THE RICE INSTITUTE

A TEST OF A MAGNETIC LENS PAIR SPECTROMETER EQUIPPED WITH
SCINTILLATION COUNTERS USING THE NUCLEAR PAIRS FROM THE
REACTION $^19\text{F}(p, \alpha)^{16}\text{O}$

by

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INTRODUCTION

Bame and Baggett\(^1\) found in their work with the spectrometer, to be described here, that geiger counters were a limiting factor when one was trying for good resolution because of the high single counting rates involved (\(~ 1000\) counts per second). They used the spectrometer to measure gamma ray energies by counting coincidences between the positron and electron pairs formed by both the off-axis and on-axis methods. In the off-axis method the source of the gamma rays, and subsequent pairs, is displaced from the axis of symmetry of the spectrometer, in which case the positrons and electrons come to focus at two distinct spots at the other end of the spectrometer. Separate counters are then placed at the two distinct focal points and coincidences between them recorded as a function of the current in the coils of the spectrometer. In the on-axis method the source is placed on the axis of the spectrometer, and one relies on a statistical separation at the other end. In both of these methods the single counting rates are much higher than the coincidence counting rate for a number of reasons:

1. It is unlikely that both the positron and the electron will come off in the solid angle of acceptance of the spectrometer.

2. It is unlikely that both the positron and the electron will have the same energy, or very nearly so, as they must in
order to both get through the spectrometer baffle system at one setting of the current in the coils.

3. Photoelectric and Compton electrons from the source, induced radioactivities, x-rays from the Van de Graaff accelerator, scattered neutrons, etc., all add to the singles counting rates.

Because of the inherently large delay times of geiger counters, good resolving times cannot be obtained for coincidences, and hence one is hampered by a large accidental coincidence rate. Geiger counters possess several other disadvantages in that they wear out quickly at these high counting rates and have to be replaced frequently, and they are generally of such a shape that it is difficult to place the sensitive areas of two different counters close together.

It was thought that scintillation counters would solve many of these difficulties because of their ability to count at high rates and to be used with fast coincidence circuits. The adoption of the spectrometer for the use with scintillation counters, the associated apparatus and a test of the equipment with the nuclear pairs from the reaction $^{19}_{8}$F$(p, \alpha)^{16}_{8}$O is described in what follows. For a more detailed description of all aspects of the experimental apparatus see Robert F. Sippel, *Thesis* (1952).
EXPERIMENTAL APPARATUS

The end plate of the spectrometer consisted of a \( \frac{1}{2} \)" aluminum plate with an exit window approximately two inches in diameter (elliptical in shape for the off-axis method and circular for the on-axis method) covered with a 10 mil aluminum sheet. Any additional apertures were then placed outside of the aluminum exit window. The anthracene crystals, light pipes, R.C.A. 5819 Photomultiplier tubes and pre-amps were all one unit separate from the spectrometer (see figures 12 and 13). The pulses from the pre-amps went to Atomic Instrument Company linear amplifiers which in turn triggered blocking oscillators. The pulses from the blocking oscillators then were fed into an IN34 diode type coincidence circuit.

Anthracene crystals were used because they are reasonably fast (decay time = \( 3.4 \times 10^{-8} \) sec) and they give larger pulses from electrons than some of the faster crystals such as stilbene. They are also easily cut and polished into the desired shapes. The thickness of the crystal to be used is determined by the energy of the electrons to be observed. The crystals should be at least thick enough to completely stop the electrons which are focused by the spectrometer in order to facilitate the biasing out of pulses from scattered electrons and annihilation radiation. There would seem to be no advantage in making the crystals any thicker than this since it would only increase the scattering problem. The nuclear pairs from
The o^-16 have an energy of about 2.5 mev, and we see from figure 1 that electrons of this energy have a range of 1.23 gm/cm² in Al. When the amount of an absorber is expressed in gm/cm², however, the range of an electron is very nearly independent of the nature of the absorber. The density of anthracene is 1.25 gm/cm³, so one concludes that the thickness of anthracene necessary to completely stop a 2.5 mev electron is approximately 1.23/1.25 = .965 cm ≈ 3/8 inch. Both 1/8" and 1/2" crystals were used, the latter proving superior as will be shown.

