EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-ISC/97.2
ISC-P88 Revised
16 January 1997

Proposal to the ISOLDE Committee

Beta decay asymmetry in mirror nuclei: $A = 9$.

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Abstract

Investigations of light nuclei close to the drip lines have revealed new and intriguing features of the nuclear structure. A most spectacular phenomenon is the occurrence of halo structures in these loosely bound systems. As intriguing but not yet solved is the nature of transitions with very large beta strength. We propose here to investigate this latter feature by accurate measurements of the beta decay asymmetry between the mirror nuclei in the $A = 9$ mass chain. We ask for a total of 15 shifts of on-line data taking plus 3 additional shifts for stable beam adjustment and calibration measurements.

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1 Introduction

This proposal falls within the general framework of the physics outlined in our contribution to the Leysin meeting and in the letter of intent "Properties of exotic nuclei close to the border lines of particle instability" [1].

We have at the PSB ISOLDE continued our studies of the light drip line nuclei. In the study of the neutron rich He and Li isotopes we have observed very strong (superallowed) Gamow Teller (GT) beta transition rates to highly excited states in the daughter nucleus [2, 3], an effect most likely connected to the halo structure of these systems. Also, studying the decay of ^{17}F we were able to demonstrate a halo effect, in this case of a decay into such a system [4]. The effect was here observed as a mirror asymmetry in the beta decay. In the present proposal we want to employ this powerful method also for the $A = 9$ nuclei.

Before presenting the physics motivation we would like to point out an important side benefit of the proposed experiment. In most of the previous works the detailed understanding of the beta delayed particle emission process via broad states has been essential. To obtain a more quantitative understanding of the beta-delayed multi-particle emission branches, which are of increasing importance when approaching the drip line, more cases have to be studied. The beta decay of ^{9}C, although complex, *involves charged particles only* and thus seems to be an ideal case from the experimental point of view. We turn now to a discussion of this nucleus, the mirror nucleus of the well studied ^{9}Li [6].

2 Physical motivation

More specifically the aim of the proposed experiment is to study asymmetries in beta decay rates of mirror nuclei. First some comments on why we have chosen to look at ^{9}C: There are indications that the two mirror decays $^9\mathrm{C} \xrightarrow{\beta} {}^9\mathrm{B}$ and $^9\mathrm{Li} \xrightarrow{\beta} {}^9\mathrm{Be}$ are very relevant. An asymmetry has already been observed [5, 6] in the decays to the $5/2^-$ states at excitation energy ~2.4 MeV, see the decay scheme in figure 1.

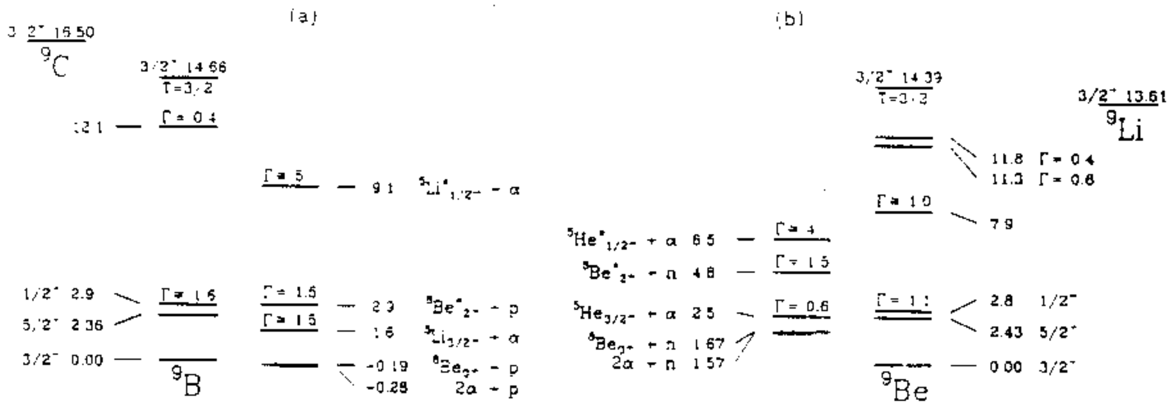

Figure 1: The decay schemes of the $A = 9$ nuclei, taken from [5].

The asymmetry parameter $\delta = (ft)^+/(ft)^- - 1$ is determined to be 1.2 ± 0.5 (and possibly larger) which is one of the largest observed asymmetries of mirror states [5]. The large uncertainty in the δ value mainly arises from incomplete knowledge of the ^{9}C decay. The $5/2^-$ states are relatively narrow and have branching ratios of 15–30 % and can thus be picked out rather easily experimentally.

