Excitation of Heavy Nuclei by the Electric Field of Low-Energy Protons*

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SEVERAL theoretical predictions[1] have been made that heavy charged particles may excite nuclei even though the collision energy is much too small to allow appreciable wave penetration of the Coulomb barrier. Nuclear forces do not take part in this type of inelastic scattering—the excitation of the nucleus results solely from the interaction of the Coulomb fields.

Barnes and Aradine[2] observed the reaction $In^{115}(p,p')In^{115*}$ (4.1 hr) with protons of energy 5.8 Mev and estimated a cross section of about 10^{-29} cm^2. However, there is some question as to whether this reaction involved barrier penetration rather than purely Coulomb excitation.

During the summer of 1952 we observed what appeared to be excitation of a low-lying level in tantalum[3] using protons of such low energy (1.4 to 1.8 Mev) that formation of the compound nucleus is entirely negligible. We observed the prompt monoenergetic gamma rays rather than induced radioactivity. More recently we have examined[4] Ta, Pt, Au, Hg, Tl, and Bi using bombarding energies in the range of proton energies, $E_p=1.4$ to 2.6 Mev.

Our experimental setup is quite simple. Monoenergetic protons from the Rockefeller electrostatic generator strike a metallic target (thick to protons) adjacent to which is the crystal of a NaI(Tl) spectrometer using an RCA 5819 and single channel discriminator. Pulse-height distribution curves are obtained in the usual manner. Co^{57}, Na^{22}, Cs^{137}, Hg^{203}, and Pb (K x-rays) were used for energy calibration.

Figure 1 summarizes the results for three different tantalum targets and a single gold target at proton energies of 1.42 and 1.48 Mev. Each Ta target shows a strong photopeak at 138±5 kev, well resolved from the K x-rays to the left (not plotted). To determine whether this gamma ray was due to impurities in the target or to reactions with scattered protons in the target assembly rather than to the 136-kev first excited state[5] in $_{73}Ta^{181}$, the following steps were taken:

(1) four targets of Ta from two sources were tested;

(2) the targets were cleaned successively with steel wool, emery, acid, water, and alcohol;

(3) iron, vanadium, and carbon targets were tested, since these are the most common bulk impurities in commercial Ta;

(4) an Au target was tested in a similar manner.

The pulse-height distributions from the Fe, V, C, and Au (see Fig. 1) targets were such that these substances could not account for the 138-kev peak in Ta. Our spectrometer would not reveal the 77-kev gammas from $_{79}Au^{197}$ (assuming they were produced) in the presence of the K x-rays. The possibility that the 138-kev line is the result of the pile-up of pulses in the NaI(Tl) crystal is also eliminated by the absence of a similar line in Au at about twice the K x-ray energy.

Another possibility suggested by Professor H. Bethe[4] is that the 138-kev peak is the result of a superposition of K x-rays from the double ionization of the K shell in Ta. We have measured the absorption of the 138-kev line relative to the K x-rays in Pb (~20 mils) and find that the x-rays are attenuated much more markedly than the 138-kev peak. Hence, the 138-kev line does not appear to be composed of lower energy quanta. What is more significant, however, is that the shape of the 138-kev peak was retained after attenuation in the Pb—the effect to be expected for a line spectrum.

The tentative conclusion is that these are $M1$ gammas from the transition $g_{7/2}$, first excited state, to $g_{7/2}$ ground state of $_{73}Ta^{181}$ induced by Coulombian excitation of the nucleus. The basis for discarding barrier penetration at the proton energies used is that the cross section for formation of the compound nucleus alone is