It was found necessary to use light pipes because 5819 photomultiplier tubes will not operate satisfactorily in a varying magnetic field. If the phototubes are placed too near the end of the spectrometer the amount of iron necessary to produce adequate shielding spoils the focus and hence the resolution of the spectrometer. With lucite rods 8" long, it was possible to adequately shield the photomultipliers without disturbing the resolution of the spectrometer. The lucite rods were 1 1/8" in diameter. One end was machined to fit the surface of the photomultiplier tubes, and the other was cut so that the crystals on the two different rods could be placed close together. All surfaces were polished, the rods were wrapped in aluminum foil, and canada balsam was used to make good optical connections.

The photomultiplier tubes were shielded on the outside by a ¼" soft iron pipe which extended several inches over
Figure 1

RANGE OF ELECTRONS IN ALUMINUM

RANGE IN AL (GM/CM²)

ENERGY (MEV)
both ends of the phototube. Inside of this there were 5 concentric galvanized iron tubes, separated by air gaps, and innermost there was a commercial mu-metal shield.

The triggering arrangement on the blocking oscillators was such that by varying the negative biases on the input grids to the blocking oscillators they could be made to trigger only on pulses larger than any desired size. Due to the pulse height distribution of the nearly monoenergetic electrons focused by the spectrometer, it was possible to bias out most of the coincidences due to scattered electrons and annihilation radiation, as will be shown.

The coincidence circuit had a resolving time adjustable from .05 microsecond to .3 microsecond by means of the discriminator on the scalar to which the pulses from the coincidence circuit were fed. It was found necessary, however, to operate at a resolving time of about .1 microsecond in order not to miss too many true coincidences.
When $^{19}\text{F}$ is bombarded with protons, the following reaction occurs.

$$^{19}\text{F} + ^{1}\text{H} \rightarrow ^{20}\text{Ne} \rightarrow ^{16}\text{O} + ^{4}\text{He} + 8.113\text{ mev}$$

The $^{16}\text{O}$ may be left in the ground state, or in one of a number of different excited states, which excited state depending on the proton bombarding energy. The excited states then go to the ground state with the emission of a gamma ray or, in one case, a nuclear pair. The resonances for the different possibilities and the nature of the emitted radiations have been studied by several groups\textsuperscript{3,4}. The nuclear pairs come from the lowest excited state of $^{16}\text{O}$, for which the gamma radiation is forbidden by a selection rule excluding a gamma transition from a state with $J = 0$ to another state with $J = 0$.

In this experiment a 9 mg/cm$^2$ calcium fluoride target was bombarded with 1.5 to 2.0 mev protons. Since this target thickness is sufficient to completely stop the protons, we were getting gamma rays and nuclear pairs from a large number of different resonances. A geiger counter placed outside of the spectrometer and 8" from the target served as a gamma ray monitor. If the proton energy is fairly constant, the ratio of the number of gamma rays to the number of nuclear pairs should be a constant. The standard way of taking data, then, was to record the number of coincidences per gamma ray monitor as a function of the current in the spectrometer coils. Both
the off-axis and on-axis methods were tried.

Off-Axis Method

A diagram of the adjustment of the spectrometer when used with this method is shown in figure 2. The beam from the Van de Graaff enters at (A), strikes the target, (B), and the positrons and electrons are focused at (E). (D) is an adjustable lucite baffle which slides on (C) and which can be moved from the outside. With this set-up the positron and electron focal points are separated by a distance of 5/8", center to center. The separation and size of the foci is shown in figure 3 which was obtained by exploring the exit window with a lead plate with a small hole in it and a geiger counter. This shows that the centers of the two spots (points of highest particle flux) are separated by .6 inch and that there is some overlap of the foci. A 1/8" thick lead plate was then placed over the aluminum exit window of the spectrometer with two 5/8" holes cut in it corresponding to the two focal points. The anthracene crystals (1/8" thick in this case) which were mounted on the ends of lucite rods, were then placed against these exit apertures, separated by 1/32" of lead. With the current in the spectrometer coils set to focus 2.5 mev electrons, the pulse height distribution of the electrons from the $^{19}F^1 + H^1$ reaction was analyzed and is shown in figure 4.
SPECTROMETER ADJUSTMENT FOR OFF-AXIS METHOD