A potentially larger asymmetry — and a much more interesting one — seems to exist in the decays to highly excited states at ~12 MeV excitation energy fed with branching ratios of 2–3 %. The transition has been investigated in detail for ^{9}Li and has [6] $B_{GT} = 5.6 \pm 1.2$. Only a lower limit on B_{GT} value is given in [5] for the corresponding transition from ^{9}C and two effects, which might increase this number, are mentioned. The first effect is experimental, high-energy protons from the decay of the 12 MeV level might escape from the detector and thus lead to a too low total energy being recorded (in [5] the ^{9}C ions were implanted into an array of Si detectors such that the total decay energy of the states fed in the beta decay could be recorded). The second effect has a physical origin, namely the presence of low energy tails from the excited levels due to the beta decay phase space. However, the latter effect will not change the extracted B_{GT} value since such long tails, if present, have to be "corrected away" in order to obtain a reliable value for the strength (see e.g. appendix A in [6]). The intensity seen in [5] corresponds to $B_{GT} \sim 1.4$, but the former effect might increase this number somewhat. If the number is confirmed it would correspond to an asymmetry of $\delta \sim 3$ which is the largest value recorded ever, but clearly the decay of ^{9}C to highly excited states in ^{9}B needs to be studied more carefully.

These large asymmetries may be due to differences in the radial wave functions of the mirror states which in turn are due to the asymmetry of the binding energies (and to some extent directly to the different Coulomb potentials), see in reference [7] for a recent formulation of the problem. A substantial amount of research was performed on such problems in the 70's and a good overview can be obtained from [8]. The asymmetries in question were typically an order of magnitude lower than the ones obtained for mass 9, one example is the very careful determination [9] of the asymmetry for the $^8\text{B} \xrightarrow{\beta} {}^8\text{Be}$ and $^8\text{Li} \xrightarrow{\beta} {}^8\text{Be}$ decays (this was originally dedicated to investigations of the weak interaction, but the asymmetry turned out to be rather difficult to understand theoretically).

The possible asymmetry for the decay to the states around 12 MeV is interesting not only due to the fact that the individual B_{GT} values are large (with large overlap in wave-functions, an unambiguous interpretation is much easier made), but also due to the special role played by this transition for the ^{9}Li decay. It seems to belong to a class of high-B_{GT} transitions observed [10] at the neutron drip line and has been suggested to be due either to a lowering of the giant Gamow-Teller resonance [11] or to the occurrence of "two-neutron → deuteron" transitions [10, 12]. Knowing whether the mirror transition on the proton rich side has a similar strength would help greatly in identifying what causes the large transition strengths. The decay $^9\text{C} \xrightarrow{\beta} {}^9\text{B}^*$ is here the only accessible decay since all other mirror nuclei (^{6}Be, ^{8}C and ^{11}O) to observed nuclei with such a strong decay branch (^{6}He, ^{8}He and ^{11}Li respectively) are particle unstable.

3 The proposed experimental set-up

We propose to use a MgO target for the production of the ^{9}C nuclei and to extract them via the $A = 25$ CO$^+$ sideband. The yield at SC-ISOLDE for a very well performing target was measured to be $4 \cdot 10^3$ s^{-1}; we shall make the slightly conservative assumption

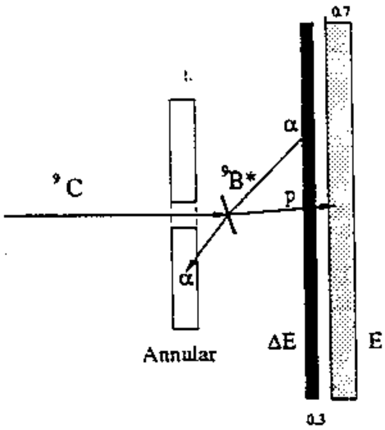

Figure 2: The collection spot is surrounded by a thick annular Si detector and a telescope consisting of a double sided Si strip detector and a thick Si detector. The detector thicknesses are given in mm.

of a collection rate of 10^3 s^{-1} in the count rate estimates below. The yield from a CaO target was two orders of magnitude lower although only measured on $A = 9$, due to a strong contaminant of ^{25}Ne at $A = 25$.

