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FUNDAMENTAL SYMMETRIES AND ASTROPHYSICS WITH RADIOACTIVE BEAMS

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ABSTRACT

A major new initiative at TRIUMF pertains to the use of radioactive beams for astrophysics and for fundamental symmetry experiments. Some recent work is described in which the β-decay followed by alpha particle emission of ^{16}N was used to find the resonance parameters dominating alpha particle capture in ^{12}C and thus to find the astrophysical S-factor of this reaction which is of crucial importance for alpha-particle burning and the subsequent collapse of stars. In some new work underway trapped neutral atoms of radioactive potassium atoms will be used to study fundamental symmetries of the weak interactions. Trapping has been achieved and soon ^{38m}K decay will be used to search for evidence of scalar interactions and ^{37}K decay to search for right-handed gauge boson interactions. Future experiments are planned to look for parity non-conservation in trapped francium atoms. This program is part of a revitalization of the TRIUMF laboratory accompanied by the construction of the radioactive beam facility (ISAC).

1. Introduction

Fig. 1 shows the layout of the TRIUMF facility including the ISAC experimental hall now under construction. Following the rejection of the TRIUMF KAON proposal in 1994 (the idea of KAON promises to live on at KEK) the existing TRIUMF program was stabilized in funding and TRIUMF undertook some major new initiatives. These included participation in LHC construction at CERN and also a development of radioactive beams and facilities for research in astrophysics and fundamental symmetries. To describe this new direction with radioactive beams this paper will focus on several touchstones. One is the recently completed "Red Giant" experiment in which radioactive ^{16}N was used to determine the S-factor for ^{12}C+α capture (Sec. 2). A second pertains to the TRINAT program, the trapping of radioactive neutral atoms to elucidate fundamental symmetries of the weak interactions and to search for new physics beyond the Standard Model of quarks, leptons and unified forces (Sec. 3).

The examples chosen serve to illustrate the strength of the TRIUMF radioactive beam work but not its breadth. In the new TRIUMF ISAC laboratory, the idea for which was initiated by John D'Auria and colleagues a decade ago, radioactive isotopes will be accelerated up to 1.5 MeV per mass unit and used for astrophysics, surface physics and much more, as indicated by the layout of Fig. 1. A complete description of the plans can be found in the TRIUMF proposal for ISAC.[1] Like the examples discussed here, the nature of the whole program is appropriate for this symposium, celebrating the 60[th] birthday of Professor Hirosayu Ejiri and honouring his many contributions to nuclear physics, hypernuclei and to elegant experiments for fundamental symmetries.