(A) 

(B) 

(C) 

(D) 

(E) 

0 1 2 3 4 5 INCHES
by the two curves at the right. The ordinate gives the num-
ber of pulses per gamma ray monitor which fall within a 3
volt interval at the corresponding value of the absissa.
The spread in the distribution for counter no. 2 probably was
due to a poor optical connection between the lucite rod and
the photomultiplier tube. The third curve was obtained by
placing a Cs\textsuperscript{137} source near the crystals with the electrons
from the fluorine bombardment cut off. The ordinate for this
curve should actually be counts per second, but it appears
in figure 4 merely to show the cutoff point. Since the energy
of the Cs interval conversion electron is .625 mev, by set-
ting the biases on the blocking oscillators so that they will
trigger only on pulses larger than 30 volts the possibility
of obtaining coincidences due to annihilation radiation is
eliminated. The possibility of coincidences due to scattered
electrons is also largely eliminated since an electron must
now lose at least .625 mev in each crystal in order to regis-
ter a coincidence. By putting 1/32" of lead between the
crystals it is made energetically impossible for an electron
to lose .625 mev in one crystal and then to transverse the
lead and lose that much energy in the second, and the only
scattering problem which remains is that caused by multiply
scattered electrons from external objects such as the end
plate of the spectrometer. Actually, for this run, the block-
ing oscillator biases were set to trigger only on pulses lar-
ger than about 50 volts. The curve for the nuclear pairs
from \textsuperscript{16}O is shown in figure 5. This curve has been corrected
Figure 5

NUCLEAR PAIRS FROM $F^{19}_7(p, \alpha)_0^{16}$

OFF-AXIS METHOD

1.5 MEV PROTONS

POTENTIOMETER IN MILLIVOLTS

COINC PER MONITOR

4.0%
for chance coincidences which were about 7% of the peak counting rate.

On-Axis Method

A diagram of the spectrometer as set up for this method is shown in figure 6. The ring focus at (B) was located by exposing x-ray film at several different positions along the chamber of the spectrometer. After locating the narrowest part of the ring focus the ring baffle was made from 1/4" aluminum with a ring 1/2" wide, which was approximately the size of the ring at the narrowest place, although the most dense part of the ring focus was about .3 inch wide. The circle of confusion was about one inch in diameter at the exit window, and the highest coincidence counting rate was obtained by placing the crystals at (C), about 1 cm from the end of the spectrometer. No exit apertures were used. The crystals were 1/2" thick and separated by 1/32" of lead. Although a careful study of the pulse height distributions was not made in this case, the conditions were considerably more favorable than with the 1/8" crystals. The distribution of pulses from the 2.5 mev electrons was narrower than in figure 4 and they were about 2\(\frac{1}{2}\) times as large as the cutoff point for the Cs electrons. The pair curve for this method is shown in figure 7. Although this curve was actually taken at a higher bombarding energy than figure 5, the ordinate has been changed so that it appears in figure 7 as though it had been
SPECTROMETER ADJUSTMENT FOR ON-AXIS METHOD

(A)

(B)

(G)

0 1 2 3 4

INCHES
Figure 7

NUCLEAR PAIRS FROM $^0_{16}$ ON-AXIS

15 MEV PROTONS

COINC PER MON

POTENTIOMETER

1.4
1.2
1.0
0.8
0.6
0.4
0.2

3.5%
taken under the same conditions as the curve in figure 5.

Comparison of the Off-Axis and On-Axis Methods

From a comparison of figures 5 and 7 it appears that the transmission of the on-axis method, for a given resolution, is considerably better than that for the off-axis method. The transmission by the on-axis method can probably be increased more by separating the coils of the spectrometer until the average angle of the accepted electrons and positrons with the axis of the spectrometer is about 45 degrees. This cannot be done with the off-axis method because with further coil separation the two focal points come closer together, and they are already about as close as they can get without overlapping considerably.

