High Energy Protons Emitted from Carbon at 90° to a 240-Mev Proton Beam*

G. M. Temmer
Department of Physics, University of Rochester, Rochester, New York
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THE differential cross section for the emission of protons at right angles to the 240-Mev circulating proton beam of the Rochester synchrocyclotron has been determined for carbon as a function of the outgoing proton energy. The energy interval from 60 Mev to 190 Mev has been studied thus far.

The energy spectrum was obtained by sampling the population of track endings in 100-micron Kodak NTA nuclear emulsions embedded at different depths of a copper absorber, a method similar to that used in meson production experiments.[1] A knowledge of the track density can then be translated into an energy distribution by use of range-energy curves[2] and from the known geometry. The absorber was inserted into the cyclotron tank at an average distance of 4.5 inches vertically beneath a graphite target and was shielded by four inches of copper from the direct proton beam. The carbon target was about 7 Mev thick to the incident beam and no thicker than 0.6 Mev to the emerging protons of lowest energy. The incident proton current necessary to affix absolute values to the cross sections was determined by the well-known carbon activation method, using a value of 48 millibarns for the $C^{12}(p, pn)C^{11}$ cross section at 240 Mev.[3]

Table I gives the values of the differential cross section per unit energy range per carbon nucleus as a function of the proton energy. A plot of the experimental points[4] is shown in Fig. 1. The rectangles indicate the extent of the probable errors in both the energy and cross-section values. The probable errors given for the latter are purely statistical; no attempt has been made to incorporate possible systematic errors. Furthermore, the entire absolute value scale has been assigned an error of ±50 percent. The principal uncertainty in the energy scale arises from the radial oscillations of the proton beam and multiple traversals of the target, contributing an estimated ±8 Mev. Range straggling in the absorber was calculated using the high energy approximation given by Livingston and Bethe[5] and was found not to exceed ±1.2 Mev.

A correction has been applied for nuclear absorption of the protons in the copper absorber, using the inelastic neutron cross sections for copper determined in "poor geometry" experiments at 95 Mev[6] and 270 Mev,[7] and one-half the total neutron cross section measured at 42 Mev;[8] corrections for intermediate energies were obtained by interpolation. This correction varied from 6 percent to 25 percent between the lowest and highest detected proton energies.

Neutron interactions in the copper absorber give rise to charged particles which contribute undesirable track endings in the emulsions. To estimate the extent of this background effect, two methods of approach were used. First, the number of neutron stars observed in the emulsion yields a value for the effective neutron flux at various depths, assuming that the star production cross section is of the order of the inelastic neutron cross section. One can then estimate the number of spurious track endings which will be produced in an effective layer of absorber adjacent to the photographic plate. Second, a plate was exposed behind four inches of copper (range of 240-Mev protons ~2.5 inches). All tracks which are seen to stop are then attributable to neutron background. Again correcting for nuclear absorption, one arrives at a figure for spurious track endings. Both of these estimates yielded a background approximately equal to one-third of the observed value of the cross section at the highest proton energies investigated. However, because of the inherent uncertainties involved in comparing different exposures in a circulating beam, it is believed that the values above ~150 Mev may be largely due to background. The break in the energy distribution in that vicinity lends support to this view.

TABLE I. Energy distribution of 90° protons from carbon. Cross sections are corrected for nuclear absorption but not for background. Uncertainties are purely statistical.

Proton energy (Mev)	No. of tracks observed	$(d^2\sigma/d\Omega dE)\times10^{29}$ (cm²/Mev-steradian)
61.2	168	4.69±0.36
73.1	195	4.89±0.36
83.6	159	3.17±0.25
93.5	149	2.17±0.16
103.1	114	2.01±0.19
113.8	150	1.45±0.12
132.1	109	0.81±0.10
143.8	70	0.59±0.07
155.7	70	0.52±0.06
167.5	64	0.54±0.07
179.8	52	0.51±0.07
191.8	35	0.50±0.08

