Relative Pulse Height of Protons and Electrons in KI(Tl)†

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The relative scintillation efficiency for protons and electrons in KI(Tl) has been measured in the energy range of a few Mev. Protons were found to give a greater light output than electrons, and a pulse-height ratio $p:e=1.42:1$ was determined.

THE relative scintillation efficiency of the various thallium-activated alkali-iodide crystals, NaI(Tl), KI(Tl), and CsI(Tl) for different mass particles has been the subject of several investigations.[1–6] Most of this work has been with particles having energies up to several Mev and particles of mass ranging from that of the proton up through some of the lighter nuclei. This work can perhaps be best summarized as follows:

1. The light output per unit energy loss decreases with increasing particle mass (and/or charge), i.e., with increasing specific ionization.

2. The light output is a nearly linear function of energy. However, significant nonlinearities are present for particles heavier than deuterons. The nonlinearities appear to be more pronounced at lower energies, and again seem to indicate a lower light output per unit energy loss when the specific ionization is higher.

The relative response for electrons and protons has been thoroughly studied only for NaI(Tl).[4] In this case, the pulse heights were found to be equal and both particles gave a linear pulse height *vs* energy curve.

The present authors have been studying the properties of KI(Tl) for possible use in fast-neutron spectroscopy.[7] In the course of this investigation the relative light output per unit energy loss was measured for protons and electrons. The result was obtained that KI(Tl) gives a greater pulse height for protons than for electrons of the same energy.

A $\frac{1}{2}$-in. thick $1\frac{1}{2}$-in. diameter KI(Tl) crystal was irradiated with monoenergetic fast neutrons produced by bombarding a thin (100-kev) deuterium gas target with deutrons accelerated by the BNL Van de Graaff generator. Monoenergetic charged particle groups were, therefore, produced within the crystal from the $K^{39}(n,p)A^{39}$ and the $K^{39}(n,\alpha)Cl^{36}$ reactions.[8] The pulse-height spectrum from the KI(Tl) crystal when irradiated with 5.07-Mev neutrons is shown in Fig. 1. The proton group from the $K^{39}(n,p)A^{39}$ reaction leading to the ground state of A^{39} is clearly resolved, while the groups leading to excited states are merged with the groups from the (n,α) reactions. However, it was possible to isolate the proton groups leading to the states in A^{39} at 1.27 and 2.42 Mev[8,9] by placing a NaI(Tl) crystal adjacent to the KI(Tl) crystal, and observing coincidences with the de-excitation gamma ray in A^{39}. The energies of the de-excitation gamma rays agreed with the energies of the proton groups as measured by Scott and Segel.[8]

The pulse height (in arbitrary units) for the protons is shown in Fig. 2. The proton energy is a bit uncertain as a small fraction of the energy is taken up by the A^{39} recoil. This recoil can be assumed to contribute a negligible amount to the total light output. The average

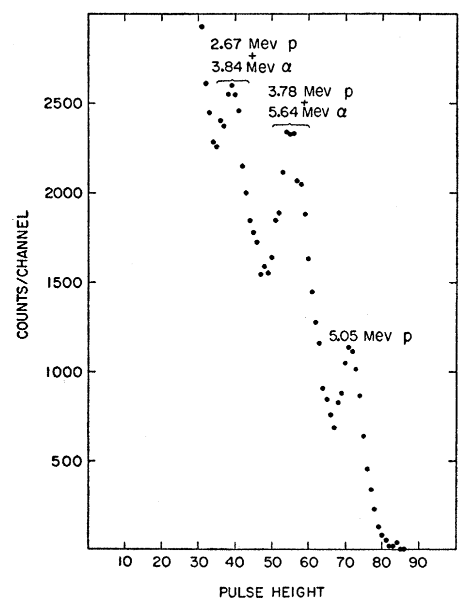

FIG. 1. Pulse-height spectrum observed in KI(Tl) crystal bombarded with monoenergetic 5.07-Mev neutrons.