The Scattering Problem

The method of setting the blocking oscillator biases and the optimum thickness of the crystals to be used in order to reduce the number of coincidences due to scattered electrons has been discussed. Figures 8 and 9 show the advantages of 1/2" crystals over 1/8" crystals for 2.5 mev electrons. With 1/8" crystals it was difficult to set the blocking oscillator biases high enough to cut down the coincidence rate due to scattered electrons without biasing out a large fraction of the true coincidences. Figure 8 resulted
from blocking oscillator bias setting which was too low, showing a rather large coincidence rate due to scattered electrons at the higher energies. The exact causes for the peculiar shape of the curve at the higher energies was not studied carefully, but it is believed to be mostly due to some sort of scattering phenomenon. Figure 9 is the rest of figure 5 and shows how the scattering problem can be largely eliminated with 1/2" crystals. The only two points taken at the higher energies were at potentiometer settings of 116 and 145, but they are both considerably down when compared with figure 6. There still seems to be an indication of a slight rise in the curve at a potentiometer setting of about 126. This could possibly be due to the 6.96 mev gamma ray from the flurine reaction, since it could produce internal pairs which would have an energy of 2.96 mev and would focus at a potentiometer setting of 126.

Calculation of the Pair Energy

Although an attempt was not made in this work to accurately determine the pair energy, an approximate calculation can be made in the following manner using the internal conversion electrons from Cs$^{137}$, BR = 3381 gauss-cm, as a basis for the calibration. Figures 10 and 11 show the Cs and flurine peaks respectively for the same spectrometer adjustment with the on-axis method. One of the curves in
figure 10 was taken with the current in the coils in one direction, and the other was taken with the current reversed, thus simulating the motion of positrons in the first field. That the two curves have slightly different shapes and positions is probably due to a slight misalignment of the spectrometer and due to the effect of the earth's magnetic field since no compensating coils to counteract the earth's field were used.

We have the following equations for the BR value of a charged particle (which is proportional to the momentum, \( p \), of the particle) in terms of its energy, and for the energy of a particle in terms of its momentum.

\[
(1) \quad BR = \frac{1}{\epsilon \epsilon} \left[ E^2 - 2m_0c^2E \right]^{1/2}
\]

\[
(2) \quad E = \left[ (m_0c^2)^2 - (pc)^2 \right]^{1/2} - m_0c^2
\]

For electrons these equations become

\[
(3) \quad BR = a \left[ E^2 - bE \right]^{1/2}
\]

\[
(4) \quad E = \left[ g^2 - d(BR)^2 \right]^{1/2} - g
\]

where

\[
a = 3335.8 \text{ gauss cm/mev}
\]

\[
b = 1.0216 \text{ mev}
\]

\[
g = 0.5108 \text{ mev}
\]

\[
d = 8.9867 \times 10^{-8} \text{ mev}^2/\text{gauss}^2 \text{ cm}^2
\]

Taking the average value of the positions of the two \( g \) peaks as 36.90 and the position of the fluorine pair peak as 108.3 we get for the BR value of the electrons from the fluorine reaction

\[
BR = \frac{108.3}{36.90} \times 3381 = 9930 \text{ gauss-cm}
\]

\[
(12)
\]
The energy is, by equation (4)

$$E = \left[ (0.511)^2 \times (5.99 \times 10^{-8}) \times (9.93 \times 10^3)^2 \right]^{1/2} - 0.511$$

$$= 2.51 \text{ mev}$$

The energy of the pair state is then

$$2(2.51) \times 1.02 = 6.04 \text{ mev}$$

Adding ~ 40 kev due to the loss of energy by the electrons in transversing part of the target and the aluminum foil on which the target was mounted, we get ~ 6.06 mev for the energy of the pair. For a detailed discussion of how to take into consideration peak shifts due to various factors in making an accurate calculation see Hornyak, Lauritzen and Rasmussen, Phys. Rev. 76, 731 (1949).
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