Elastic d-p Scattering at 190 Mev

MARTIN O. STERN AND ARNOLD L. BLOOM
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
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AS a result of recent theoretical interest, a comprehensive program has come into being, the purpose of which is to deduce some properties of the neutron-neutron interaction at high energies.

So far, p-p experiments have been carried out by Birge[1] at 100 Mev, and by Chamberlain, Segrè, and Wiegand[2] at (among other energies) 120 Mev. Professor Wilson M. Powell[3] is engaged in the study of n-d scattering using 90-Mev neutrons. We are measuring the scattering on protons, both elastic and inelastic, of the 190-Mev deuterons of the Berkeley 184-in. cyclotron. In all these experiments the relative velocities are comparable.

In this letter, we present our results to date on the elastic d-p scattering, first reported by one of us (A.L.B) at a recent meeting[4] of the American Physical Society. A more complete report, giving the details of the experiment, and possibly extending the data to larger and smaller angles, will be published in the near future.

The experimental arrangement was akin to that used by Chamberlain and Wiegand.[5] Deuterons scattered out of the cyclotron were collimated and made to impinge on a target. Coincidences between protons and deuterons were observed by means of stilbene crystals. Either one crystal, or two in coincidence, detected the scattered protons; another crystal, in coincidence with the former, the deuterons. Suitable tests were performed to convince us that only the desired events were being observed.

Carbon and polyethylene targets were used alternately to obtain the scattering cross section by subtraction. The data accumulated so far are shown in Fig. 1. The differential scattering cross section, in 10^{-27} cm^2 sterad^{-1} in the center-of-mass system, is shown as a function of the angle of deflection of either particle in that system. Table I gives the weighted averages of the cross sections for a given angle. The slight relativistic correction has been taken into account.

The solid curve of Fig. 1 shows the theoretical cross section as

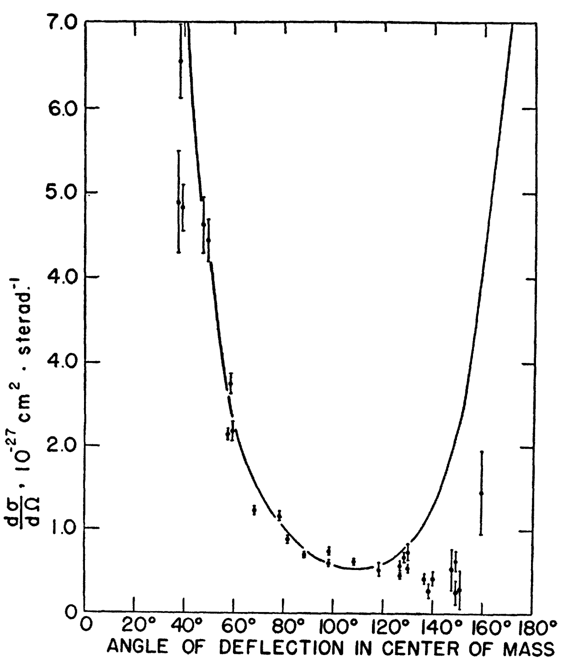

FIG. 1.

TABLE I. Differential scattering cross sections in the center-of-mass system, in 10^{-27} cm^2 sterad^{-1}, averaged over all data for a given angle, as a function of the angle of deflection in the center-of-mass system.

Angle	Cross section	Angle	Cross section
38°	5.4 ±0.4	98°	0.65±0.05
48°	4.5 ±0.4	108°	0.61±0.05
58°	2.3 ±0.2	118°	0.52±0.09
68°	1.22±0.09	128°	0.55±0.05
78°	1.16±0.10	138°	0.40±0.05
82°	0.89±0.08	149°	0.44±0.09
88°	0.70±0.06	159°	1.5 ±0.5

given by Chew.[6] Evidently, the fit is excellent from 60° to 110°, but at larger angles the measured cross section is lower than Chew's; this means that at this energy the pick-up process which causes a rise in the cross section in this region is less important than the Born approximation with Serber potentials for the n-p and p-p interaction would lead one to expect.

The errors shown in Fig. 1 are compounded of the standard deviations due to counting statistics and the estimated uncertainties in the factor which determines how much of the carbon count must be subtracted from that of the CH_2 target to yield the hydrogen effect. In addition, certain systematic errors, due to the uncertainties in the voltage plateaus, beam integration, and steadiness of the beam, etc., may occur. These have been estimated to amount to no more than 7 percent standard deviation, and have been taken into account in the errors quoted in Table I.

