncertain by a factor of two because of uncertainties in the shape of the curve and in the deuteron beam intensity. The most abundant isotope measured, Mo^{99}, has a fission yield of 5 percent.

With respect to the mechanism for the fission of bismuth with high energy deuterons, it is probably necessary to assume that only those nuclei to which the dueteron gives up a large fraction of its energy will undergo fission. According to Serber,[8] the nucleons of a heavy element like bismuth should present, on the average, about two mean free paths between collisions by projectile nucleons in the energy range considered here and should receive about 25 Mev per collision. A moderate percentage of the projectiles should therefore give up all of their energy upon entering the bismuth nucleus and most of such events should result in fission. The observations are not in disagreement with this theory, since the measured cross section for fission is less than one-tenth of the geometric cross section and it is plausible that most of the highly excited nuclei will boil off neutrons until fission takes over as the means for further energy dissipation. The agreement of theory with the data is good here since the fissionability parameter, Z^2/A, has about the same value for a nucleus such as Po^{198} as for U^{236}.

The facts outlined above, in particular the equality of the n/p ratio in both fission fragments, suggest that the fission reaction is relatively fast and takes place with excitation energy above the threshold since the two products could be left in a lower energy state if there were a rearrangement of neutrons and protons during fission. That is, the formation of two stable nuclei would be energetically more economical than the production of one which is unstable with respect to β^--emission and one toward orbital electron capture or β^+-emission. The absence of such marked asymmetry as is noted for the slow neutron fission of uranium may also be related to the supra-threshold energy at which the reaction occurs.

The cooperation of Dr. Duane Sewell and Mr. J. T. Vale and all those of the 184-inch cyclotron group is gratefully acknowledged. This work was performed under Contract No. W-7405-eng-48, with the Atomic Energy Commission in connection with the Radiation Laboratory of the University of California, Berkeley, California.

[1] I. Perlman, R. H. Goeckermann, D. H. Templeton, and J. J. Howland, Phys. Rev. **72**, 352 (1947).
[2] A 56-hr. β^--emitter which proved to be the parent of 5-min. Cu^{66}.
[3] A 56-hr. β^--emitter tentatively assigned to Cu^{67} on the basis of the mode of disintegration and half-life.
[4] M. Lindner and I. Perlman (submitted for publication).
[5] A. F. Reid and A. S. Keston, Phys. Rev. **70**, 987 (1946).
[6] L. E. Glendenin and R. R. Edwards, Phys. Rev. **71**, 742 (1947).
[7] D. E. Mathews and M. L. Pool, Phys. Rev. **72**, 163 (1947).
[8] R. Serber, Phys. Rev. **72**, 1114 (1947).

Theoretical Evidence for the Existence of a Light-Charged Particle of Mass Greater than That of the Electron

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January 29, 1948

FROM theoretical considerations developed in a previous paper,[1] it can be deduced that particles with a charge equal to that of the electron and having a mass equal to 1.444 times that of the electron may be expected to exist.

It was shown that for an elementary charge the electrostatic potential

$$U=-(1/2K)\log[1-(2Ke/r)+(2K^2e^2/r^2)],$$

where e is the charge and K is a constant, satisfies the conditions that the integral of the charge density should be convergent and equal to e, and that the integral of the energy density should also be convergent. The value of the energy integral depends on that of K, and it also depends on the sign of e; the value is equal to

$$(e/4K)[(\pi/2)+1] \quad \text{or} \quad (e/4K)[(3\pi/2)-1],$$

depending on whether e is negative or positive. The ratio of these two values is 1.444. Setting the value of the energy integral equal to the mass of the electron gives us the value of K, which will thus depend on the sign chosen for the charge of the electron. If this is arbitrarily taken to be negative, then we obtain $K=3.8\times10^{\ 4}$. There should then exist a positive particle of mass equal to 1.444 times that of the electron. A positive counterpart of the electron can also exist, but it should have a tendency to be annihilated by combining with an electron.

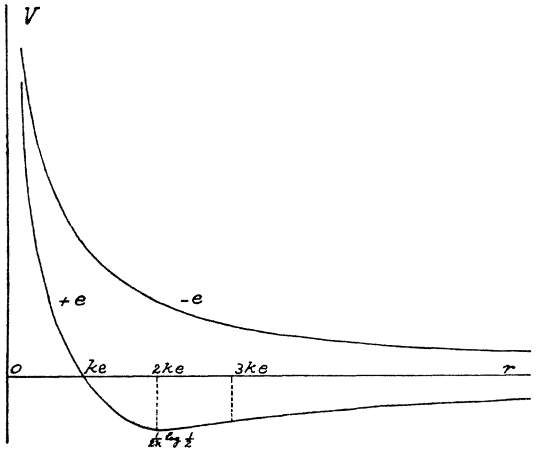

Fig. 1.

According to the sign of e, the potential curve takes one of the two forms shown in Fig. 1. For $e<0$, the curve has no minimum, and the force on a particle of the same sign is always repulsive. For $e>0$, there is a minimum at $r=2Ke$, and the field becomes attractive at distances smaller than $2Ke$. The force on a particle of opposite sign becomes repulsive at very small distances. With the value $K=3.8\times10^{-4}$ we find that the field changes sign for $r=3.7\times10^{-13}$.

Evidence for the existence of positive particles of mass greater than that of the electron occurring in the neighborhood of β-ray emitters has been found by Smith and Groetzinger.[2] A rough estimate of the mass, determined from the loss of momentum of the particle in a foil, has led the authors to a value approximately equal to 1.5 to 2 times the electron mass.[3]

It has also been recently reported in the press that charged particles of mass about three times that of the electron have been found by Auger in cosmic radiation.

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[1] M. Hessaby, Proc. Nat. Acad. Sci. (June 1947).
[2] L. Smith and G. Groetzinger, Phys. Rev. **70**, 96–97 (1946).
[3] Private communication by G. Groetzinger.

Production of Cosmic-Ray Mesons

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March 19, 1948

IT is currently believed that cosmic-ray mesons are produced in nuclear events induced by primary protons near the top of the atmosphere. The well-known difficulty of the absence of nuclear interaction by sea level mesons and the recent experiments with photographic emulsions[1] have led to the idea[2] that π-mesons, of mass 180 Mev, are the ones produced initially and that each π-meson quickly decays (10^{-7}–10^{-10} sec. lifetime) into an "ordinary" μ-meson of mass 100 Mev and a neutral recoil. An investigation has been undertaken to see whether these ideas are in quantitative agreement with actual observations on meson spectra and intensities.

It is found that there is indeed agreement if the mean free path for absorption of the primary protons is taken to be $\sim$5 cm Hg and if about half the primary energy goes to charged π-mesons, the average multiplicity being around 5 at high latitudes and increasing roughly as the square root of the primary energy.

Our analysis is based on the following argument. No meson theory has as yet proved adequate, but if one uses the general picture that a field of virtual mesons surrounds