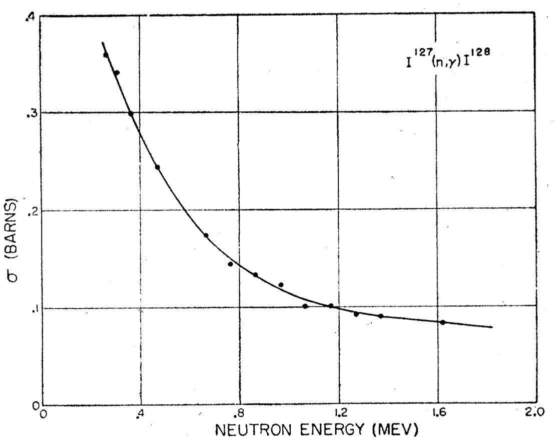

FIG. 1. Cross section for the $I^{127}(n, \gamma)I^{128}$ reaction.

varying the proton energy. Several clear cubic crystals weighing from 2.5 to 5 grams were used in obtaining the data. Each crystal was placed in a cadmium-shielded test tube and covered with mineral oil; for each datum a crystal was irradiated for 1600 seconds. A flat-response long counter,[3] also at 0°, monitored the neutron flux during the irradiation. The absolute flux was determined by comparison with a standard RaBe source, calibrated to ±5 percent, placed at the gas target. In each case the transmission of the sample was measured so that a correction could be made for attenuation of the neutron beam in passing through the crystal.

After irradiation the crystals were submerged in a mineral oil well on a 5819 photomultiplier, and their activities were detected by feeding pulses from the photomultiplier to an amplifier and scaler. In all cases clean 25-minute activities due to I^{128} were observed. Extrapolation of the detecting system's integral bias curve to zero bias indicated that about 98 percent of all pulses from the scintillator were above normal operating bias. Within experimental error, the value obtained for the cross section at a given neutron energy was found to be independent of the size of the activated crystal. No induced activity was observed in a crystal that was irradiated behind a 30-cm long tungsten shadow-cone, indicating a negligible slow neutron background.

Figure 1 shows the (n, γ) cross section as a function of neutron energy. The estimated error in the absolute values is ±7 percent; the energy spread for each datum is about 50 kev. The cross section is very nearly proportional to $1/E$ in this energy range. These results are essentially in agreement with values for the (n, γ) cross section that have been obtained at several isolated points.[4]

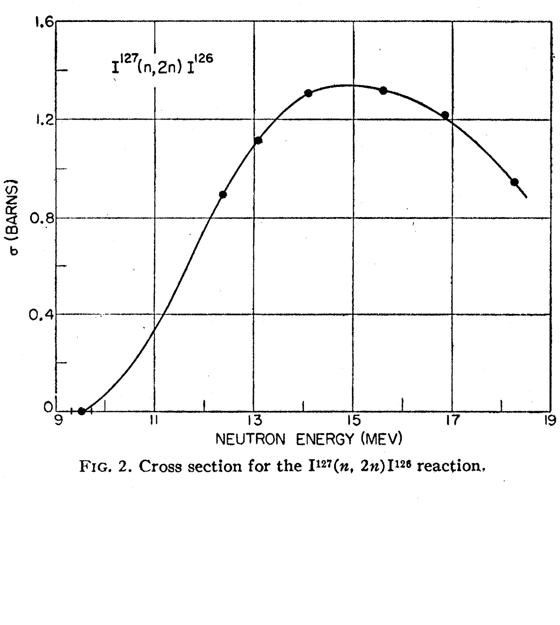

FIG. 2. Cross section for the $I^{127}(n, 2n)I^{126}$ reaction.

A relative $(n, 2n)$ activation curve was obtained by placing the NaI(Tl) crystals at appropriate angles around the tritium gas target at a distance of 12 cm and accelerating monatomic deuterons to 2.00 Mev to produce the $T(d, n)He^4$ reaction.[2] The crystals were counted as in the case of the (n, γ) reaction, and for each crystal the 13.1-day I^{126} activity was observed for about 40 days with no longer-lived period becoming apparent. While the error in the relative activities of the crystals is only about ±4 percent, the cross-section values shown in Fig. 2 depend upon the angular distribution of the $T(d, n)He^4$ neutrons, which is known to about ±10 percent. For a deuteron energy of 2 Mev, at the angular positions where the crystals were irradiated, the laboratory differential cross sections for neutrons shown in Table I have been used. These values seem most consistent with presently available data on the $T(d, n)He^4$ reaction.[2,5] To fix the absolute value of the $(n, 2n)$ cross section, a crystal was irradiated with 14.1-Mev neutrons produced by a Cockcroft-Walton accelerator, with the absolute neutron flux monitored to ±5 percent by observing the alpha-particles from the $T(d, n)He^4$ reaction. The error in the absolute value of the $(n, 2n)$ cross section at 14.1 Mev is estimated to be ±6 percent. The neutron energy spread at each point is about 0.7 Mev; the threshold of 9.52±0.20 Mev is determined from the value reported for the (γ, n) reaction.[6]

TABLE I. Laboratory differential cross sections for $T(d, n)He^4$ neutrons at a deuteron energy of 2 Mev.