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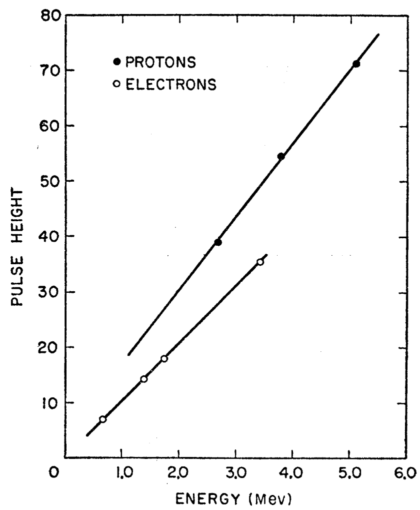

FIG. 2. Relative light output for protons and electrons in KI(Tl). The pulse-height scale is in arbitrary units though, of course, it is the same for both particles.

proton energies depend on the angular distributions of the various $K^{39}(n,p)A^{39}$ reactions, and these angular distributions are not known. The energies in Fig. 2 are given assuming that the protons are emitted isotropically. If the protons are emitted primarily in the forward direction, these energies should be raised by $\sim 3\%$. This uncertainty does not affect the basic conclusion of this paper.

The ratio of the slope of the straight line drawn in Fig. 2 for protons to that drawn for electrons is equal to 1.28, which differs somewhat from the measured pulse-height ratio of 1.42. The pulse heights could be determined to about 1% and the electron energies were known to a considerably higher accuracy. However, as explained above, the proton energies were uncertain to $\sim 3\%$ and, as only about a 2:1 range of proton energy was covered, the slope of the proton line could be in error by as much as several percent. An error in slope could explain why the proton line in Fig. 2 fails to extrapolate through the origin. Of course, a real nonlinearity in the light output *vs* proton energy cannot be precluded.

The relative electron pulse height was measured by irradiating the same crystal phototube combination with gamma rays from Cs^{137} (0.661 Mev), Na^{24} (1.38 and 2.76 Mev) and PoBe (4.43 Mev). For the higher energy gamma rays, only the second escape peak[10] was clearly resolved. Finally, a spectrum was taken with the crystal being irradiated simultaneously with both neutrons and gamma rays, in order to normalize the proton and electron measurements to the same energy scale.

The results of the electron pulse-height measurements are shown in Fig. 2 which also contains the proton data. The straight lines drawn through both sets of data indicate that KI(Tl) is roughly linear, though the measurements are not sufficiently assurate to detect nonlinearities of less than a few percent. From Fig. 2 it can be seen that the pulse height per unit energy loss from the protons is greater than that from the electrons, the pulse-height ratio being $p:e=1.42:1$ (accurate to $\sim 5\%$).

A rough determination was made of the relative alpha-particle pulse height by channeling the NaI(Tl) counter at 1.95 Mev and, therefore, isolating the (n,α) group leading to the 1.95 state in Cl^{36}.[11] A proton to alpha pulse-height ratio of $p:\alpha=1.38:1$ was thus found, in agreement with the value of 1.51 ± 0.15 found by Scott and Segel.[8] Combining the $p:e$ and the $p:\alpha$ data, one would expect electrons and alpha particles to have approximately equal pulse heights. Indeed, a direct comparison of the pulse height produced by U^{235} alpha particles and those of electrons yielded $e:\alpha=1.09$.[12]

Finally, we note that in the present work both the protons and the electrons were created internally in the crystal and, therefore, surface effects could not have played a major role.

In the only previously published work on relative pulse heights in KI(Tl), Franzen, Peele, and Sherr[6] found $p:e=1.12$ for 16.4-Mev protons, and $e:\alpha=1.08$ for 5.30-Mev alpha particles. The $p:e$ of these workers differs from that found in the present work, even if we take the $p:e=1.28$ from the ratio of the slopes of the lines in Fig. 2, though Franzen *et al.* also found a greater pulse height for protons. It is not possible to determine from the data presently available whether the difference is due to an experimental discrepancy or to a nonlinearity in the pulse height *vs* proton energy response.

No direct measurement has been published for the relative pulse height of protons and electrons in CsI(Tl). Bashkin *et al.*[1] found $p:\alpha=1.70:1$. Reading the data from the graph published by Halbert[2] (a dangerous practice), one obtains $e:\alpha=1.35:1$ for 4-Mev alpha particles. Combining these two results, one obtains for CsI(Tl) $p:e=1.26:1$. Therefore, CsI(Tl) appears to be similar to KI(Tl) in that protons give larger pulses than electrons.

