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Search for Pair Production by Protons

W. E. STEPHENS* AND H. STAUB
University of Zurich, Zurich, Switzerland

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A search was made for pairs produced in the collision of heavy particles by bombarding tantalum with protons of energy up to 1.64 Mev. Only a very small number of positrons was detected, giving an upper limit of 6×10^{-13} pair per proton at 1.54 Mev, in contrast to the theoretical value of 38×10^{-13} pair per proton obtained by Born approximation.

INTRODUCTION

THE creation of positron-electron pairs in collisions between charged particles with sufficient (but nonrelativistic) energy has been predicted by Dirac-theory calculations using the Born approximation. Heitler and Nordheim[1] give the order of magnitude of the pair production cross section,

$$\phi\approx\frac{\mu^2 r_0^2 Z_1^4 Z_2^2}{137^2 M_1 c^2 T_1}\left(1-\frac{M_1 Z_2}{M_2 Z_1}\right)^2,$$

for the impact of particle M_1, Z_1 with kinetic energy T_1 upon a nucleus M_2, Z_2. Here r_0 is the electron "radius" and μ the electron rest energy. This predicted cross section is approximately 10^{-30} cm^2 for protons of 1.5-Mev energy striking tantalum. The availability of intense proton beams and sensitive positron detectors prompted a search for such pair production to test the theory in this nonrelativistic region.

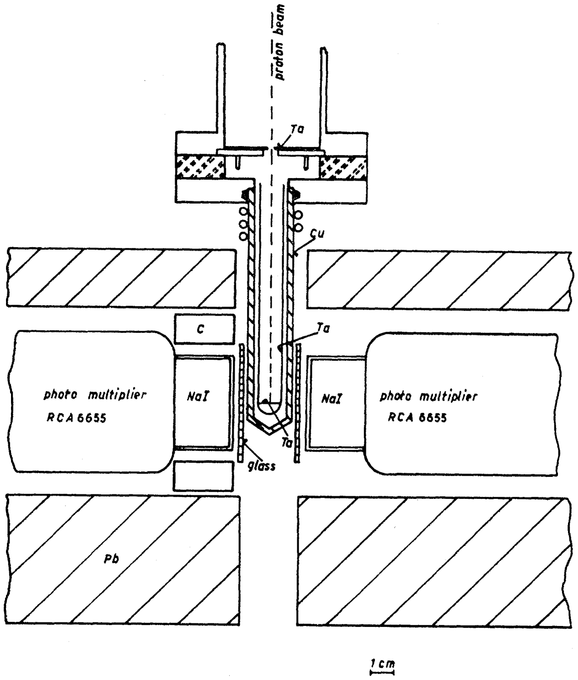

FIG. 1. Schematic diagram of detecting arrangement.

EXPERIMENT

The protons were accelerated in an electrostatic generator to energies up to 1.64 Mev and currents up to 50 microamperes. This proton beam was collimated by tantalum disks with 4-mm holes and directed onto a tantalum (or other) target in a Faraday cup. The Faraday cup was cooled by circulating kerosene of high electrical resistance so that the target current could be measured by a current integrator. The large power in the proton beam heated the tantalum target white hot which aided in cleaning the target and in keeping it clean. Near each side of the target tube were placed sodium iodide crystals and scintillation detectors as shown in Fig. 1. This detecting system is the same as that used by C. Frei and H. Staub in their study of gamma-ray induced pair production in light elements and described more fully in their report to be published in *Helvetica Physica Acta*. We are indebted to Mr. Frei for able assistance in this part of the present experiment.

The pulses from the photomultipliers were amplified, discriminated, and fed into a coincidence circuit whose resolving time was approximately $\frac{1}{2}$ microsecond. The channel for each detector was set to pass pulses equivalent to photon energies between 420 kev and 640 kev. This effectively includes the 511-kev annihilation radiation photopeaks whose widths at half-maximum were 56 kev. The photopeak efficiency ϵ of each scintillation detector is approximately 0.16 of the annihilation photons falling upon it. The efficiency for detecting positrons is then $d=2\omega(\epsilon f)^2$, where ω is the solid angle subtended by either crystal, ϵ is the photon detection efficiency, and f is the fraction of the photons passing through the target wall, etc. For the arrangement shown in Fig. 1, ω is calculated to be 0.13 while f is 0.87. This gives d about 5×10^{-3}. This efficiency was measured more directly by the use of Cu^{64} positron radioactivity whose yield was determined by beta-ray counting.[2] The calibrated Cu^{64} was placed in the position of the target and the coincidences counted. This measurement gave an efficiency of $(5.4\pm0.2)\times10^{-3}$ coincidence count per positron.

