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Effects on low-energy phenomena of some recent results obtained in high-energy physics*

B. A. Logan
Department of Physics, University of Ottawa, Ontario, Canada

A. Ljubičić
Institute "Rudjer Bošković," Zagreb, Yugoslavia

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Two of the more interesting results obtained recently in high-energy physics have been the observation of neutral current phenomena in weak interactions and the possible existence of a light scalar boson as suggested by discrepancies in the x-ray energies of muonic atoms. Some phenomena in low-energy physics can be effected by the possible consequences of these high-energy results. The effects, and possible experimental arrangements by which they can be investigated, are discussed and analyzed.

[RADIOACTIVITY $^{16}N(\beta -)$, $^{14}O(\beta +)$, $^{18}Ne(\beta +)$; possible use of these decays to investigate some fundamental processes.]

I. INTRODUCTION

The possibility of experimental and theoretical results obtained in elementary particle and high-energy physics having measurable consequences in low-energy nuclear physics phenomena is a topic of considerable interest. Unfortunately, there has usually been a distinct separation between the two fields, and experiments which bridge this gap are of particular importance.

It is generally assumed that nuclear levels, at energies below nucleon separation energies, decay by γ-ray emission, by internal conversion, or by internal pair formation. Recently, the possible existence of a light scalar boson ϕ has been discussed.[1,2] If this boson exists, nuclear levels of sufficient excitation can decay by its emission. Possible experimental arrangements suitable for investigating this decay mode are discussed in Sec. II.

The recent discovery of neutral currents occuring in weak interaction phenomena is a fundamental result.[3,4] A consequence of the existence of neutral currents is that excited nuclear levels can decay by the emission of a neutrino-antineutrino pair.[5] The possibility of observing this decay mode is discussed in Sec. III.

II. EFFECTS PRODUCED BY THE ϕ BOSON

A. Theoretical background

Discrepancies between experimental and theoretical x-ray energies in muonic atoms have led to speculation on whether a light scalar boson, with a mass in the range of 10^{-4} eV–30 MeV, exists.[1,2] If the ϕ boson mass is a few MeV, it was estimated that the 6.052 MeV 0^+ first excited level of ^{16}O can decay by ϕ boson emission with a 2–3% probability. Recently, Kohler, Becker, and Watson[6] searched for electron-positron pairs which could have been created in ϕ boson decays after deexcitations of the 6.052 MeV ^{16}O level and in the 20.2 MeV transition in ^4He. No pairs were observed, and it was suggested that the ϕ boson mass was not in the range 1.02–16 MeV. This negative result suggests that it would be useful to develop a completely different experimental technique. We suggest an approach based on measuring nuclear recoil velocities. Two possible arrangements, based on different initial excitation mechanisms are discussed: (a) excitation in $^{16}N(\beta -)^{16}O$; (b) excitation via nuclear reactions.

B. Excitation via $^{16}N(\beta -)^{16}O$

The principal features of the $^{16}N(\beta -)^{16}O$ decay are shown in Fig. 1. Only the high energy γ-ray transitions are shown. If β particles feeding the 6.052 MeV ^{16}O level, with energies near the maximum value of 4.370 MeV, are selected, the energy and linear momentum of the associated antineutrino will be small, and the linear momentum of the recoiling excited ^{16}O nucleus will be approximately equal and opposite to that of the β particle, the recoil velocity of the ^{16}O nucleus being 9.8×10^4 m/sec. The final velocity of the ^{16}O depends on the details of the subsequent decay process.

The principal decay mode of the recoiling excited ^{16}O nuclei is via internal pair formation. This mode of decay has been investigated,[7] the angular distribution being $1+0.6\cos\theta$ (θ is the angle between the electron and positron direction). The

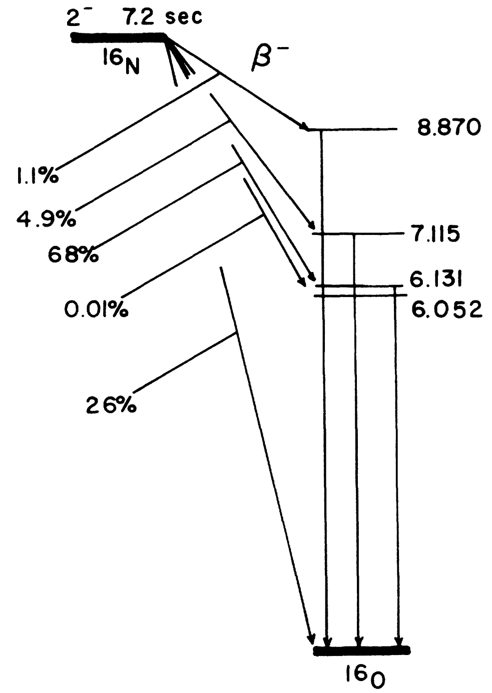

FIG. 1. The decay scheme of $^{16}N(\beta^-, \gamma)^{16}O$. Only high-energy γ-ray transitions are shown.