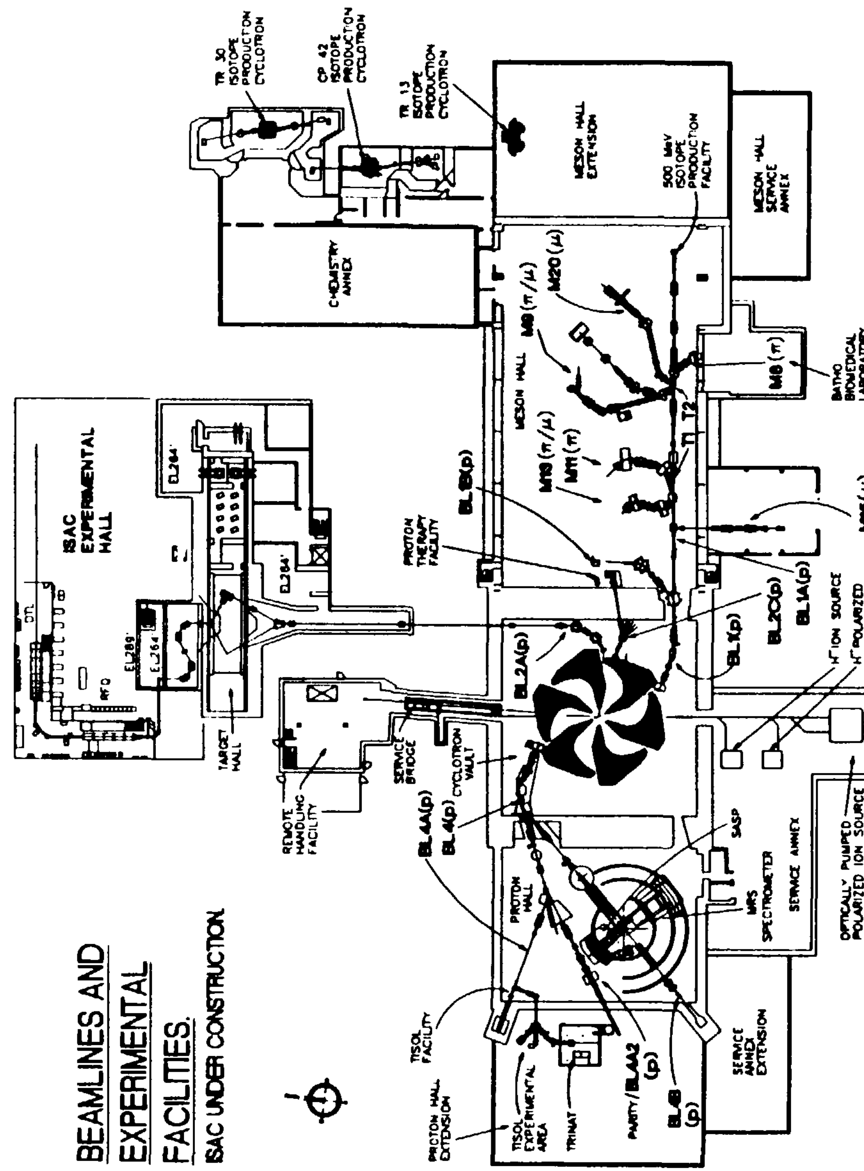

Fig. 1. Layout of the TRIUMF facility including the ISAC experimental hall now under construction.

2. The TRIUMF "Red Giant" Experiment

The recent[2] TRIUMF "Red Giant" experiment made a major impact on one of the most crucial processes for nuclear astrophysics. Nuclear astrophysics has received remarkable new attention in recent years for two reasons. One involves the great current interest in neutrinos with major large new facilities, worldwide, directed at both terrestrial and extra-terrestrial neutrinos, dedicated to elucidate neutrino properties. The second involves a new generation of studies pertaining to nucleosynthesis. Both areas of interest are full of new ideas and in need of data much more precise than heretofore.

For the analysis of solar neutrinos the most urgent need, among nuclear reactions, is for remeasurement of the ^{7}Be + p capture process and the estimation of its S-factor. At this conference we heard a report by T. Motobayashi of experiments at Riken to measure this process indirectly via the Coulomb breakup of ^{8}B in collisions with heavy nuclei. There are plans at TRIUMF, by Lothar Buchmann and colleagues, to measure ^{7}Be + p capture directly in two different ways: (i) production of a ^{7}Be target (of, perhaps 10^{17} atoms produced in irradiation of several months) for proton bombardment experiments and more ambitiously, (ii) producing beams of radioactive ^{7}Be for bombardment of a hydrogen target.

For nucleosynthesis we live in a universe in which all possible reactions of all the isotopes (stable or unstable) of all the elements may play a role. In the progression of a star through various stages of burning to its final collapse, there are a few reactions of special importance. Among these the ^{12}C + α capture has loomed large recently because its S-factor dominates alpha-particle burning and the production of the elements critical for final collapse and also because the experimental S-factor-unlike those of the other critical reactions-remained uncertain by about two orders of magnitude. For the life of a star it was as though all the facts pertaining to its adolescence were shrouded in uncertainty. The recent TRIUMF "Red Giant" experiment[2] succeeded in removing much of that uncertainty.