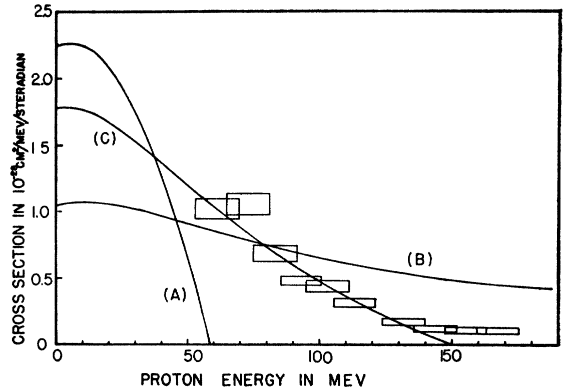

FIG. 1. Comparison of experimental points with theoretical energy distributions for protons emitted at right angles, based on different models for complex nuclei: (A) degenerate Fermi gas, $E_{max}=22$ Mev, $V=30$ Mev; (B) distribution of Chew and Goldberger (see reference 10), characteristic energy $E_p=18$ Mev; (C) same as (B) with the additional assumption of a cut-off at $E_c=72$ Mev. Rectangles denote experimental points multiplied by 2.2.

The particles whose track endings are observed are believed to be mostly protons because (a) particles with higher charge, even with maximum energy compatible with conservation laws, have ranges which are smaller than those observed here, (b) mesons are produced about 100 times less abundantly at our energies,[1,9] (c) high energy deuterons are emitted preferentially forward, but do presumably constitute a small fraction of the particles observed. However, for a given proton energy value the deuteron energy would be about 35 percent higher.

The presence of protons at right angles to the beam with energies up to ~150 Mev and possibly beyond sheds some light on the high momentum nucleons present in the carbon nucleus. The necessity for high momenta was pointed out by Chew and Goldberger[10] when they attempted to interpret the production of high energy deuterons reported by Hadley and York.[11] High energy photoprotons from carbon have also been observed[12] and again seem to require high target nucleon momenta for their interpretation.[13] There is also some evidence along these lines derived from π^+ meson production in carbon.[14]

It should be noted that the upper limit of the secondary proton spectrum predicted by the degenerate Fermi gas model with 22-Mev maximum energy for single nucleon-nucleon encounters is 59 Mev. A target nucleon energy of 72 Mev is required to account for 150-Mev protons at 90° in single collisions. Although favorable secondary collisions within the nucleus make high energy protons energetically possible, they are not believed to be the primary mechanism contributing to the high energy "tail" of the observed distribution, in view of the fact that the nucleon-nucleon collision mean free path is only slightly less than the diameter of the carbon nucleus (6.4×10^{-13} cm). The magnitude of the observed cross section lies close to the values predicted by simple theoretical models based on single encounters only, which necessarily represent upper limits, since the cross section integrated over all angles and energies yields 0.378 barn for carbon, while the observed inelastic cross section for neutrons of 270 Mev is only 0.144 barn.[7] The theoretically expected distribution for single collisions with a degenerate Fermi gas[15] is shown in Fig. 1, curve (A). Curve (B) represents the theoretical distribution expected on the basis of the momentum distribution deduced by Chew and Goldberger[10] from the deuteron pick-up process.[11] Curve (C) was calculated like (B) with the additional empirical assumption of a cut-off in the momentum distribution at 72 Mev. The rectangles indicate the experimental values multiplied by 2.2. Within the accuracy of the experiment some distribution such as that leading to curve (C) adequately represents the data, except for the very high energy points discussed above.

The differential diffraction scattering cross section for carbon at 90° is about 4×10^{-29} cm²/steradian when calculated according to the model of Fernbach *et al.*[16] It is planned to extend measurements into the region of elastically scattered protons in order to look for this contribution.