additional recoil velocity of the ^{16}O depends on the details of the internal pair formation and ranges from $0-1.2\times10^5$ m/sec. The final velocities of ^{16}O nuclei, still moving in a forward cone, range from $0-2.18\times10^5$ m/sec. The velocity distribution will be a slowly varying function with a most probable value at the maximum velocity.

The recoil velocity v induced by ϕ boson emission depends on m_ϕ, the rest mass of the ϕ boson. For decay of the ^{16}O 6.052 MeV level via ϕ boson emission

$$\frac{m_\phi c^2}{\sqrt{1-\beta^2}} = 6.052 \ .$$

β is the ratio of the velocity of the ϕ boson to the velocity of light c and $m_\phi c^2$ is in MeV units. Equating the linear momenta of the ^{16}O and the ϕ boson we obtain

$$v = 1.22\times10^5\left[1-\left(\frac{m_\phi c^2}{6.052}\right)^2\right]^{1/2} \text{ m/sec.}$$

Values of v for various $m_\phi c^2$ values are given in Table I.

We propose a measurement of the velocities of ^{16}O nuclei moving in a forward cone, directed opposite to the β-particle momentum. The kinematics are defined by requiring a coincidence with β particles having energies near 4.37 MeV. A possible arrangement is shown schematically in Fig. 2. The β particles emitted into a backward cone are deflected and observed in a Si(Li) detector. A cone defines the ^{16}O direction and serves to limit the range of final velocities. Preferably it should be fabricated with a material sensitive to low-energy ions and which can give an anticoincidence signal if an ion collides with it.

The widths of the ^{16}O final recoil velocities are given in Tables II and III for cones of half-angles 10° and 15°. Values are given for a variety of mechanisms, some of which will be discussed below, and for various assumed m_ϕ values. The velocity width of the recoils associated with ϕ boson decay decreases with decrease of the cone half-angle.

As is implied by Tables II and III, other background contributions have to be considered. Recoiling ^{16}O nuclei will also be produced via excitation of the higher ^{16}O levels. The second excited level of ^{16}O is at 6.311 MeV and an energy gate of 4.311–4.370 MeV on the β particle will eliminate contributions from higher excited levels. However, some of the higher excited levels produce γ rays of sufficient energy that Compton events in the Si(Li) detector will produce background. In our proposed system the β particles are deflected to allow the Si(Li) detector to be shielded from the γ rays.

Background can also be produced by electrons from the pair created in the internal pair formation, with energies near 4.37 MeV. This would correspond to a very asymmetrical sharing of the kinetic energy available to the pair and is not very probable. The final nuclear recoil velocities associated with this have a broad distribution ranging from $0-1.96\times10^5$ m/sec. Some other decay mechanisms for the 6.052 MeV level have very low probabilities. For example, both internal conversion deexcitation[8] and double γ-ray emission[9] have been measured to have probabilities four orders of magnitude below that of internal pair formation.

β decay directly to the ^{16}O ground state is relatively intense and its contribution has to be con-

TABLE I. The induced recoil velocity of the ^{16}O nucleus for various values of the ϕ boson mass.

Mass of ϕ boson (MeV)	^{16}O recoil velocity v (m/sec)
2	1.15×10^5
3	1.06×10^5
4	9.1×10^4
5	6.9×10^4
5.5	5.1×10^4

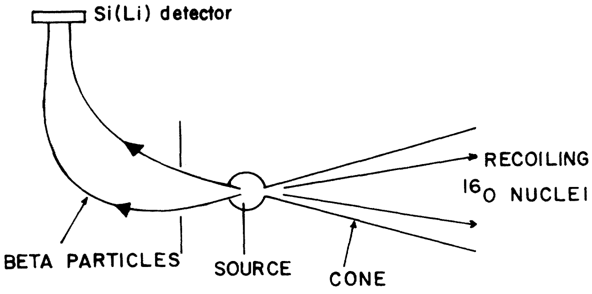

FIG. 2. A schematic diagram of the proposed experimental arrangement.

sidered. The β-particle energy gate defines an antineutrino energy of 6.05 MeV and this will induce an ^{16}O recoil velocity of 1.22×10^5 m/sec. Fortunately, if we define a forward emission cone, there is a difference in the ^{16}O final velocity distributions for ϕ boson decay and the ground state β decay. This background contribution can be estimated by selecting β particles with energies just above 4.370 MeV.