The problem for the S-factor of ^{12}C + α capture is that it is dominated by resonances in ^{16}O whose properties nature has chosen to hide. The threshold for ^{12}C + α capture lies at 7.142 MeV in ^{16}O. The action in alpha-particle burning takes place in the vicinity of 0.300 MeV above threshold where the Coulomb barrier reduces the cross section by a factor of about 10^6 from the vicinity (down to about 1 MeV) at which laboratory measurements are possible. Only very few resonances play any role in the capture process and one needs to know their alpha-particle reduced widths. A 2^+ level at 9.85 MeV (leading to $E2$ capture) and a 1^- level at 9.60 MeV (leading to $E1$ capture) are easily measured. However, the only other 2^+ and 1^- levels lying lower in energy have been placed, mischievously, by nature very close to the threshold (at 6.92 MeV and 7.12 MeV, respectively) where they are bound to be of great importance for the S-factor but also play no role at 1 MeV where their alpha-particle reduced widths might be measured. That is why this important S-factor remained so elusive.

The recent TRIUMF experiment succeeded in pinning down the properties of the 1^- subthreshold level-and therefore the $E1$ contribution to the S-factor-through the "back-door", so to speak. (Since the $E1$ & $E2$ contributions were known to be

very roughly equal, from angular distribution measurements, this experiment then substantially removed the uncertainty in the total S-factor). The β-decay of ^{16}N, produced in TRIUMF's TISOL facility, feeds all of the levels of ^{16}O involved in the alpha-capture process. If one measures the α emission following ^{16}N β-decay one sees, on Fig. 2 that the subthreshold level interferes destructively with the known 1^- level at 0.60 MeV. It was no mean feat, in the TRIUMF experiment, to accurately measure the small alpha particle rates but in measuring the interference, with the R-matrix fit, as shown on Fig. 2, one accurately determined the subthreshold α-particle width.

Although much of the uncertainty has been removed, this is not the end of the ^{12}C $+\alpha$ capture story. Improved global analyses[3] of the ^{12}C + α reactions reveal that the experimental uncertainty in the S-factor is still a factor of two or so, largely because of the unknown α-width of the subthreshold 2^+ level. Further, I have recently explored[4] the reliability of the R-matrix analysis in extrapolating from the known

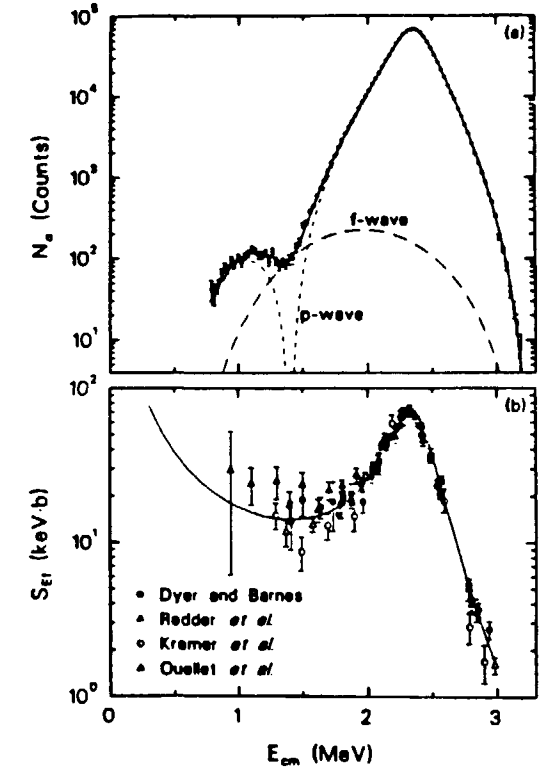

Fig. 2. R-matrix fits to the cross sections pertinent to the $E1$ S-factor of ^{12}C + α capture. a) fit to the ^{16}N β-decay-delayed α-spectrum in which the p-wave interference term pins down the alpha-particle reduced width of the 1^- state near threshold; b) the resultant ^{12}C$(\alpha,\gamma)^{16}$O $E1$ S-factor.

data, near 1 MeV, down to the astrophysical region (near 0.3 MeV) where the S-factor is relevant. I will digress here for a moment to describe my own intervention.

Various frameworks exist for the description of resonance reactions. In each, one attempts to make appropriate approximations–for example, by focussing on only a few of the resonances and a few of the reaction channels– and counts on the framework to provide the dynamics–the variation of the cross sections with energy. For no framework are the relevant approximations problem-free. To be conservative the analysis[2] of the recent TRIUMF ^{16}N experiment was carried out with both the R-matrix framework and the K-matrix framework and found consistency, among the frameworks, for the $E1$ contribution to the S-factor.