We wish to thank Dr. O. Chamberlain and Dr. E. Segrè for their constant assistance and interest in this work. This work was performed under the auspices of the Atomic Energy Commission.

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Nuclear Compressibility and Fission

W. J. SWIATECKI
Institute for Theoretical Physics, Copenhagen, Denmark
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AS is well known, many features of the fission phenomenon find a simple explanation in the theory of the compound nucleus; and, in particular, it has been possible to arrive at an approximate estimate of the critical fission energy for heavy nuclei. So far, however, no simple explanation has been found for the pronounced asymmetry of the nuclear division in fission.[1] In a search for an explanation of this phenomenon we have examined the effects of nuclear compressibility and of the polarizability of nuclear matter (separability of neutrons and protons), and it seems that these effects may play an important part in fission.

The reason is that the deformation energy of a nucleus is a small difference between large changes in electrostatic and surface energies, and that consequently even relatively small corrections to the estimate of these energies may have a decisive influence.

As a model of the nucleus we used a drop of a classical, compressible, polarizable neutron-proton fluid whose density distribution is constantly changing as the fission proceeds. Only the "adiabatic" approximation was considered, in which the density distribution at any instant is given by the equilibrium distribution corresponding to the instantaneous deformation. The total energy of the nucleus was taken to be the sum of volume, coulomb, and surface energies in the absence of compressibility plus a (negative) correction ΔE due to compressibility. That there is in general a factor in ΔE which favors asymmetric fission can be seen as follows: if the volume of the nucleus which is undergoing fission is divided conceptually into two regions corresponding to the nascent fission fragments, the density redistribution due to compressibility can be thought as due to (a) a transfer of matter from one region to the other and (b) the remaining density adjustment. Now (a) will contribute only if the fragments are unequal; and therefore, the associated energy decrease will be greatest for some asymmetric configuration.

We can separate ΔE into ΔE_{scale} and ΔE_{red}, associated with a uniform change of scale and a redistribution of density inside the nucleus, respectively. The former is easily shown to be:

$$\Delta E_{scale} = -(1/2E_v'')[(2-3\dot{\gamma})E_s - E_c]^2, \quad (1)$$

where E_c, E_s are the coulomb and surface energies calculated in the absence of compressibility, E_v'' is the nuclear compressibility coefficient,[2] and $\dot{\gamma} = (n/\gamma)d\gamma/dn$ is a dimensionless parameter giving the dependence of the specific surface energy γ on the bulk density n.

A general method of calculating the density redistribution and ΔE_{red} for a nucleus of *any shape* was developed along the lines of reference 2. If $f(\mathbf{r})$ and $g(\mathbf{r})$ denote the deviations of the local proton and neutron densities from their average values, it is found that (using the notation and assumptions of reference 2)

$$g(\mathbf{r})/f(\mathbf{r}) = \text{constant} = (S-Q)/(S+Q), \quad (2)$$

$$f(\mathbf{r}) = e(S^{-1}+Q^{-1})[\bar{v} - v(\mathbf{r})], \quad (3)$$

$$\Delta E_{red} = -\tfrac{1}{2}e^2(S^{-1}+Q^{-1})\int[\bar{v} - v(\mathbf{r})]^2, \quad (4)$$

where $v(\mathbf{r})$ is the electrostatic potential of a *uniform* proton distribution, $\bar{v}$ is the average of $v(\mathbf{r})$ over the nucleus, e is the proton charge, S and Q are coefficients related to separability and compressibility[2] [e.g., $Q = (4/9n)(E_v''/A)$], and the integration in Eq. (4) extends over the nucleus.

To find the correction to the threshold energy and the "barrier" against asymmetric fission[3,4] one should repeat the calculations of reference (3) with ΔE included in the deformation energy. As an estimate of these effects we have calculated $\Delta E(\lambda)$ for the configuration of tangent spheres as a function of λ, the ratio of the radii. Figure 1 gives ΔE_{scale} and ΔE_{red} for $A=235$, $E_s^0=587$ Mev, $E_c^0=827$ Mev (undistorted surface and coulomb energies), $E_v''=60.62A$ Mev (see reference 2; an upper limit $E_v''\lesssim 96A$ Mev has since been obtained under certain assumptions). In Eq. (4) S^{-1} can then be neglected in comparison with Q^{-1}, so that ΔE is just proportional to $(E_v'')^{-1}$.