As can be seen from Tables II and III, the recoils associated with ϕ boson decay have a velocity spectrum which could be used to give information on the ϕ boson mass. Except for the ground state β decay, the other background contributions give wide velocity distributions and, assuming a 2–3% ϕ boson emission probability, a reasonably clear peak should be obtained. Unfortunately, the counting rates will be low. Assuming cone half-angles of 15°, the counting rate of ^{16}O nuclei associated with ϕ boson emission will be about 1/h for a 1 mCi ^{16}N source.

C. Excitation via nuclear reactions

The 6.052 MeV ^{16}O level can be excited by such reactions as ^{15}N$(p,\gamma)^{16}$O, ^{16}O$(p,p'\gamma)^{16}$O, and ^{19}F$(p,\alpha\gamma)^{16}$O.[10] As we are interested in differentiating between different recoil velocities induced by different decay modes, it is advantageous to minimize the initial recoil velocity induced by the proton.

A resonance at 0.338 MeV in ^{15}N$(p,\gamma)^{16}$O would be most suitable. The decay scheme is shown in Fig. 3.[10] The 6.052 MeV level is fed by a 6.39 MeV γ ray and it will be necessary to define a coincidence with this γ ray if the excited ^{16}O nucleus is to have a defined initial velocity. The recoil velocity induced by the captured proton is 5.05×10^5 m/sec, and by the emitted γ ray is 1.29×10^5 m/sec. Unfortunately, the proton induced recoil velocity is still large when compared to those induced by the various subsequent emissions.

III. PHENOMENA ASSOCIATED WITH NEUTRAL CURRENTS

The existence of neutral currents[3,4] in weak interactions implies that deexcitation of a nuclear level by emission of a neutrino-antineutrino pair is possible.[5] As the helicities of the neutrino and antineutrino are opposite in sign, in a transition between spin-unity and spin-zero levels the neutrino and antineutrino will be emitted in opposite directions. Because of phase space considerations the neutrino and antineutrino will tend to share the available transition energy equally and the induced nuclear recoil velocity will be peaked about zero. In other competing decay processes the nucleus nearly always receives a recoil velocity. The study of recoil phenomena has recently been suggested as a possible method for observing "right-handed" neutrinos.[11]

Examples of suitable nuclear decays occur in the positron decay of ^{14}O and ^{18}Ne. The principal features of the decay schemes are shown in Figs. 4 and 5. The levels at 2.311 MeV in ^{14}N and 1.045

TABLE II. The final velocities of the ^{16}O nucleus for the various mechanisms, assuming a cone half-angle of 10°.

Decay mechanism	Mass of ϕ boson (MeV)	Final velocity range of ^{16}O (10^4 m/sec)
ϕ boson emission	2	19.6–21.3
ϕ boson emission	3	19.0–20.4
ϕ boson emission	4	17.4–18.9
ϕ boson emission	5	15.0–16.7
ϕ boson emission	5.5	13.0–14.9
Ground state β decay	⋯	21.0–22.0
Internal pair production	⋯	0 –21.8
Gating by electron of pair	⋯	0 –19.6

TABLE III. The final velocities of the ^{16}O nucleus for the various mechanisms, assuming a cone half-angle of 15°.

Decay mechanism	Mass of ϕ boson (MeV)	Final velocity range of ^{16}O (10^4 m/sec)
ϕ boson emission	2	18.6–21.3
ϕ boson emission	3	17.6–20.4
ϕ boson emission	4	16.0–18.9
ϕ boson emission	5	13.4–16.7
ϕ boson emission	5.5	7.4–14.9
Ground state β decay	···	19.7–22.0
Internal pair production	···	0 –21.8
Gating by electron of pair	···	0 –19.6

MeV in ^{18}F are of interest. The basic arrangement is similar to that discussed in Sec. II. Energy selection of the positrons feeding the relevant level can allow the associated neutrino to have negligible momentum and the excited recoiling nuclei will have approximately equal and opposite momenta to that of the positrons. A coincidence between the positron and the recoil nucleus is required.

