Fission Asymmetry as a Function of Excitation Energy of the Compound Nucleus

J. L. FOWLER, W. H. JONES,* AND J. H. PAEHLER
Oak Ridge National Laboratory, Oak Ridge, Tennessee
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The yield of Mo^{99} and Ag^{111} relative to Ba^{140} has been measured for proton produced fission in normal uranium. For this type of fission, as well as for fission obtained in other ways, the variation with compound nucleus excitation energy of the ratio of the yield of Ag^{111} to that of Ba^{140} is discussed in terms of the statistical theory of nuclei.

A PRELIMINARY investigation of asymmetry of fragment mass distribution from proton induced fission has been made as a function of energy in the range 11–18 Mev. Foils of normal uranium (100 mg/cm^2) separated by aluminum were bombarded at a fixed radius with the internal beam of the 86-inch cyclotron. In different experiments, the energy of the proton beam at the bombarding radius was found from the known p,n and $p,2n$ excitation curves of Cu^{63} [1] and the range energy relations in copper. The 2.5 cm×0.6 cm foils of uranium and aluminum were supported behind a 11-mil window of a water-cooled Al probe, and the energy of the protons at each foil was found to ±1.0 Mev from the incident proton energy and the range energy curves in U and Al.

For each U foil, the fission yields of Mo^{99} and Ag^{111} relative to Ba^{140} were determined by use of radiochemical procedures.[2] Mo^{99} and Ba^{140} occur at the peaks of the thermal neutron fission mass distribution; Ag^{111} occurs in the valley of this distribution. Relative yields were obtained in terms of known yields by performing the identical radiochemical analysis for thermal neutron fission in similar quantities of normal uranium. Neutron fission background was found in foils placed beyond the proton range.

The ratio, Yield Mo^{99}/Yield Ba^{140}, is almost constant as a function of proton energy and is the order of 60 percent higher than in the case of thermal neutron fission in U^{235}. The ratio, Yield Ag^{111}/Yield Ba^{140}, varies with proton energy in such a way as to indicate that the probability of symmetrical fission increases rapidly with excitation energy. In Fig. 1, the asymmetry of fission as produced in a number of ways is compared. As ordinate on log scale, the ratio, Yield Ag^{111}/Yield Ba^{140}, is plotted against the quantity $(E_x-5)^{-\frac{1}{2}}$, where E_x is the bombarding particle energy plus its binding energy in Mev. The binding energies are calculated from semi-empirical mass tables.[3] The abscissa, which varies inversely as the square root of energy, suggests reciprocal nuclear temperature. The quantity 5 Mev which is subtracted from the excitation energy to give a linear relationship on the semilog plot is interpreted as the effect of cooling of the nucleus as it is distorted to give fission. This checks with the γ-ray fission threshold, which is about 5 Mev.

With $(E_x-5)^{\frac{1}{2}}=bT$, where T is the nuclear temperature of the distorted nucleus, Fig. 1 shows Yield Ag^{111}/Yield Ba^{140} varies as $3.5\exp(-9.6/bT)$. Since in the case of nuclear phenomena as well as in atomic phenomena, the relative probability of two states separated in energy by ΔE is of the form $\exp(-\Delta E/T)$, $9.6/b$ is interpreted as the energy difference between the asymmetrical mode of oscillation of the distorted uranium

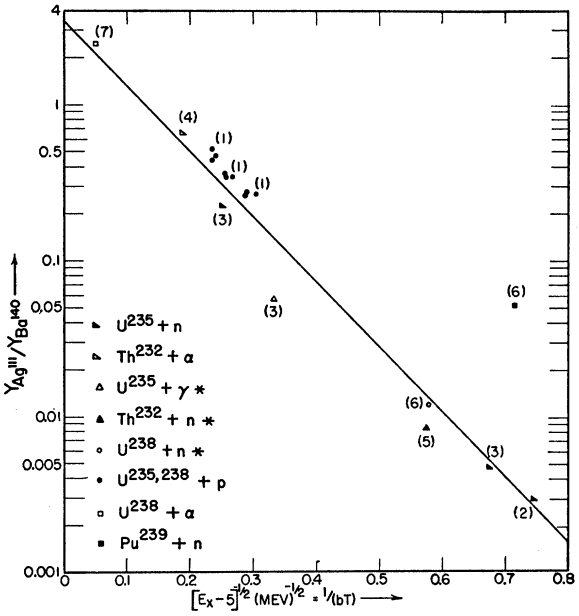

FIG. 1. Fission asymmetry as a function of excitation energy of the compound nucleus. (*) Average over neutron energy spectrum. References: (1) Jones, Fowler, and Paehler, Phys. Rev. **87**, 174 (1952); (2) Revs. Modern Phys. **18**, 513 (1946); (3) R. W Spence, unpublished Atomic Energy Commission report AECU 645 (1949); (4) A. S. Newton, Phys. Rev. **75**, 17 (1949); (5) A. Turkevich and J. B. Niday, Phys. Rev. **84**, 52 (1951); (6) Appendix B, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1950), National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV; (7) P. R. O'Connor and G. T. Seaborg, Phys. Rev. **74**, 1189 (1948).