θ_{lab} deg	0	52.5	75	127.5	150
$\sigma(\theta_{lab})$ mb/sterad	23.0	13.4	10.1	8.0	8.0

We are indebted to Mr. Arthur Frentrop for the irradiation at the Cockcroft-Walton accelerator.

* Work done under the auspices of the U. S. Atomic Energy Commission.

[1] Jarvis, Hemmendinger, Argo, and Taschek, Phys. Rev. 79, 929 (1950).
[2] Hanson, Taschek, and Williams, Revs. Modern Phys. 21, 635 (1949).
[3] A. O. Hanson and J. L. McKibben, Phys. Rev. 72, 673 (1947).
[4] U. S. Atomic Energy Commission Report AECU-2040.
[5] T. F. Stratton and G. D. Freir, Phys. Rev. 88, 261 (1952).
[6] Ogle, Brown, and Carson, Phys. Rev. 78, 63 (1950).

Precision Measurement of Co^{60} Gamma-Radiation

G. LINDSTRÖM, A. HEDGRAN, AND D. E. ALBURGER*
Nobel Institute of Physics, Stockholm, Sweden
(Received January 19, 1953)

BECAUSE of the usefulness of Co^{60} as a gamma-ray standard, Lind, Brown, and DuMond have made[1] precision determinations of the gamma-ray energies from this isotope. Their values of 1.1715±0.0010 Mev and 1.3316±0.0010 Mev are based on curved crystal spectrometer measurements of wavelengths. Recently it was reported[2] by Muller, Hoyt, Klein, and DuMond that an unsuspected nonlinearity was present in the crystal spectrometer at the time of the Co^{60} experiments. From Fig. 7 of their paper it can be seen that if a correction is made for this, it would raise the Co^{60} values by about 0.1 percent.

In order to obtain a check on the Co^{60} gamma-rays, we have determined their energies in the following way. The K line of the highly converted 1.41-Mev transition occurring in the decay of 20-min RaC (electron energy about 1.32 Mev) was first measured absolutely in a semicircular focusing uniform field spectrometer. The technique was similar to that previously described[3] in connection with ThC″ measurements except that both photographic and counter detection were used. In the latter case a NaI gamma-ray monitor counter was employed to correct for decay. Sources consisted of tungsten wires 20 microns in diameter on which the activity had been collected electrostatically. Measurements of both the magnetic field along the path in terms of the proton resonance and the source to slit (or image) distance were done according to previous procedures. The weighted average of two counter and two photographic measurements gives a momentum of 5874.4±0.6 gauss-cm for the extrapolated high energy edge of the line. This corresponds to a RaC′ transition energy of 1.4158 ±0.0002 Mev, if finite line width effects are not taken into account.

The RaC line was then compared in the 50-cm radius double-focusing spectrometer with the K shell internal conversion electrons due to the 1.33-Mev Co^{60} transition. The cobalt sources were 3×15 mm electrolytic deposits on copper backings. Source thickness effects prevented the use of a spectrometer resolution better than 0.25 percent, but this was sufficient to resolve the L line well enough so that the extrapolated high energy edge of the K line was practically unaffected. The $K/(L+M)$ ratios of both cobalt transitions were found to be close to 10. For the RaC runs the sources were collected on copper strips 3 mm wide and a gamma-ray monitor corrected for decay. Using a slit 3 mm wide to accurately define the position of the sources, the extrapolated edges of the RaC and Co^{60} conversion lines were compared and found to be about 0.08 percent apart. By using the weighted average of three comparisons and adding the Ni K shell binding energy of 8.337 kev,[4] the cobalt gamma-ray is found to have a value of 1.3325±0.0003 Mev.

The two cobalt K conversion lines were then compared in the double-focusing spectrometer in order to obtain their momentum ratio. Because these are ∼10 percent apart in momentum, it was considered advisable to accurately check the linearity of the instrument over this range. This was done by first making an absolute determination in the semicircular spectrometer of the strong RaC line at 1.02 Mev. The momentum of its extrapolated edge was found from photographic measurements to be 4839.8 ±0.8 gauss-cm. Together with the 1.32-Mev electrons of RaC, these two lines represented well-established momentum points and could be used to study the linearity of the double-focusing spectrometer. The difference between the calibration constants derived from these two lines was 2 parts in 10^4, which is within the combined probable errors of the absolute values. This indicates that the error in the comparison of the two cobalt lines due to uncertainties in the linearity is probably not more than 1 part in 10^4. The value of the lower energy cobalt gamma-ray based on four comparisons between the 1.17- and 1.33-Mev conversion lines is 1.1728±0.0005 Mev. It is seen that although both of the present values of the Co^{60} gamma-rays agree with those of Lind, Brown, and DuMond within the combined probable errors they are, in fact, about 0.1 percent higher.

