π-mesons is comparable to that for protons. Secondary nuclear events occurring in the chamber are now being analyzed to provide more direct information in this matter.

* Assisted by the joint program of the ONR and AEC.
** AEC Predoctoral fellow.
[1] A complete description of the apparatus will be published.
[2] We are very grateful to the ONR for securing so promptly these machined gold plates.
[3] Brown, Camerini, Fowler, Heiller, King, and Powell, Phil. Mag. **VXL**, 862 (1949).
[4] W. B. Fretter, Phys. Rev. **73**, 41 (1948); **76**, 511 (1949).
[5] J. R. Winckler, private communication to Marcel Schein.
[6] J. Tinlot, Phys. Rev. **73**, 1476 (1948); **74**, 1197 (1948).
[7] T. G. Walsh and O. Piccioni, Echo Lake Conference, (June, 1949).

The Measurement of Proton Energies with Scintillation Counters*

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EXPERIMENTS with energetic heavy particles frequently require the use of energy indicating detectors of large stopping power. Scintillating crystals, due to their high speed of response, are promising materials for this purpose. The size of the light flash produced can usually be interpreted in terms of the energy of the bombarding particle. However, existing information on this question is not very complete.[1-6] For this reason, the response to protons from the Princeton cyclotron as a function of proton energy for sodium iodide, potassium iodide, and anthracene has been investigated, and the widths of the resulting pulse height distributions have been studied.

The apparatus used in this investigation consisted of a scattering tube holding a 0.1-mil platinum foil which caused protons from the external collimated cyclotron beam to be scattered through 30° into the scintillating crystal which was mounted in optical contact with a RCA 5819 photo-multiplier tube. Pulses from the photo-multiplier were amplified by a cathode follower and a Model 501 amplifier (having a "rise time" of 0.15 μsec. and a "decay time" of 5 μsec.) and analyzed by a single-channel differential discriminator. Energy calibration of the beam was accomplished by an air range measurement which yielded a value of 16.9 Mev, estimated to be accurate to ± 0.2 Mev.

The types of pulse height distributions obtained for the three types of crystals are illustrated by Fig. 1. With sodium iodide and anthracene, nearly Gaussian distributions are observed having a width at half-maximum of three percent of the peak pulse height (bombarding energy 16.4 Mev). The energy spread in the beam does not contribute significantly to this width.

The relationship between the peak pulse height and the energy of the incident protons for the three materials is illustrated by Fig. 2. The energy of the incident protons was varied by interposing aluminum foils. At low energies, the experimental points are less precisely located by this procedure than at high energies. For this reason the intercepts of the straight lines drawn through the experimental points in the cases of sodium iodide and potassium iodide are somewhat indefinite; a shift of $+0.2$ Mev in the energy assumed for the primary proton beam would cause both straight lines to pass through the origin. In anthracene the deviation from proportionality is more marked and cannot be accounted for by the uncertainty of this order in the beam energy.

The noticeable qualitative difference in the behaviors of the ionic crystals and of anthracene indicated by this study is further

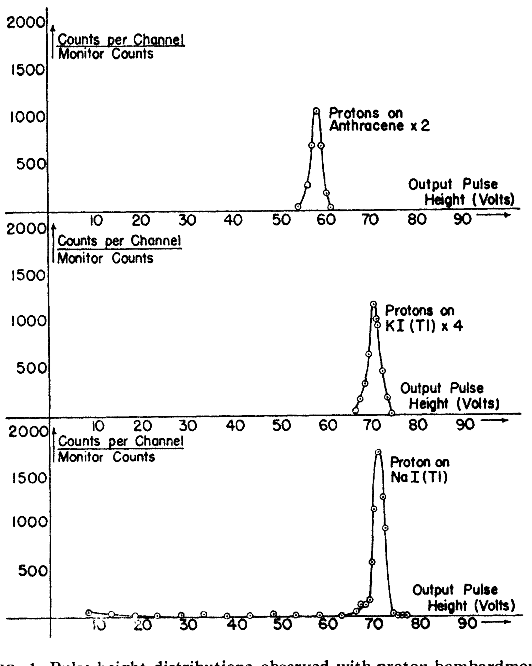

Fig. 1. Pulse height distributions observed with proton bombardment of sodium iodide, potassium iodide and anthracene crystals. The bombarding energy was 16.4 Mev. In the case of sodium iodide, the observed background of small pulses (below the main peak) is shown.