Another check on the detecting sensitivity was made by measuring the 137-kev gamma ray from Ta^{181} which was Coulomb-excited by the proton beam in the course of the experiment. At 1.5-Mev proton energy, we

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* On sabbatical leave from University of Pennsylvania, Philadelphia, Pennsylvania.

[1] W. Heitler and L. Nordheim, J. phys. 5, 449 (1934).

[2] We are indebted to Dr. Walter and Mr. Heinrich of this laboratory for this careful measurement.

observed 330 counts in the photopeak per microcoulomb of protons. Allowing for absorption in the target tube, solid angle and crystal detection efficiency, we estimate 29 000 gamma rays per microcoulomb of protons. This is in reasonable agreement with the value of 20 000 gammas per microcoulomb estimated from the data of Stelson and McGowan.[3]

The positron detecting efficiency determined above is for positrons annihilating in the copper foil in the position of the target. There is some uncertainty in the actual position of annihilation of the proton-induced positrons. At least half of these positrons go into the target and annihilate there. Many of the remaining positrons will annihilate in the walls of the target tube nearby. Consequently, the effective coincidence count per pair may be expected to be between 2.5 and 5.4×10^{-3}, or approximately 4×10^{-3}.

The experiment was performed by measuring the coincidence count for a certain integrated proton current at various proton energies and with various targets. Background was determined by deflecting the proton beam off the target and running for an equal length of time. A number of bothersome backgrounds were found and at least partially eliminated in the course of the experiment. A first lead target contained so much fluorine contamination that the excitation curve of the $F^{19}(p,\gamma)O^{16*}$ pair level was easily obtained. Positron radioactivities of a few minutes and ten minutes half-life were observed and ascribed to $C^{12}(p,\gamma)N^{13}$, $O^{16}(p,\gamma)F^{17}$, and $N^{14}(p,\gamma)O^{15}$. These backgrounds were reduced most effectively by heating the target with the proton beam. The best target arrangement was found to be a loose tantalum disk (0.2 mm thick) laid in the bottom of a tantalum cup in the copper target tube. The tantalum disk became white hot under bombardment and the most intense beams actually melted the surface of the tantalum. To further reduce the contribution of the positron activities, the individual runs were kept short (one-half to three-quarters of a minute) followed immediately by a background run with the beam deflected off the target. The effect of a positron radioactivity with disintegration constant λ produced in the target at the rate R, together with a prompt positron production at the rate P, can be calculated under these simple assumptions. The beam strikes the target for a time T during which time the counters detect a positron annihilation count of A. The beam is then deflected from the target for an equal time T during which time the counters detect the annihilation of the radioactive positrons plus any other background for a count of B. The net count rate is taken as $(A-B)/T$ which corrects approximately for the background. A detailed calculation shows that at "equilibrium" (i.e., after a long period of alternating A and B)

$$y=\frac{(A-B)}{T}=P+R\left[1-\frac{2(1-e^{-\lambda T})}{\lambda T(1+e^{-\lambda T})}\right].$$

Since in many cases the runs could not be considered in "equilibrium," at least with half-lives as long as 10 minutes, a calculation was made for the case in which no radioactivity exists at the start and the periods A and B alternated 10 times. The average net counting rate for these 10 periods is

$$\bar{y}=\frac{\langle A-B\rangle_{\text{Av}}}{T}=P+R\left\{1-\frac{1}{10\lambda T}\frac{(1-e^{-\lambda T})}{(1+e^{-\lambda T})^2}\times[20+21e^{-\lambda T}-e^{-21\lambda T}]\right\}.$$

In Fig. 2 is plotted this estimated contribution to the net count of a background radioactivity as a function of the observation period in units of the radioactivity half-life, both for equilibrium (dashed line) and for 10 periods with no initial radioactivity (solid line). It will be noted that for periods T less than the half-life of the radioactivity, the error is less than 5% of the radioactivity rate. Since it was not usually possible to identify the background half-life or lives due to low counting rates, it was not possible to apply this second-order correction for radioactivity. However, for a reasonable assumption of the half-life (more than 1 minute), the correction was always smaller than the statistical uncertainty. In confirmation of these calculations, deliberately longer runs for T equal to 5 or 10 minutes often gave a larger net count than short runs. They were not used in the reported data.