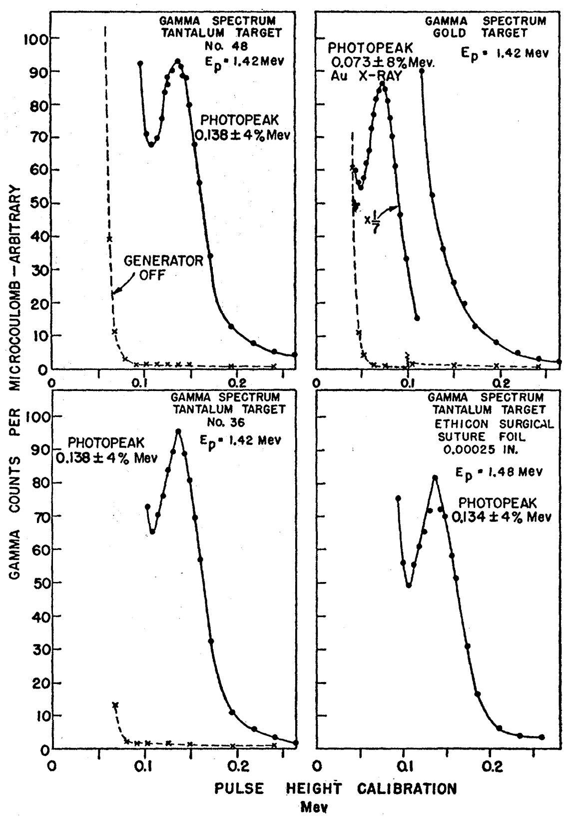

FIG. 1. Pulse-height spectra for Ta and Au. The pulse height has been calibrated with 511-kev annihilation radiation from Na^{22}, and the energy of the gamma ray may be read directly from the position of its photopeak.

only about 10^{-39} cm^2 at $E_p=1.5$ Mev. It would be even smaller for $\sigma(p,p')$.

Because the yield of gammas has been measured only for thick Ta targets, only rough estimates can be made of the observed cross section. We calculate this to be about 0.4 millibarn and essentially constant for $E_p=1.4$ to 1.6 Mev. However, assuming 80 percent internal conversion of the 138-kev gamma, the cross section would be about 8 millibarns.

Naturally we were reluctant to accept the above conclusions without additional experimental evidence. Dr. de-Shalit suggested[6] that we bombard platinum since there are two low-lying levels:[5] a $p_{1/2}$ at 97 kev and an $f_{5/2}$ at 126 kev above the $p_{1/2}$ ground state in $_{78}Pt^{195}$. We have done this, with the results shown in Fig. 2. Clearly there is a peak at about 127 kev for $E_p=1.64$, 1.78, and 2.0 Mev. There is also evidence at these energies, and at 1.51 Mev as well, for some radiation between 90 and 100 kev, since otherwise the curve should dip much more in this region (see corresponding section of Au data in Fig. 1). We, therefore, tentatively conclude that nuclear gammas from $_{78}Pt^{195}$ have been activated by the purely Coulombian process. We are unable at this time to quote a cross section for Pt, but it certainly appears to be substantially less than for Ta for the same proton energy.

The results with Au, Hg, Tl, and Bi are more preliminary than those for Ta and Pt. The first measurements with Au (Fig. 1) show no evidence of the 191-kev radiation[5] from the second to the first excited state. More recent measurements with an improved resolution crystal (Harshaw) show two small peaks which we very tentatively would attribute to 250- and 450-kev gammas. The improved resolution also revealed another higher peak in Ta (not evident in Fig. 1) which increased in height as the proton energy was increased. We would tentatively assign this an energy of about 500 kev. Conceivably this radiation may be from the next

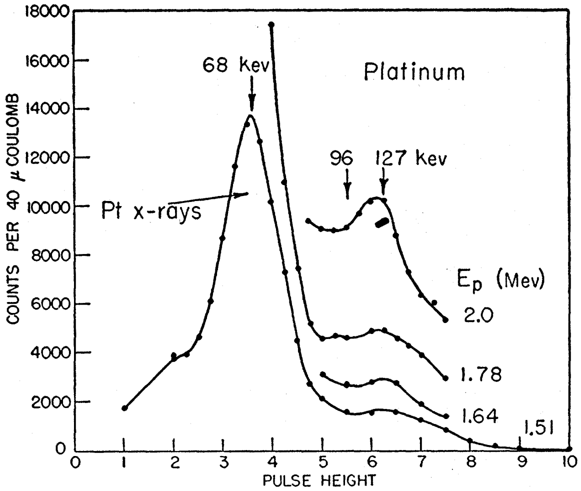

FIG. 2. Pulse-height spectrum of Pt at four proton energies E_p. A small adjustment has been made in the horizontal position of the data taken at $E_p = 2.0$ Mev in order to correct for electronic drift in the spectrometer.

higher level in $_{73}Ta^{181}$ decaying to the ground state. This would imply the presence of 345-kev radiation as well, and some evidence for this has been observed.

After studying the Au radiation, we made an amalgam and examined the increment due to Hg. There is clearly a reproducible break in the curve at an energy of about 200 kev which increases with proton energy. At least two isotopes of Hg are reported to have levels which could account for radiation of this energy.

We examined Tl (cp) and observed a well-resolved peak at 380±10 kev. This radiation does not correspond to transitions between known levels to the best of our knowledge. The 280-kev radiation, from Tl^{203}, if present, would have been obscured by the Compton peak from the 380 kev and the high-energy tail of the x-rays. Preliminary tests on Bi as yet have yielded no significant results.