With $\dot{\gamma}=0.3$ (estimated by using results of reference 5) $\Delta E(\lambda)$ falls away rapidly from $\lambda=1$, thus decreasing the energies of asymmetric with respect to symmetric configurations. In fact it can be shown[3] that the increase in energy of an incompressible nucleus, when a small asymmetric $\alpha_1 P_1(\cos\theta)$ term is added to the expansion of the saddle-point shape in Legendre polynomials, is $+0.113\alpha_1^2$ (in units of E_s^0), whereas the addition of our ΔE changes this to $-0.043\alpha_1^2$, so that *the asymmetric configuration now has lower energy.* [Note that for tangent spheres $\lambda = (1-\frac{1}{2}\alpha_1)/(1+\frac{1}{2}\alpha_1)$.]

The effect of compressibility affords, therefore, a possible explanation of the asymmetry of fission. The present estimates are crude, but they have brought to light a large effect which does not appear to be sensitive to the approximations made.

We are not in a position to deduce the size of the asymmetry. The minimum in ΔE occurs at a fragment mass ratio of 8:1, but this neglects the dependence on λ of the energy of the incompressible configurations. A tentative estimate of this dependence gives a mass ratio ~2:1.

The calculations also indicate that the compressibility may have a considerable effect on the threshold energy. Actually, the order of magnitude, as given by $\Delta E(1)-\Delta E(0)=5.7$ Mev, is comparable with the empirical threshold energy. This problem and the allied question of the effect of compressibility on nuclear stability are being studied further.

The effect on ΔE of changes in γ due to changes in the curvature of the nuclear surface (like ΔE_{scale} of order $A^{1/3}$) was found to be small.

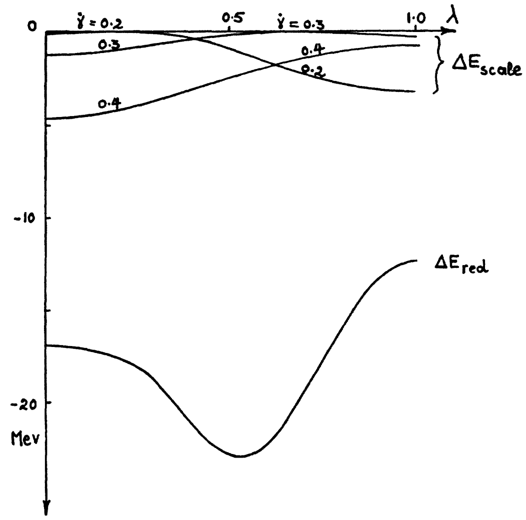

FIG. 1. Corrections ΔE_{scale}, ΔE_{red} due to compressibility for the configuration of tangent spheres as functions of λ, the ratio of the radii.

Quantitative results may be obtained in the future by repeating the calculations of reference 3 with ΔE included in the energy. The asymmetry of the saddle-point shape may provide a possible method of estimating E_v'' empirically.

A fuller account of these investigations will be published in the *Communications* of the Copenhagen Academy of Science.

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Low Excited States in Li^6 and Be^9

C. P. BROWNE,* R. M. WILLIAMSON,† D. S. CRAIG, AND D. J. DONAHUE
University of Wisconsin, Madison, Wisconsin‡
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VARIOUS investigators[1] have reported an energy level in Li^6 at about 2.5 Mev. Pollard and Margenau[1] find a resonance in the yield of alpha-particles scattered by deuterons indicating a level at 2.4 Mev, and Hushley[1] has observed 3-Mev gamma-radiation when beryllium is bombarded with protons. There is also some indication of a resonance in the yield of deuterons scattered from helium in the early data of Heydenberg and Roberts.[1] Unpublished work of Boyer[1] on the $Li^7(d,t)Li^6$ reaction indicates a level at approximately 2.3 Mev in Li^6.

In the present experiment alpha-particles from the reaction $Be^9(p,\alpha)Li^{6*}$ have been observed with a spherical electrostatic analyzer.[2] Protons of well-defined energy from the Wisconsin cylindrical analyzer were allowed to strike targets of thin beryllium foils or thin layers of beryllium evaporated onto nickel foils of 1×10^{-5} cm thickness. The energy of particles emitted at 135° from the incoming beam are measured with the spherical analyzer. A scintillation counter is used for detection. Figure 1 is a plot of number of emitted particles *vs* energy for an incident beam energy of 2.35 Mev. Peaks corresponding to singly, doubly, and triply charged Li^6 particles and doubly charged alpha-particles from the ground-state reaction are found. In addition, peaks attributed to singly and doubly charged alpha-particles from the excited state