As an example consider the ^{14}O decay. Excited ^{14}N nuclei recoil with a velocity of 5.62×10^4 m/sec and subsequent neutrino-antineutrino pair emission will tend to leave this velocity unchanged. However, the dominant competing transitions induce recoil velocities. For example, the recoil velocity induced by γ-ray emission is 5.5×10^4 m/sec. If the observations are limited to a forward cone, the final nuclear recoil velocities will group around 1.20×10^3 m/sec and 1.11×10^5 m/sec. Both of these velocity groups are easily distinguishable from the positron induced initial recoil velocity. The positron decay to the ^{14}N ground state is weak but its effects should be noted. This decay involves a neutrino with an energy near 2.3 MeV and the induced ^{14}N recoil velocity will be the same as for γ-ray emission.

Internal conversion is many orders of magnitude less probable than γ-ray emission.[12] The kinematical details depend in principle on which atomic shell is converted and on how the vacancy is filled. For ^{14}N the atomic binding energies are negligible when compared to the transition energy and the emitted electron can be assumed to have the full transition energy. In a forward direction the final ^{14}N recoil velocities group around 1.22×10^5 m/sec and are easily distinguishable from the original excited ^{14}N recoil velocity.

There are some weak processes which can give background at the original ^{14}N recoil velocity value. The 2.311 MeV level of ^{14}N can decay by internal pair formation. Background will be produced when the electron and positron are oppositely directed with equal kinetic energy. The relative probability of internal pair formation, and the angular distribution of the pairs, has been calculated.[13,14] For an $M1$ transition of this energy the probability of internal pair formation is only about 10^{-4} of that of

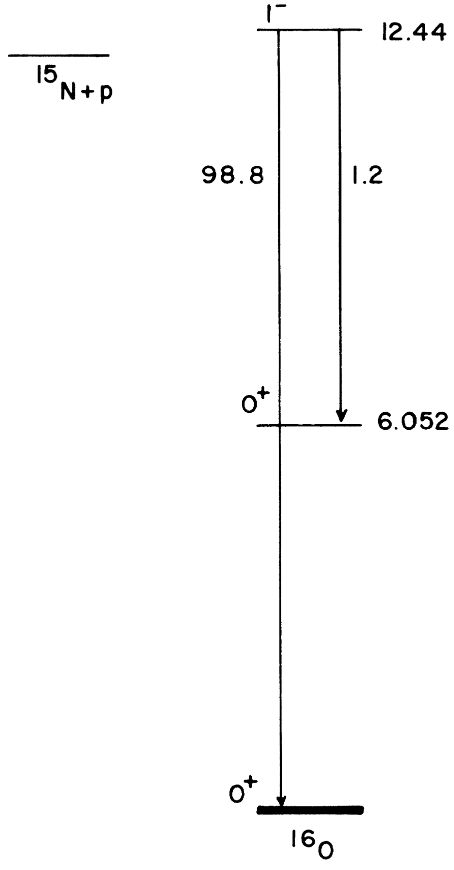

FIG. 3. The decay of the 0.338 MeV resonance in $^{15}N(p,\gamma)^{16}O$.

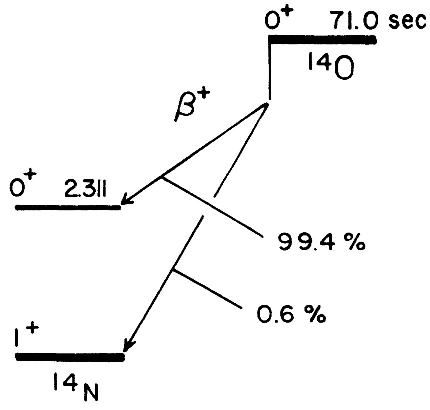

FIG. 4. The decay scheme of $^{14}O(\beta^+,\gamma)^{14}N$.

γ-ray emission. The angular distribution favors emission along the same direction, emission at 180° only being 2×10^{-4} as probable. Such deexcitations can give background in the velocity range of interest of the order of 10^{-8} per γ-ray decay. In the ^{18}F 1.045 MeV transition such contributions would be negligible.

Another potentially troublesome lower limit on the sensitivity is set by double γ-ray decay.[9,15] For $0^+ \rightarrow 0^+$ transitions this has been observed to be four orders of magnitude less probable than the conversion decay. The relative probability of this process will be several orders of magnitude less when γ-ray decay is allowed.