In the future we plan to use only thin targets since these are not only essential for accurate cross-section measurements, but also result in a greatly reduced x-ray background. We can also further reduce the x-ray background by critical absorption foils, a technique which we have already used successively to a limited extent.

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Radiative Corrections to Nuclear Forces in Pseudoscalar Theory*

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IT has been recently pointed out by the author, Gell-Mann, and Goldberger[1] (in a paper to be referred to as I) that a simple subset of radiative corrections to the nucleon propagation function has the effect of strongly depressing nucleon pair formation in pseudoscalar theory with pseudoscalar coupling. The effects on meson scattering and nuclear forces are then very pronounced. It is the purpose of this note to show that these effects also appear in a simple way in a consistent formulation of the relativistic two-body problem. For this we consider the Bethe-Salpeter equation for the bound state[2] (the consideration of the scattering problem is not essentially different) which has the form

$$\varphi(p_1, p_2) = S_F(p_1)S_F(p_2)\int d^4p_1'd^4p_2' \times G(p_1, p_2; p_1', p_2')\varphi(p_1', p_2'), \quad (1)$$

where $G(p_1, p_2; p_1', p_2')$ is the kernel of the integral equation. A method proposed for attacking this problem is to expand the kernel in a power series in the coupling constant but to attempt to solve the resulting simplified equation exactly. The first approximation to the integral equation [Eq. (1)] can then consistently be assumed to arise from taking all contributions of order g^2 which lead from the state $\varphi(p_1, p_2)$ to the state $\varphi(p_1', p_2')$. These are shown in the form of Feynman diagrams in Fig. 1.

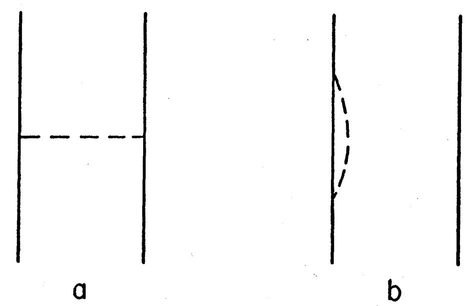

FIG. 1. Feynman diagrams for the g^2 contributions to the kernel.

Diagram (a) of this figure gives rise to the usual "ladder" approximation;[2,3] the second diagram (b) corresponds to a vacuum fluctuation for the nucleon and would give no contribution in a Born approximation calculation. The finite contribution from this graph is, however, not in general zero (vanishing only on the energy shell) and cannot be consistently dropped in this approximation. It can be treated in the following way; in the zeroth approximation (of order g^2) to the kernel, one obtains the following contributions:

$$G^0(p_1, p_2; p_1', p_2') = G^0_{\text{ladder}}\delta(p_1+p_2-p_1'-p_2') + G^0_{\text{radiative}}\delta(p_1-p_1')\delta(p_2-p_2'), \quad (2)$$

where

$$G^0_{\text{ladder}} = g^2\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2(\gamma_5)_1(\gamma_5)_2 D_F(p_1-p_1') \quad (3)$$

and

$$G^0_{\text{radiative}} = g^2\sum_{\lambda=1}^{2}\boldsymbol{\tau}_\lambda\cdot\boldsymbol{\tau}_\lambda\int[\gamma_5 S_F(p_\lambda-k)\gamma_5]_\lambda D_F(k)d^4k. \quad (4)$$

The finite parts of $G^0_{\text{radiative}}$ have been previously evaluated; in the notation of I,

$$G^0_{\text{radiative}} = -(3g^2/16\pi^2)[f(p_1)+f(p_2)]. \quad (5)$$

The only property of $f(p)$ which we shall consider here is that $f(p)$ vanishes on the energy shell but is approximately equal to one if the momentum-energy relation between $\gamma\cdot p$ and M is that of an antiparticle.

The integral equation [Eq. (1)] now becomes

$$\varphi(p_1, p_2) = S_F(p_1)S_F(p_2)\{1+(3g^2/16\pi^2)[f(p_1)+f(p_2)]\}^{-1} \times\int d^4p_1'd^4p_2' G^0_{\text{ladder}}\delta(p_1+p_2-p_1'-p_2')\varphi(p_1', p_2'), \quad (6)$$

which differs from the ladder approximation in that the propagation functions $S_F(p)$ have been replaced by $S_F'(p)$, where

$$S_F'(p_1)S_F'(p_2) = S_F(p_1)S_F(p_2)\{1+(3g^2/16\pi^2)[f(p_1)+f(p_2)]\}^{-1}.$$

The corresponding modification of the Feynman diagrams which