After all these improvements and precautions, the net coincidences observed from tantalum are shown in

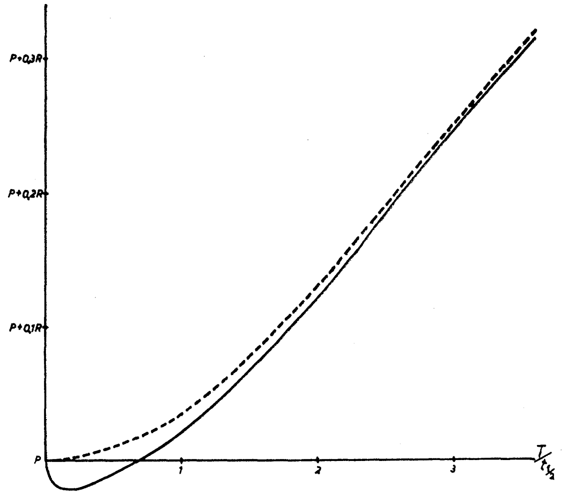

FIG. 2. Effect of radioactivity background on net counting rate as a function of observation period.

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[3] P. H. Stelson and F. K. McGowan, Phys. Rev. 99, 112 (1955).

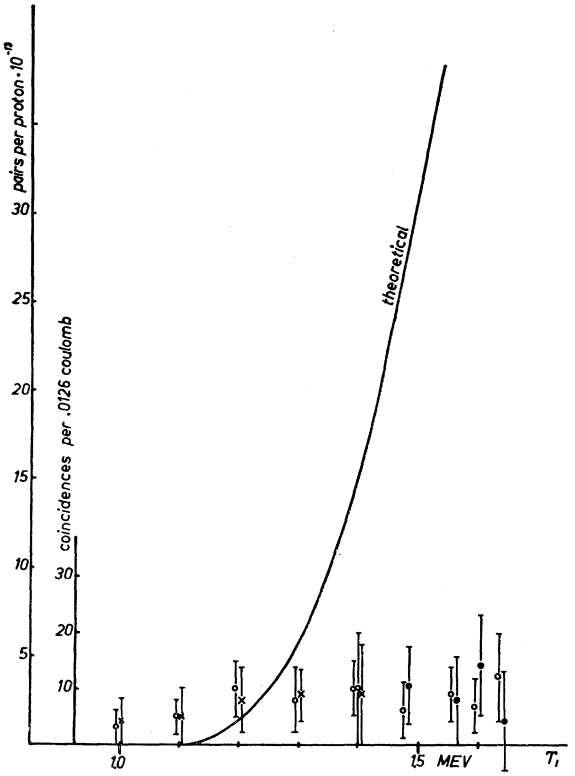

FIG. 3. Observed coincidences per 0.0126 coulomb of protons on tantalum as a function of proton energy. The points marked ○, ×, ● represent three different independent measurements. Solid curve is theoretically predicted value for tantalum.

Fig. 3 for proton energies from 1.0 to 1.64 Mev. With a detecting efficiency of 4×10^{-3} the coincidence rate is transformed to pairs per proton, which scale is also marked on the abscissa. It is not clear to what this remaining positron production is due. In any case, the observed values may be considered an upper limit of a true proton pair-production yield.

Molybdenum gave results similar to tantalum for proton energies up to 1.5 Mev. Above this energy, a sharp rise in positron production occurred but the origin of this rise has not been identified. Platinum gave initially similar results to tantalum but could not be cleaned as well because of its lower melting point.