The authors are indebted to Dr. W. Forsling for chemical preparation of the Co^{60} plating solution.

* National Science Foundation fellow on leave from Brookhaven National Laboratory.

[1] Lind, Brown, and DuMond, Phys. Rev. **76**, 1838 (1949).
[2] Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).
[3] G. Lindström, Phys. Rev. **87**, 678 (1952).
[4] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).

The Mass Relation of Heavy Particles

H. Enatsu*
Columbia University, New York, New York
(Received January 13, 1952)

In a previous note[1,2] on the mass spectrum of heavy particles, our calculation of self-energies was carried out only for the case of nucleons. We have now extended our treatment to the case of heavy nucleons. Before presenting our results, we should like to outline the method used. (A) We assume derivative couplings for interactions between nucleons (and heavy nucleons) and mesons. (B) Self-energies of nucleons and heavy nucleons are calculated to the second order in the coupling constants by using the method described in the preceding paper.[1] (C) Self-energy divergences are canceled out by mixing two kinds of mesons. (D) The mass relations are derived from the conditions of the elimination of logarithmic divergences and are independent of the charge of the mesons.

Let us assume the following interactions:

$$i\frac{g}{\kappa_0}\bar{\psi}_N\gamma_5\gamma_\nu\psi_N\frac{\partial\phi_\pi}{\partial x_\nu}+\text{h.c.}, \tag{1}$$

$$i\frac{G}{\mu_0}\bar{\psi}_V\gamma_\nu\psi_N\frac{\partial\phi_c}{\partial x_\nu}+\text{h.c.}, \tag{2}$$

and

$$i\frac{L}{\kappa_0}\bar{\psi}_V\gamma_5\gamma_\nu\psi_V\frac{\partial\phi_\pi}{\partial x_\nu}+\text{h.c.}, \tag{3}$$

where ψ_N, ψ_V, ϕ_π, and ϕ_c are the wave functions for nucleons ($m=1836\ m_e$), heavy nucleons (m_1), π-mesons ($\kappa=276\ m_e$), and cohesive mesons (μ), respectively. The couplings (1) and (2) have been considered already for the case of nucleons in the previous note.[1] In order to eliminate self-energy divergences of heavy nucleons caused by the interaction (2), we must introduce another new interaction. Generally speaking, we have no restriction on the choice of the new coupling. However, the hypothesis of symmetry between nucleons and heavy nucleons seems most suitable at the present stage. In fact, as will be shown in the following, we can achieve the desired compensation of divergences by assuming the form (3). In connection with these interactions, it is interesting to refer back to the proposal made by Pais[3] on the types of couplings of heavy particles. According to him, the so-called strong couplings can be written in the forms

$$(N_0N_0\pi_0), \tag{4}$$

$$(N_0N_1\pi_1), \tag{5}$$

$$(N_1N_1\pi_0), \tag{6}$$

or

$$(N_iN_j\pi_k);\quad i+j+k=\text{even},$$

which correspond to (1), (2), and (3) above.

Now, the expression for the mass relation can be written as

$$\frac{\mu^2}{x^2}=\frac{1}{120\beta-105}\left\{(2\beta-1)\left(75\frac{\kappa^2}{x^2}+65\right)-(60\beta^3-75\beta^2+66\beta+6)\right\}, \tag{7}$$

where

$$\beta=y/x.$$

In the case of self-energies of nucleons, $x=m$, $y=m_1$, and $\beta=m_1/m$. On the other hand, in the case of heavy nucleons, $x=m_1$, $y=m$, and $\beta=m/m_1$ because of the symmetry between nucleons and heavy nucleons. Using the relation (7), we have computed the mass values of cohesive mesons for the cases of heavy nucleons and the results are given in Table I. It may be worth pointing out that in both cases mass values are of the order

TABLE I. Masses of cohesive mesons for the corresponding masses of heavy nucleons.

Case of the nucleon[a] self-energy		Case of the heavy nucleon self-energy	
m_1	μ	m_1	μ
1836 m_e	1474[b] m_e	1836 m_e	1474 m_e
1900	1378	1900	1645
2000	1263	2000	2107
2100	1152	2098	$+\infty$
2200	1042	2220[c]	···
2220	1019	2222	0
2230	1006	2230	412
2240	995	2240	595
2250	988	2250	715
2260	973	2260	819
2270	963	2270	884
2280	949	2280	970
2290	937	2290	1029
2300	923	2300	1078
2350	857	2350	1269
2400	787	2400	1400

[a] Nucleon =1836 m_e, π-meson =276 m_e.
[b] Professor N. M. Kroll pointed out that the self-energy of the nucleon caused by the interaction ($N_0N_0\pi_1$), which is of the scalar type with vector coupling, should be zero with the computation method suggested by him. However, in the present note we have regarded ($N_0N_0\pi_1$) as a special case of ($N_0N_1\pi_1$) in the limit of $m_1\rightarrow m$, which gives us nonvanishing values. The author is much indebted to Dr. Kroll for discussion on this point.
[c] For this case we have no real mass value.