In my own paper I asked how reliable is the R-matrix framework for the energy extrapolation which achieves the required S-factor? In the R-matrix theory one achieves unitarity by establishing a Hermitian boundary value problem in which one adds to the nuclear Hamiltonian a chosen matching radius, a_c, for each reaction channel and a corresponding real boundary condition number, b_c. Ever since the inception of R-matrix theory it has been a cherished belief that the a_c are arbitrary and indeed, the R-matrix analysis[2] of the ^{16}N experiment varied a_c over quite a wide range. However, the knowledge of the S-factor depends on the accurate energy extrapolation of barrier penetration: if one doesn't know a_c, where the channel merges with the compound nucleus, how can one say anything reliable about barrier penetration?

I found that contrary to popular belief of half a century, the matching radii, a_c, are uniquely determined. The unique value emerges from the physics of the nuclear mean field. The value of a_c lies just beyond the mid-point radius of the mean field. Using this value one adds reliability to the estimation of the S-factor through barrier penetration and one finds that in situations such as the ^{16}N analysis,[2] the standard R-matrix analysis (without Coulomb barriers being rounded by the nuclear mean field) overestimates the S factor by about 10–15%. The change in barrier penetrations from 1.0 MeV to 0.3 MeV is altered by the mean field, resulting in the reduction in the S-factor.

3. TRINAT and Fundamental Symmetries

Perhaps no other field of experimental physics has experienced such explosive growth, over the last few years, as laser trapping of atoms. TRIUMF's radioactive beam facility (ISAC) promises to provide the world's most intense source of many radioactive isotopes, especially alkali isotopes. The TRIUMF Neutral Atom Trap (TRINAT) facility is being developed to carry out experiments on fundamental symmetries with trapped neutral atoms.[5] The current physics spokesmen for the TRINAT group are Otto Häusser, John Behr and Peter Jackson.

Some weeks ago the TRINAT was put on line with TRIUMF's present radioactive beam facility, TISOL, and trapping was achieved of 700 atoms of radioactive ^{37}K and about 2000 atoms of ^{38m}K. It is anticipated that in a few month's time, with only a modest increase in trapping, the first new results will be obtained with these K isotopes on the fundamental symmetries of the weak interactions. In this brief report I propose to outline the physics of the initial experiments.

Why neutral atoms? the trapped atoms are very cold ($\sim 1\ \mu K$, or average velocities of 1 cm/s), very compact and very dense (about 4×10^{10} atoms in 1 cm^3), very polarized (optical pumping easily achieves 95% polarization) and the radioactive decay is carrier-free (distortion-free momenta). In the experiments the radioactive ions produced by spallation must be slowed, neutralized, cooled and trapped in less than a second during which their energy changes by about seventeen orders of magnitude! The experimental techniques are wonderfully elegant, for example in the recent experiments[6] to achieve Bose-Einstein condensation of trapped atoms below 200 nanokelvin. The final trapped atoms reveal themselves through fluorescence from the trapping lasers.

Two examples may serve to illustrate what TRINAT might achieve., Both search for physics beyond the Standard Model.[7] In the first ^{38m}K will be used to search for scalar interactions. In the second ^{37}K decay will be used to establish limits on right-handed interactions.

Even before the advent of parity-violation and V-A theory, Jackson, Treiman and Wyld[8] gave the general structure of the beta decay in terms of various interactions by the following expression of the transition probability:

$$\begin{aligned} dW \;=\; & dW_0 \xi \Big\{ 1 + a(\vec{p}_e \cdot \vec{p}_\nu / E_e E_\nu) + b(\Gamma m_e / E_e) \\ & + < \vec{J} > \left[A'(\vec{p}_e / E_e) + B(\vec{p}_\nu / E_\nu) + D(\vec{p}_e \times \vec{p}_\nu / E_e E_\nu) \right] \\ & + \vec{\sigma} \cdot \left[G(p_e / E_e) + Q'(\hat{p}_e \hat{p}_e \cdot < \vec{J} >) + R(< \vec{J} > \times \vec{p}_e / E_e) \right] \Big\} . \qquad (1) \end{aligned}$$