THEORY

Heitler and Nordheim[1] treat the case of a particle of mass M_1, charge Z_1, kinetic energy T_1, and momentum P_1, which makes a collision with a bare nucleus of mass M_2 and charge Z_2 at rest. For energies T_1 small compared to M_1c^2 and M_2 large compared to M_1, the pair-production cross section is calculated by using the Born approximation for dipole interaction. The result is

$$\phi=\frac{4\pi}{3}\left(\frac{r_0}{137}\right)^2\frac{\mu}{M_1c^2}Z_1{}^4Z_2{}^2\left(1-\frac{M_1Z_2}{M_2Z_1}\right)^2F,$$

where

$$F=\int\int\frac{\mu}{T_1}\left(\ln\left|\frac{P_1+P}{P_1-P}\right|\right)$$

$$\times\left\{\Delta^2\left(\ln\left|\frac{p^+ + p^-}{p^+ - p^-}\right|\right)-2p^+p^-\right\}\frac{d\epsilon^+d\epsilon^-}{\Delta^4},$$

and where P is the momentum of particle 1 after collision, p^+/c and p^-/c are the momenta of the positron and electron respectively, ϵ^+ and ϵ^- are the total energies of the positron and electron, and $\Delta=\epsilon^+ + \epsilon^-$. The expression is to be integrated over all values of ϵ^+ and ϵ^- possible for a given T_1. Performing this integration graphically gives the results tabulated in Table I.

TABLE I. Results of graphical integration.

T_1 (Mev)	F	$\int_{2\mu}^{T_1}FdT_1$ (Mev)	Φ_{Ta} (10^{-31} cm^2)	$\int_{2\mu}^{T_1}\Phi_{\mathrm{Ta}}dT_1$ (10^{-8} Mev-barns)	Y_{Ta} pairs per proton
1.028	0	0	0	0	0
1.130	0.0009	0.00002	0.16	0.04	0.2×10^{-13}
1.232	0.0042	0.00024	0.77	0.44	2.4×10^{-13}
1.336	0.0094	0.00087	1.72	1.59	8.8×10^{-13}
1.438	0.0157	0.00203	2.87	3.71	20.6×10^{-13}
1.541	0.0225	0.00380	4.10	6.95	38.4×10^{-13}

It will be noted that in this energy region, the phase-space factor F is much smaller than unity although it is rising fairly rapidly. Also tabulated in Table I are the integral of F, the pair production cross section for tantalum, and the integrated cross section for tantalum. In the last column is given the thick-target yield for tantalum in units of pairs per proton obtained from the integrated cross section by the relation

$$Y=n_{\mathrm{pairs}}/n_{\mathrm{protons}}=(N/kM_2)\int_{2\mu}^{T_1}\phi(T_1)dT_1,$$

where N is Avogadro's number and k is the rate of energy loss of the protons in the target in Mev per g per cm^2. The constants used in evaluating the tantalum yield are:

$$M_1=1,\quad Z_1=1,\quad M_2=181,\quad Z_2=73,\quad \mu=0.511\text{ Mev},$$
$$M_1c^2=938\text{ Mev},\quad r_0=2.8\times10^{-13}\text{ cm},$$
$$k=60\text{ Mev/g/cm}^2.$$

DISCUSSION

While the Born approximation is expected to be inaccurate in this region of proton energies because of its neglect of the distortion of the particle waves in the Coulomb field of the nucleus, it is still surprising that the predicted value of 38×10^{-13} pair per proton at 1.54 Mev is so much larger than the observed upper limit of 6×10^{-13} pair per proton. In the case of pair production by gamma rays of equivalent energy, the Born value is less than the observed value.[4] More exact calculations, using Coulomb wave functions for the incident and deflected proton, would be of considerable interest in order to see if such a calculation gives a smaller cross section.

Since the cross section is not expected to vary rapidly with nuclear charge or mass, we have not continued the study of other elements. Likewise, we have not tried alpha bombardment because of the weak beams available, despite the probable reduction in background. The most promising extension would be to higher proton energy. The predicted cross section is rising rapidly and in the region of 2 to 3 Mev might be expected to have a value some 10 times its value at 1.5 Mev. The pair-production effect then might be measurable.

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[4] W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, New York, 1954), third edition, p. 267.