Two set-ups are envisaged as shown in figures 2 and 3. They differ in that the first will stop also very high energy protons whereas the second will give more geometrical information on the decay products. The first set-up consists of three silicon detectors. The beam of ^{9}C ions passes through a hole in an annular detector and is implanted in a thin carbon foil. When the ^{9}C nucleus decays, the excited daughter nucleus ^{9}B will break into three charged particles: a proton and two α-particles. These three particles are measured by the annular, ΔE and E silicon detectors. The sum of the three measured energies gives us directly the excitation energy in ^{9}B. The ΔE detector will be a double sided strip detector with 16x16 strips and total dimension 5x5 cm^2, it can register two or more particles in coincidence and was successfully used during the last ^{31}Ar experiment. To detect the high energy protons the ΔE detector will be complemented by a 700 μm thick 2000 mm^2 E-detector. The total thickness of the ΔE-E telescope is 1.0 mm for a perpendicular impact. suffices to stop the protons from decays of the 12 MeV state. It is also (except at the centre of the detector) enough to stop protons from the so-far undetected narrow isobaric analog state (IAS) of ^{9}C in ^{9}B (E^*=14.66 MeV, T=3/2).

A schematic diagram of the second type set-up is shown in figure 3. The ^{9}C ions are stopped in a thin foil and the ^{9}B* decay products are registered by two Si strip detectors (5x5 cm^2, 8x8 strips obtained by adding strips two by two), which can be triggered by a scintillation detector measuring β-particles from the decay of ^{9}C. The energies and angles of all fragments will thus be measured in order to obtain the proton+alpha+alpha correlations. The data rates expected with this set-up are given in the appendix. If high accuracies are needed we shall run with the full 16x16 strip granularity of the detectors, but this complicates both the electronics set-up and the off-line analysis.

We can distinguish protons and alpha particles kinematically due to the complete detection. This will be illustrated for the case of the first set-up where the energy of the third particle registered by the annular detector can be compared with a value calculated using the measured energies and angles of the other two particles.

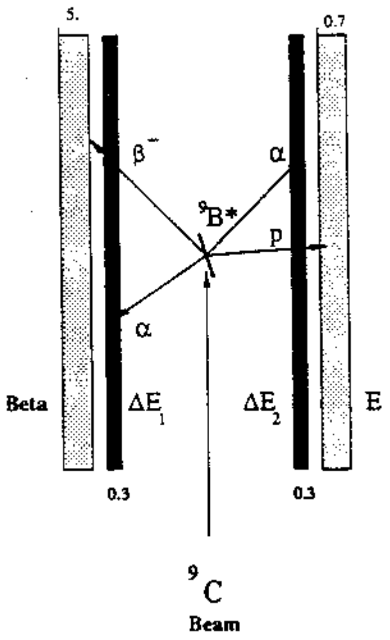

Figure 3: Two Si strip counters are placed on each side of the collection point. Detector telescope operation is obtained by placing a scintillation detector for beta detection and a thick Si detector, respectively, behind each strip detector. The detector thicknesses are given in mm.

This energy E_3 is calculated using momentum conservation in the rest frame of ^{9}B:

$$\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 = 0$$

or

$$E_3 = \frac{m_1 E_1 + m_2 E_2 + 2\sqrt{m_1 E_1 m_2 E_2} \cos\theta_{1-2}}{m_3},$$

where θ_{1-2} is the angle between the particles 1 and 2. As can be seen from the equation, the E_3 value strongly depends on the masses m_1, m_2, m_3. A comparison with the measured E_3 value thus allows to make a particle mass identification. Indeed, in our experiment only the following three mass combinations (proton: m=1 and alpha: m=4) are possible: i)$m_1 = 1, m_2 = m_3 = 4$; ii)$m_1 = 4, m_2 = 1, m_3 = 4$; iii)$m_1 = m_2 = 4, m_3 = 1$. The case iii) gives ~4 times higher value of E_3 in comparison with i) and ii) and is therefore easy to distinguish. The cases i) and ii) also give reasonably different E_3 values in practically the whole range of measured angles and energies. The only exceptions occur when two particles have equal energies or when the angular resolution is poor.

The registration of three-particle coincidences gives an extremely low background level which is important due to the low event rate. To suppress the background and get precise data we should minimize the solid angles of the detectors. A good resolution is also important to minimize the effects of beta summing. A Monte Carlo simulation of the experiment was performed to find a compromise between resolution and count rate, the details can be found in the appendix.