In NaI(Tl), as previously noted, protons and electrons are equally efficient light producers.[4] NaI(Tl) therefore differs from KI(Tl) [and apparently also from CsI(Tl)] in this respect.

From the results reported herein, it can be concluded that the scintillation efficiency in KI(Tl) is not merely

[10] For a complete discussion of pulse-height spectra resulting from gamma-ray irradiation of a scintillating crystal, see P. R. Bell, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. V. The "second escape peak" corresponds to the following event: 1. The incoming gamma ray creates a positron-electron pair in the field of a nucleus. The total kinetic energy of the pair is $E_\gamma - 1.02$ Mev. 2. Both members of the pair dissipate their kinetic energy in the crystal. 3. The positron annihilates with an electron, yielding two 0.511-Mev gamma rays. 4. Both gamma rays escape the crystal. The pulse height in the second escape peak, therefore, corresponds to $E_\gamma - 1.02$ Mev.

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a decreasing function of specific ionization. Though saturation effects appear to play a predominant role in reducing the light output for particles heavier than a proton, other effects must inhibit the scintillation when electrons are the ionizing particles.

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Optical Model Evidence for Surface Absorption of Neutrons

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Data-matching with the complex square well model for neutron scattering suggests that the imaginary part of the potential should be largest at the nuclear surface; such an effect is also in accord with present physical pictures of the interaction. However, when a diffuse edge is attached to the model and the other parameters are changed to provide experimental agreement, the need for surface absorption appears diminished. To investigate further, cross sections resulting from a surface-absorbing and a uniformly absorbing potential, both with a diffuse edge, are calculated and compared. The results differ considerably less from each other than from the data, but the strength of absorption is more nearly independent of mass number when it is concentrated near the surface.

I. INTRODUCTION

EARLY in the development of the optical model[1] for neutron scattering, it was noticed that the calculated compound-nucleus-formation cross section was too small and that the imaginary part of the complex square well should decrease with mass number. It was then suggested that if most of the absorption were made to occur near the surface instead of uniformly throughout the nucleus, so that the absorbing volume would increase only as the square of the radius rather than the cube, the absorption strength might depend less on mass number. It was also hoped that a new location for the absorption might increase the probability of compound-formation.

Both of these conjectures were verified quantitatively at zero energy in an early investigation,[2] which retained a square well for the real part of the potential but concentrated the absorption to a narrow shell just *beneath* the surface of the real part. Sinking the absorbing shell beneficially increased the compound-formation cross section, and locating it near the edge allowed its strength to be the same for all nuclei. However, although the potential continued to yield these same improvements at nonzero energies,[3] the calculated angular distributions of elastic scattering were no better than those of the complex square well.

Meanwhile, it was found that attaching a diffuse edge onto the complex square well improved *both* the compound-formation and the differential cross sections.[4] Since such a potential was also more physically appealing, there was no longer any reason to sink the imaginary part of the potential beneath the surface. Nevertheless, there still persisted the separate question whether the absorption should be concentrated toward the edge in order for a single value of the absorption parameter at each energy to give the correct-size giant resonances over the complete range of nuclear radii.

Diffusing the edge of the complex square well has made the answer to this problem more difficult to determine. For, if a square and diffuse edged potential both have the same constant ratio of imaginary part to real part, the diffuse-edged form, by allowing more of the wave to penetrate its surface, will produce the larger fluctuations in the cross sections. In order to damp down these fluctuations to experimental values, one must increase the absorption, which in turn reduces the chance that neutrons having penetrated the surface will reach the interior of the core.[5] Thus, even when the imaginary part of the potential is proportional to the real part, more neutrons are absorbed at the surface for a diffuse-edged potential than for a square well when an attempt is made to match the same data.

Recently, diffuse-edged surface-absorbing potentials have been shown to yield excellent fits with experimental data,[6] and it has been mentioned that the comparisons with nonelastic cross sections were better than when uniform absorption was used. (This conclusion is apparently independent of the spin-orbit coupling.) Although the present calculations partially

* Operated for the U. S. Atomic Energy Commission by the Westinghouse Electric Corporation.
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