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Calculations Concerning the Measurement of the Energy of Charged Particles by Small Angle Scattering*

HARTLAND S. SNYDER
Brookhaven National Laboratory, Upton, Long Island, New York
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A COMMON method for determining the energy of particles in photographic emulsions is to measure the mean absolute angle between successive chords on a track. For the papers by Snyder and Scott[1] and by Scott and Snyder[2] various tables of distribution functions were computed and relations determined from which one can find the relationships among the mean absolute angle $\bar{\alpha}$ between successive chords on a track, the momentum p of the particle, the velocity v of the particle, the chord length s, and the composition of the matter through which the particle is passing. Defining the scattering constant K, which is a function of $s_0=s/\beta^2(\beta=v/c)$, by

$$K(s_0)=\bar{\alpha}pv/s^{1/2},\tag{1}$$

one obtains

$$K(s_0)=\sqrt{2}(\bar{\alpha}'/z^{1/2})(\eta_0 pv/\lambda^{1/2}),\tag{2}$$

in which $\bar{\alpha}'=\alpha/\eta_0$ is a function of z. The quantities z, λ, and η_0 are

TABLE I. Calculated values of the scattering constant $K(s_0)$.

z	s_0	$\bar{\alpha}'/z^{1/2}$	$K(s_0)$
100	0.0801	0.912	22.96
400	0.3205	1.001	25.20
1600	1.282	1.085	27.32
6400	5.128	1.153	29.02
25600	20.51	1.219	30.69

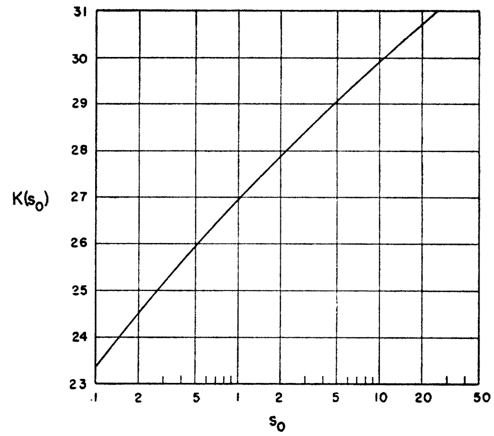

FIG. 1. Graph of $K(s_0)$ against s_0 on a semilogarithmic scale. The scattering constant K is given in units of Mev-deg/$(100\mu)^{1/2}$. The quantity $s_0=s/\beta^2$ is given in units of 100μ.

defined by

$$z=2s/\lambda,\tag{3}$$

$$1/\lambda=(4\pi/\beta^2)(\hbar/mc)^2\sum N_iZ_i^{4/3},\tag{4}$$

and

$$\eta_0^2p^2v^2/\lambda=4\pi e^4\sum N_iZ_i^2.\tag{5}$$

The meanings of the symbols in these equations are given in the above-mentioned papers. For the values of $\sum N_iZ_i^2$ and $\sum N_iZ_i^{4/3}$ the composition of a standard Ilford emulsion was used, and the corresponding values were found to be 3.704×10^{25}/cm³ and 3.33×10^{24}/cm³. Substituting numerical values in Eqs. (2) and (3), one obtains[3]

$$z=1248s_0\tag{6}$$

if s_0 is measured in units of 100μ, and

$$K(s_0)=25.18\bar{\alpha}'/z^{1/2}\tag{7}$$

if K is measured in units of Mev-deg/$(100\mu)^{1/2}$. The values of $\bar{\alpha}'$ were computed for various values of z from tables available at Brookhaven National Laboratory. The results of this calculation are given in Table I. These values of $K(s_0)$ are also plotted against s_0 on a semilogarithmic scale in Fig. 1.

From these values of K and measured values of $\bar{\alpha}$, one can obtain by use of Eq. (1) the value of pv (in Mev) for the particle.

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[3] The relation (6) among z, s, and β is valid only for large β, approximately for $\beta>\frac{1}{3}$, because the Born approximation was used in determining the effect of screening on the mean free path, λ. If a better value of λ is used, then Eq. (3) should be used to determine z. Since K is a function of z only, a graph of K as a function of z enables one to determine the appropriate value of the scattering constant for any given case. Actually, a precise value of λ is not very important, since a change in λ by a factor of four changes the scattering constant by about five percent.

Neutron Deficient Europium and Gadolinium Isotopes*

R. W. HOFF, J. O. RASMUSSEN, AND S. G. THOMPSON
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California
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A STUDY has been made of the light europium and gadolinium isotopes produced by bombardment of samarium and europium oxides with energetic protons, deuterons, and helium ions. In addition to the natural oxides, electromagnetically concentrated isotopes of samarium were used as target materials.[1] In some of the bombardments chemical separations of the target