4 Summary and Beam time request

We propose a further investigation of the beta decay of ^{9}C, to obtain a conclusive measurement of the beta decay asymmetry between mirror nuclei as well as a deeper understanding of the loosely bound 'halo systems' appearing close to the drip lines.

This experiment will drastically reduce the large statistical errors in B_{GT} values measured so far [5], in particular obtain a reliable measurement for the 12 MeV state, and distinguish the contributions from the overlapping $1/2^-$ and $5/2^-$ states of ^{9}B. Furthermore, additional detailed information about direct and sequential decay modes of the $^9B^*$ states will be obtained.

We shall use the first set-up to get an overview of the beta strength distribution, and the second set-up to get the detailed knowledge of the decay of the broad levels in order to make a proper correction when extracting the B_{GT} value (this due to the influence of the long tails mentioned in section 2).

Our collaboration is very well acquainted with the running of the ISOLDE facility.

We request, from a MgO target with a plasma ion-source, a total of 15 shifts of on-line data taking plus an additional 3 shifts for stable beam adjustments and calibration measurements. For having as low background as possible we request to work at the LA1 beamline. We also request the use of the ISOLDE computer cluster and data acquisition system.

Appendix. Monte-Carlo simulation of the experiment.

An optimal choice of the experimental set-up is a necessary part of exclusive triple coincidence measurements. Because of the extremely low rate at which the statistical base is built up, we must use detectors which subtend large solid angles. Large-aperture detectors, however, cause a severe smearing of structural features in the measured spectra, so that ambiguities may be introduced in the interpretation of the data. An additional important factor is the available beam time and target life time. These circumstances impose severe and conflicting requirements on the geometric conditions for the experiment. The actual set-up configuration, under which the experiments on the three-particle decay are to be carried out, is simulated by a Monte Carlo method [13]. The following factors are incorporated in these calculations: the energy spread and the geometric characteristics of the beam, the energy loss of the particles in the target, the width of the decaying nuclear state, and the positions, solid angles and energy resolutions of all detectors. The results of the calculation are the probabilities for detecting a triple (double) coincidence per decay event, the single fragment energy spectra, and the angular and energy correlations from kinematically complete measurements. The optimal positions and solid angles of the detectors are those for which the assumed fine structure in the measured spectra is revealed in minimum time.

We illustrate this in more detail via a simulation of the measurements of alpha-proton correlations from the decay of the $^9B^*(5/2^-)$ state in the second set-up (fig. 3). A well investigated [14] 3-body decay mechanism for this level was applied.

The calculated energy correlations are shown in figure 4. The upper 'Dalitz' scatter plot illustrates the case of small solid angles (one pixel dimension is 3x3 mm^2, the distance between the $^9B*$ source and the detectors is 25 mm), the lower plot the large solid angles (the pixel size is 6x6 mm^2, same distance). Relative intensities are indicated by the contours. As can be seen from the plots, the energy spread is very sensitive to the solid angle values.