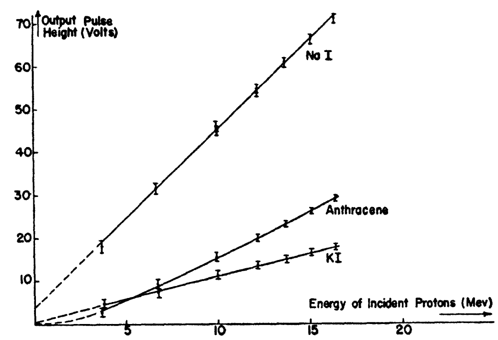

Fig. 2. Relationship between the pulse height deduced from the peak of the pulse height distribution curve and the energy of bombarding protons for the three types of crystals.

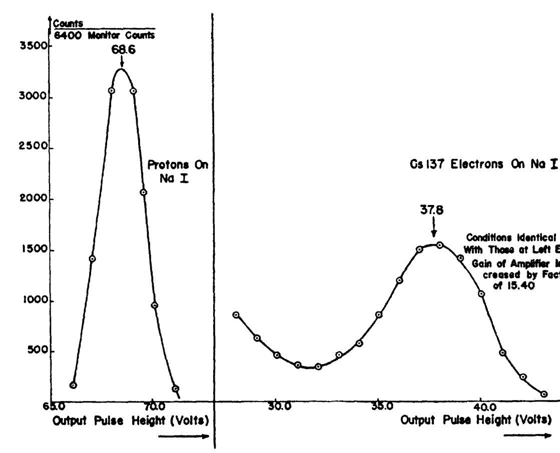

Fig. 3. Comparison between the pulse height distribution observed with 16.4-Mev protons and 0.624-Mev Cs^{137} conversion electrons bombarding sodium iodide. To obtain these curves, a thin Cs^{137} source on a 1.7-mg/c^2 aluminum foil was mounted in the path of the proton beam at a distance of 4 cm from the surface of the crystal.

borne out by a comparison between the response of these materials to protons, electrons, and alpha-particles. For sodium iodide, a ratio of 26.8 between the proton beam energy and the energy of Cs^{137} conversion electrons corresponded to a pulse height ratio of 28.0. (The manner in which this comparison was carried out is illustrated by Fig. 3.) The corresponding pulse height ratios for potassium iodide and anthracene were 30.1 and 16.4 respectively. Similarly, a ratio of 8.70 between the energy of polonium alpha-particles bombarding the crystal surface and the energy of Cs^{137} conversion electrons corresponded to a pulse height ratio of 6.46 in the case of sodium iodide, 8.18 in the case of potassium iodide, and 0.82 for anthracene. It is believed that these pulse height ratios are affected somewhat by the surface structure of the crystal in the case of alpha-particle bombardment and by backscattering out of the crystal for electron bombardment. Nevertheless, the measurements show that the ionic crystals exhibit a response which is much closer to proportionality with energy (independent of particle type) than is the case for anthracene. Sodium iodide particularly, with suitable calibration, seems to be a very promising material for the observation of monoenergetic groups of high energy heavy particles.

* Supported by the joint program of the ONR and AEC.

[1] T. Broser and H. Kallmann, Nature **163**, 20 (1949).
[2] W. H. Jordan and P. R. Bell, Nucleonics **5**, No. 4, 30 (1949).
[3] Harding, Flowers, and Epstein, Nature **163**, 990 (1949).
[4] G. F. J. Garlick and R. A. Fatehally, Phys. Rev. **75**, 1446 (1949).
[5] J. I. Hopkins, Phys. Rev. **77**, 406 (1950).
[6] S. A. E. Johannson, Nature **165**, 396 (1950).