This expression has no assumptions regarding invariance with regard to parity, charge conjugation and time-reversal. The various coefficients $(\xi, a, b, A, B, D, G, Q', R)$ involve the complex coupling constants of beta decay, Γ is a Coulomb factor, $< \vec{J} >$ is the nuclear vector polarization and $\vec{\sigma}$ the electron spin. In the Standard Model the coefficients b, D and R vanish while a, A, B, G and Q' depend only on angular momentum and the ratio of matrix elements, $\gamma = g_A M_{\sigma T} / g_V M_F$.

In the $0^+ \to 0^+$ Fermi decay of ^{38m}K one will measure the beta-neutrino angular correlation (the a term in Eq. (1)) for evidence of a scalar interaction. Unlike the V-A interaction of the Standard Model, a scalar interaction demands like helicities for both leptons and antileptons. For the former, back-to-back emission of the electron and neutrino is forbidden: for the scalar interaction it is maximal. The TRINAT experiment will measure β^+ and ^{38}Ar recoils in coincidence.

Although an induced scalar interaction is forbidden, in the Standard Model, by both CVC and the absence of second-class currents it could be produced by the exchange of scalar bosons as in many extensions of the Standard Model. As Adelberger[9] has pointed out, present limits on the scalar interaction are poor. A 1% measurement of a from ^{38m}K would be interesting and appears to be possible with TRINAT. Information about scalar interactions is not unimportant for the double-beta decay experiments which have been of long-term interest by Ejiri and his colleagues, here at Osaka.

Where are the right-handed gauge boson interactions? A muon-decay experiment at TRIUMF[10] by Strovink *et al.* first set reasonably stringent mass limits on W_R (dependent on some model assumptions) about a decade ago. However some evidence for W_R in the mass-range 240-380 GeV/c^2 persists and it would be of great interest to have evidence, or upper limits, up to the 1 TeV regime. The present status of experiments for right-handed interactions was reviewed here at Osaka (Weak and Electromagnetic Interactions International Conference) by Deutsch[11] last June.

With TRINAT it is the decay of trapped ^{37}K atoms which is intended to provide information about the handedness of the weak interaction. Measurement of the beta asymmetry parameter A, and of the ratio R_a of longitudinal β^+ polarization in the direction of the nuclear spin and opposite to it could have an impact[10] on the relevant mass region of the W_R if accuracies of 0.3% in A and 0.6% in R_a could be achieved. The well-known TRIUMF muon-decay constraints[10] on W_R, as well as constraints from nuclear beta decay, are usually given in terms of manifest left-right symmetries (MLRS) models involving two parameters a mixing angle and the W_R mass. However more general left-right symmetric models involve two additional parameters[11] (the ratio of gauge-coupling strengths, g_R/g_L, and the ratio, U^R_{ud}/U^L_{ud} of CKM matrix elements) and therefore the β-decay results which suggest lower W_R masses are not necessarily incompatible with them muon decay results. Recent direct searches for W_R at Fermilab[12] have placed limits of 500-600 GeV/c^2 on the existence of a heavy charged W (again assuming MLRS). If the search extends to the region of 1 TeV/c^2 then a major effort would be required to obtain the necessary accuracy in R_a from trapped ^{37}K atoms. The reward of finding heavy gauge bosons-beyond the Standard Model-is very great and the trapping experiments are now in their infancy.

There are also TRINAT proposals for the measurement of Parity Non-Conservation (PNC) with trapped neutral francium isotopes. Such atomic experiments provide results about the "weak charge" of the electroweak theory which are complementary to those obtained with LEP. TRIUMF can produce the francium isotopes copiously and they are more favourable for atomic PNC measurements than the recent Cs experiments.[13]

4. Conclusions

This general survey has indicated some of the new directions for TRIUMF. This conference is devoted to new frontiers in nuclear physics. It is a time of great challenges and, more than ever elegant new experimental techniques to meet them. We all hope and expect that Professor Hirosayu Ejiri and his colleagues will continue to be involved with that frontier for many more decades.

5. Acknowledgements

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