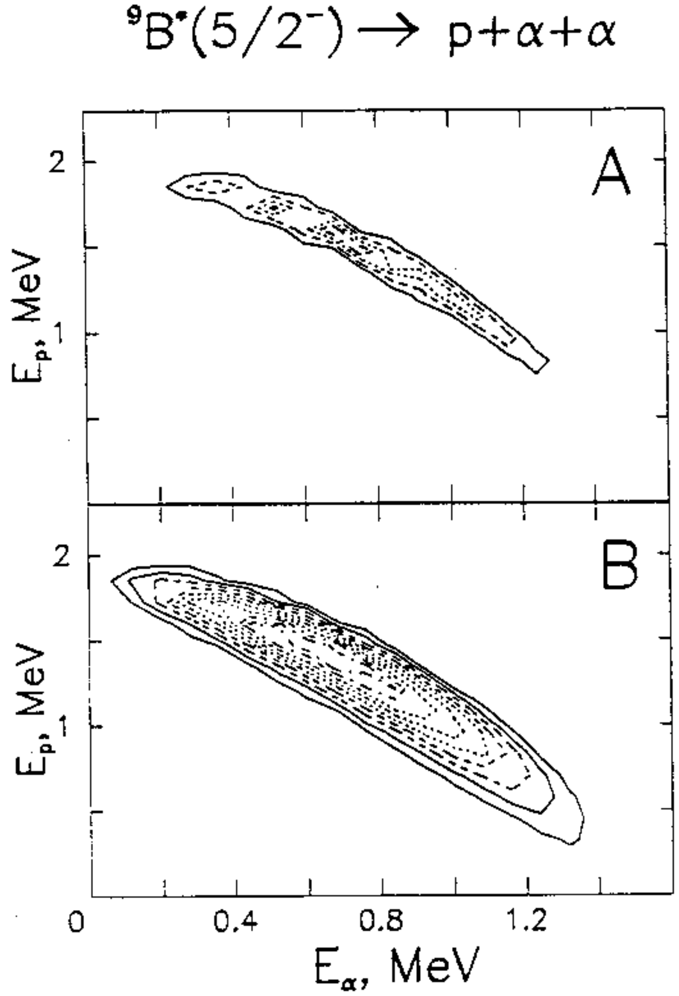

Figure 4: The correlation in energy for p-α coincidences measured with the set-up in figure 3 from the decay of the $5/2^-$ level in ^9B. Both figures correspond to a detector-source distance of 25 mm. The upper panel has a pixel size of 3x3 mm^2, the lower panel has 6x6 mm^2.

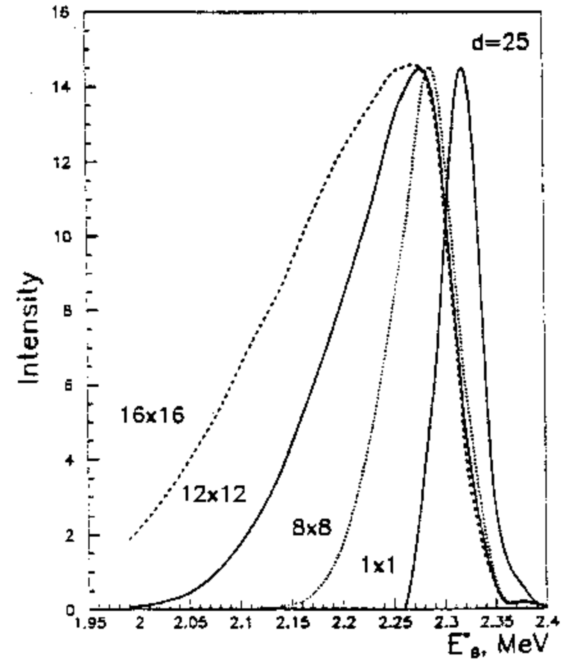

Figure 5: Simulation of the distribution of excitation energy in ^{9}B deduced from two-particle coincidences from decays of the 2.36 MeV level. The reconstructed energy is given for different angular resolutions. The detector-source distance is $d = 25$ mm and the detector pixel size is noted (in mm^2) for the different curves.

The distributions of ^{9}B* excitation energy, calculated on the basis of measured energies, are demonstrated in figure 5. Different curves correspond to different pixel dimension (given in mm^2) for the same distance d=25 mm to the collection point. All curves are normalized to have the same amplitude. As can be seen from fig. 5, an energy resolution of ~100 keV requires detectors with pixel size smaller than 8x8 mm^2 at a distance of 25 mm.

We turn now to the simulations described in the proposal. For the first proposed experimental set-up (see fig. 2 and the text above), the solid angle of the annular detector was chosen to be large, 10% of 4π. The probability to register a proton-alpha coincidence with such a geometry is $\sim 7 \cdot 10^{-5}$. This gives us a counting rate of ~ 0.012 count/s for a branching ratio of 17% for the β-transition to the ^{9}B$^*(5/2^-)$ state assuming a ^{9}C intensity of 1000 s^{-1}. Thus we record ~1000 ^{9}B$^*(5/2^-)$ decays during 3 shifts. For the case of the transition to the 12.1 MeV state the corresponding branching ratio is a factor ~10 smaller, so we expect to record ~100 events. (Note that this in some respect is a pessimistic estimate since this assumes the beta asymmetry to be present.) The angular resolution is reasonably good, resulting in an energy spread of ~50 keV for the excitation energy of ^{9}B*.

For the second experimental set-up, shown in figure 3, both distances from the ^{9}C source to the detectors were chosen as 40 mm (to keep the angular resolution about the same). The total efficiency for a triple coincidence is in this case 0.12% and we will in 12 shifts record ~5000 decays through the 12.1 MeV state. This level of statistics is needed in order to get a reliable description of the major decay branches of the state, e.g. to derive the angular momenta between the fragments. As mentioned above we must understand the decay of this broad level in detail in order to extract a final B_{GT} value.

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