The Weinberg unified theory of weak and electromagnetic interactions[16,17] has been used to estimate the relative probability of various nuclear levels of astrophysical interest, decaying via neutrino-antineutrino pair emission.[18] These calculations can be extended to our situation. For ^{14}N the decay constant $\lambda_{\nu\bar{\nu}}$ for neutrino-antineutrino pair emission is $\sim10^{-3}$/sec. The γ-ray decay constant λ_γ for the 2.311 MeV level is about 10^{13}/sec giving a predicted relative probability for pair emission of $\sim10^{-16}$. This agrees with an earlier estimate.[5] This is several orders of magnitude below what could be achieved in our most optimum system as physical phenomena will give background of $\sim10^{-8}$ γ-ray decay. Even so, an experimental measurement could still be worthwhile as it is of interest to put even crude experimental limits on such fundamental processes.

IV. PRACTICAL CONSIDERATIONS

Only gaseous radioactive sources have been considered. All the sources can be used if nuclear accelerators are available on site.[19-21] In principle many other nuclei can be investigated, but as low-energy ions are to be measured the multiple scattering in solid state media would tend to mask the physical information in the basic kinematics. In gaseous sources such effects are minimized. For example, the mean free path of molecules is 20 m at pressures of 10^{-5} Torr and many successful neutrino recoil experiments have been carried out at pressures of 10^{-6}—10^{-5} Torr.[22-26] Differentially pumped source arrangements are envisaged and it is hoped that much of the initial velocity information will be preserved.

There is some uncertainty as to what the molecular state and charge of the recoils will be. In some cases diatomic molecules are involved while free atoms have been assumed in the kinematic analysis. In all the cases discussed the recoil energies are at least an order of magnitude higher than the binding energy associated with molecular bonds and complications introduced by binding energy effects need not be serious. The charge states and atomic nature of recoil ions produced in nuclear decay processes have been studied extensively.[23,27,28] If unambiguous results are to be obtained it is necessary to measure the charge, mass, and velocity of the recoil ion. Techniques for measuring energy to mass ratios and charge to mass ratios for low-energy ions are standard. The ions have energies of about 1 keV and can be detected in channel electron multipliers which are used routinely to detect individual ions at energies down to a few hundred eV.[29] Of course, the energy resolution of the detector is limited, but in our proposed arrangements an electron, a positron, or a γ-ray are also detected in a coincidence arrangement, and the ion velocity can be determined from its time of flight. Extended versions of such basic systems as those developed by Snell and Pleasonton[25,26] are envisaged as practical possibilities.

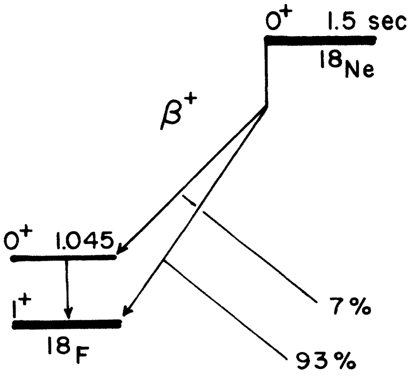

FIG. 5. The decay scheme of $^{18}Ne(\beta^+,\gamma)^{18}F$.

V. CONCLUSIONS

Some possible experimental arrangements suitable for investigating the effects in low-energy phenomena of some recent results obtained in high-energy physics have been analyzed. The proposed experiments are difficult, and in some cases perhaps prohibitively so, with currently available techniques. However, one of the main aims of this work is to emphasize that potentially important physical information is available to be measured.

It is also probable that more suitable transitions than the ones we have analyzed are available. For example, in the case of ϕ boson emission any two levels with the same spin and parity are potential candidates. The ^{16}O level we analyzed is only fed directly in about 0.01% of the β decays.[30] A level which is fed more strongly would have obvious practical advantages. Similarly, any transitions between spin-one and spin-zero levels of the same parity will be suitable for neutral current investigations. Relatively long-lived levels where the pair emission could be more competitive would offer advantages.

In general, relatively high energy transitions in light nuclei, which can be formed as gaseous sources, are most favorable, as they offer the advantages of large recoil velocities and a minimization of multiple scattering distortions. There is no doubt that experiments of this type will require patience and ingenuity but the fundamental nature of the physics involved should make the effort worthwhile.

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