* Research Participant from Emory University, Atlanta, Georgia.

[1] S. N. Ghoshal, Phys. Rev. **80**, 939 (1950).

[2] W. W. Meinke, unpublished Atomic Energy Commission report AECD 2738 (1949).

[3] N. Metropolis and G. Reilwiesner, unpublished Atomic Energy Commission report NP 1980 (1950).

nucleus and the symmetrical mode. Nuclear temperature, defined by $1/T=d\ln\omega(E)/dE$, can be estimated from the expression for nuclear level densities; $\omega(E)=C\exp[2(E/a)^{\frac{1}{2}}]$. For uranium $C=10$ and $a=0.244$ gives the observed 5 electron volt spacing of levels at excitation energy of about 6 Mev. Under the assumption that the energy level density in the distorted nucleus varies in the same way, b becomes $(0.244)^{-\frac{1}{2}}$ and ΔE is 4.7 Mev. Figure 1 then indicates that the symmetrical mode of fission requires the order of 4.7 Mev more energy than the asymmetrical mode.[4]

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[4] *Note added in proof.*—Professor V. F. Weisskopf (private communication) uses $C=0.005$ and $a=0.08$ for the level densities in uranium. With these constants, ΔE becomes 2.7 Mev.

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Non-Adiabatic Treatment of the Relativistic Two-Body Problem

MAURICE M. LÉVY
Institute for Advanced Study, Princeton, New Jersey

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The method of Tamm and Dancoff, for the non-adiabatic treatment of the relativistic interaction of two nucleons, is generalized in order to include nucleon pair creation and higher order effects in the exchange of mesons. This generalized form of the Tamm-Dancoff method is shown to give results which are equivalent to those obtained from the relativistic equation of Bethe and Salpeter. A detailed study is made of two limiting cases: (a) no pair of nucleons is created in the intermediate states, but an arbitrary number of mesons can be present at the same time; (b) the maximum number of mesons present at a given time is one, but the number of pairs is unrestricted.

The two methods are applied to the calculation of the lowest order correction to the scalar meson interaction of two nucleons. It is shown that the exact correction, which is of the second order in the nucleon velocities, can only be obtained through the inclusion of the fourth- and sixth-order interaction processes involving, in the corresponding Feynman diagrams, the crossing of the meson lines.

1. INTRODUCTION

THE study of a system of two bound particles interacting through a quantized field has usually been done by means of the so-called "adiabatic" approximation, that is: an effective potential between the interacting particles is calculated, neglecting their motion during the exchange of field quanta; this potential is then introduced into a wave equation, and the motion of the interacting particles is worked out as a second step. This method yields good results for nonrelativistic potentials but fails in the case of intrinsically relativistic interactions, such as that yielded by the pseudoscalar meson theory. It has been shown, in this case,[1] that the adiabatic approximation does not allow the system to bind, even if a relativistic calculation is made to the second order in the coupling constant. Furthermore, the notion of effective potential becomes ambiguous when higher order effects are considered.[2]

Since the physical evidence has focused the attention on the pseudoscalar meson theory, it is important to calculate the energy levels of a system of two bound nucleons by means of a method which does not separate the calculation of the interaction to a given order in the coupling constant, from the derivation of the equations of motion, valid to the same order. Such an approach has first been made independently by Tamm[3] and Dancoff,[4] who derived an approximate second-order equation for two particles interacting through a scalar meson field. Another way to treat non-adiabatically a bound system of two particles is provided by the covariant equation which has been proposed by Bethe and Salpeter[5] and subsequently derived from field theory by Gell-Mann and Low.[6]

It is the purpose of the present paper:

(a) to generalize the method of Tamm and Dancoff (abbreviated as T.D. in the following) as to include pair creation and higher order effects in the exchange of mesons, in order to bring it into a suitable form for the study of the pseudoscalar meson interaction between nucleons;

(b) to compare this extended form of the T.D. formalism, where the physical meaning of all quantities is clear at all stages, with the results obtained from the equation of Bethe and Salpeter (abbreviated as B.S. in the following); it will be shown that both descriptions are equivalent, although the way in which the interaction is expanded in powers of the coupling constant is quite different;

[1] M. M. Lévy, Phys. Rev. **84**, 441 (1951).
[2] Y. Nambu, Prog. Theor. Phys. **5**, 614 (1950).
[3] I. Tamm, J. Phys. (U.S.S.R.) **9**, 449 (1945).
[4] S. M. Dancoff, Phys. Rev. **78**, 382 (1950).
[5] E. Salpeter and H. A. Bethe, Phys. Rev. **84**, 1232 (1951).
[6] M. Gell-Mann and F. Low, Phys. Rev. **84**, 350 (1951).