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Gamma Rays from $C^{13}+d$ and the Excited States of C^{14}†

E. K. WARBURTON AND H. J. ROSE*
Brookhaven National Laboratory, Upton, New York

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A study has been made of the γ rays produced by the bombardment of C^{13} by deuterons from the Brookhaven Van de Graaff accelerator with particular emphasis on the γ rays from the $C^{13}(d,p)C^{14}$ reaction. A search for C^{14} γ-emitting states and cascade transitions was made using a three-crystal pair spectrometer and other scintillation counters at bombarding energies up to 3.7 Mev. From coincidence measurements the assignment of the 0.81-Mev γ ray to the cascade transition between the C^{14} 6.89- and 6.09-Mev states was confirmed and a previously unreported 0.62-Mev γ ray was assigned to the cascade transition between the C^{14} 7.35- and 6.72-Mev states. Limits on the lifetimes of the C^{14} 6.89-, 6.72-, and 6.1-Mev states were obtained from measurements of the Doppler shifts of the 0.81-, 6.72-, and 6.1-Mev γ rays. The lifetime limit for the 6.72-Mev state was combined with previous measurements to give a most probable assignment of $J^\pi=3^-$ for the 6.72-Mev state, while the lifetime limit for the C^{14} 6.89-Mev state showed that the 0.81-Mev transition is chiefly dipole. Measurements of the angular correlation of the 0.81- and 6.1-Mev γ rays were interpreted by expressing the angular correlation functions in terms of the relative populations of the magnetic substates of the C^{14} 6.89-Mev state. By this method an assignment of $J=0$ was obtained for the C^{14} 6.89-Mev state.

I. INTRODUCTION

IN spite of its anomalously long lifetime, the C^{14} nucleus is difficult to reach by any of the more usual nuclear reactions with the exception of $C^{13}(d,p)C^{14}$. In fact, all that is known about the excited states of C^{14} has been determined from observations on the proton groups and γ rays following the bombardment of C^{13} by deuterons. Proton groups have been observed[1,2] corresponding to bound C^{14} states at 6.091, 6.589, 6.723, 6.894, and 7.346 Mev in addition to eight other states above the neutron binding energy (8.169 Mev). Angular distributions have been obtained[2–4] for the proton groups corresponding to these bound states and have been analyzed by the stripping theory of Butler to determine the parities and a range of possible J values for the states. Gamma-rays of 0.81, 6.1, and 6.7 Mev observed[5] following the bombardment of C^{13} enriched targets by deuterons have been assigned to the transition between the C^{14} 6.89- and 6.09-Mev states and to the ground-state transitions of the C^{14} 6.09- and 6.72-Mev states. These γ transitions have not been studied in great detail. The present investigation was undertaken, then, to gain additional information concerning the excited states of C^{14} from a study of the γ rays following the bombardment of C^{13} by deuterons.

Using relatively high efficiency techniques, a search was made for γ rays originating from C^{14} states which might have escaped previous detection. Coincidence measurements were used to assign cascade γ rays—one of which was observed in the coincidence measurements only. Doppler-shift measurements were made on several γ rays and the lifetime limits obtained from these measurements gave information concerning the γ-emitting states involved. In one case, angular correlation measurements were used to give a definite spin assignment to a C^{14} state.

II. GAMMA-RAY SPECTRUM FROM $C+d$

All the observations on the γ rays following the bombardment of carbon by deuterons reported herein were carried out by using a 100-μg/cm^2 target of C^{13}, 70% enriched, cracked onto a 0.004-in. gold backing. The deuterons were accelerated by the Brookhaven 4-Mev research Van de Graaff accelerator. Detection of the γ rays was accomplished using two 2 by 2 in.

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* Guest Physicist at Brookhaven National Laboratory on a fellowship of Deutsche Forschungsgemeinschaft.

[1] Sperduto, Buechner, Bockelman, and Browne, Phys. Rev. **96**, 1316 (1954).

[2] McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).

[3] R. E. Benenson, Phys. Rev. **90**, 420 (1953).

[4] F. A. El Bedewi, Proc. Phys. Soc. (London) **A69**, 221 (1956).

[5] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).