The Problem of Red Giants and Cepheid Variables

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According to the accepted model of the main sequence stars, these consist of a central convective zone (Cowling's zone) surrounded by an envelope in a state of radiative equilibrium. The energy producing thermonuclear reaction (carbon cycle) takes place near the center of the star, and the convective currents account for the uniform depletion of hydrogen through the entire convection region. The detailed calculations of this model[1] indicate that as the hydrogen in the convective zone gradually changes into helium (assumed change of molecular weight from $\mu=1$, corresponding to original hydrogen content, to $\mu=2$, corresponding to completely dehydrogenized material), the fraction of the stellar mass contained in the convective zone decreases from 15.0 to 8.1 percent. Thus, toward the end of this process, the star will consist of a central core (8 percent) of completely dehydrogenized material, a transitional layer (7 percent) with varying hydrogen content, and the outer envelope (85 percent) of virgin stellar material. Approaching this state of evolution, the star may be expected to pass into the so-called shell source model[2] consisting of an isothermal de-hydrogenized core with the carbon cycle taking place at the boundary between this isothermal region and the hydrogen-rich layers, so that further evolution will consist in a gradual advance of the shell source into the virgin material and the corresponding growth of the central isothermal core. However, more detailed calculation on this model[3] leads to a peculiar difficulty; namely, that no solutions exist which correspond to an equilibrium condition of the star when the amount of material in the isothermal core exceeds 10 percent of the total mass.

Some attempts have been made to remove this difficulty by taking into account the electron degeneracy at the center of the isothermal core. These calculations lead to the interesting result that there exist solutions which make the outer radius of the star increase by a large factor thus bringing it into the region of red giants.[4] Unfortunately, however, all these solutions correspond again to small isothermal cores (less than 10 percent) and can hardly be considered as possible transient stages of normal stellar evolution. In fact, since the shell source cannot be formed within the convective zone, we need such solutions only after the hydrogen in the original Cowling zone is used up and, since that zone contains about 10 percent of the total mass, we find that the solutions disappear just when we can use them!

We want to point out here that although the models with larger cores allow no static solutions, they permit some oscillatory solutions with finite amplitude (as, for example, in the case of an ordinary electric bell). Briefly, the argument in favor of the oscillatory solutions is as follows. Suppose a shell-source star undergoes radial oscillations,

$$r=x[1-\eta(x)f(t)], \tag{1}$$

where x is the average position of an element of mass, $f(t)$ averages to zero over a cycle, and $\eta(x)$ is the relative amplitude of oscillation. P_0, ρ_0 and T_0 are defined to be the pressure, density and temperature at the instants when $r=x$. One now writes down the time-dependent equations for the star; namely, the equation of motion, the equation of state, and the radiation transfer equation. Assuming adiabaticity over a cycle, one averages the time-dependent equations over a cycle, keeping only the zero- and second-order terms in $\eta(x)$. The equation of motion, for example, then has the form

$$A(x)\partial P_0/\partial x=-(GM_x\rho_0/x^2)B(x). \tag{2}$$

Here G is the gravitational constant and M_x is the mass contained within a sphere of radius x. $A(x)$ and $B(x)$ are functions which differ from unity only by terms of the second order in $\eta(x)$. Equation (2) reduces to the static equation when the amplitude of oscillation goes to zero. The equation of state between P_0, ρ_0 and T_0 is of course unchanged by the oscillation, but the radiation flux term also acquires a factor $C(x)$.

One now tries to define new quantities

$$P_1=f(x)P_0,\quad \rho_1=g(x)\rho_0,\quad T_1=h(x)T_0 \tag{3}$$

in such a way that P_1, ρ_1 and T_1 satisfy the ordinary static equations for the shell source model. It has been found possible to do so. It has been found that when P_1, ρ_1, T_1 correspond to a star with, say, 10 percent of the mass in the core, the actual quantities P_0, ρ_0, T_0 correspond to a star with more than 10 percent of the mass in the core, depending on the square of the amplitude of oscillation. The main effect of the oscillation seems to be to let radiation flow more easily into the envelope, raising the temperature and pressure, and consequently pushing some of the mass into a region of weaker gravitational attraction.

Although in calculating the functions A, B and C, we took the pressures, densities, temperatures and relative amplitudes $\eta(x)$ for the normal Cowling star,[5] the result does not seem to depend critically on this fact. We therefore conclude that an oscillating shell-source star can be stable on the average when its depletion of hydrogen exceeds the maximum amount for a static star, although our perturbation method does not allow us to say how far the depletion can be raised over the maximum for the static case.

The above picture may present a possibility for understanding the pulsating properties of cepheid variables. There is also a chance that the above-described oscillations may ultimately become unstable and develop into periodic explosions in which large amounts of nuclear energy are liberated in every cycle. (U-Geminorum stars?)

We hope in the future to carry out some calculations concerning the stability of these oscillations for continuously growing dimensions of the energy producing shell.