On the Behaviour of a "Ghost" Peak seen in the Reaction ^{6}Li(^{3}He,p)

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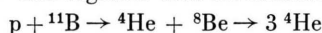*Dedicated to Professor Dr. W. Gentner on the occasion of his 60th birthday*
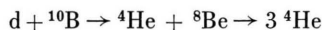
A "ghost" or "ghost state" peak in an energy spectrum of particles produced by a nuclear reaction is commonly understood to be the satellite of a "proper" peak, corresponding to a well known level of the residual nucleus. If this proper level is sufficiently close to a threshold for particle emission, the appearance of the satellite peak can be explained by the strong energy dependence of the penetrability coefficient in that region [1, 2]. For a well known example the ghost of the ground state of Be-8 has been mentioned in [1−3]. The reaction

$$p + {}^9Be \rightarrow d + {}^8Be \rightarrow d + 2\ {}^4He$$

is treated in [2] and together with the reactions

$$p + {}^{11}B \rightarrow {}^4He + {}^8Be \rightarrow 3\ {}^4He$$

and

$$d + {}^{10}B \rightarrow {}^4He + {}^8Be \rightarrow 3\ {}^4He$$

also in [3]. In all cases a ghost peak is seen at a typical energy of excitation of approx. 0.8 MeV above the ground state of ^{8}Be. It is shown that a reasonably good fit to the spectra by the formula given in [1−3] is possible.

An apparently similar situation, where this explanation did not seem to apply, was recently encountered in this institute. The reaction

$$^3He + {}^6Li \rightarrow p + {}^8Be \rightarrow p + 2\ {}^4He \qquad (1)$$

has been investigated using the ^{3}He beam of the tandem Van de Graaff. Proton spectra have been taken by solid-state detectors protected by thin Al absorbers against particles with $Z = 2$. At first variations in the proton spectra were checked by covering the easily attainable angular and energy range. The reaction angle was varied between $15°$ and $165°$, the energy of the incident ^{3}He beam between 5.5 MeV and 18.0 MeV. Data points were taken at intervals $\Delta\Theta \leqq 15°$ and angular distributions at energy intervals $\Delta E = 0.5$ MeV. Apart from the characteristic behaviour of the differential cross section similar to the results quoted in [4], the most conspicuous feature was the appearance of a rather pronounced "ghost" peak in the proton spectra (fig. 1). The maximum energy of this peak, corresponding to 0.8 MeV excitation in ^{8}Be, seemed to be well consistent with that of the ghost state of [1−3]. But differently than those references

would lead to expect, this peak was only seen at bombarding energies between 10 MeV and 11 MeV and at reaction angles of at least $155°$. Further measurements in the range $9.5\ \text{MeV} \leqq E(^3He) \leqq 11.5\ \text{MeV}$, at backward angles and with energy intervals $\Delta E = 0.25$ MeV between data points were therefore made. Resolution had been improved by reducing target thickness and slit width, statistics by longer counting times. To confirm an impression hereby gained two further measurements at $E(^3He) = 12$ MeV and $E(^3He) = 14$ MeV were made under conditions elsewhise similar.

The impression just mentioned was that of a motion of the "ghost" peak according to the variation of the bombarding energy. The observation of this effect is difficult, because the peak is easily seen only when coinciding with the minimum between the proton groups leaving ^{8}Be in ground and first excited state. Superposition with the ground state peak as well as "moving upward" on the high energy shoulder of the broad first excited state peak suggest disappearance of the peak in question. Yet the results of the last measurements with improved resolution and statistics definitely show its displacement (Fig. 1−4).
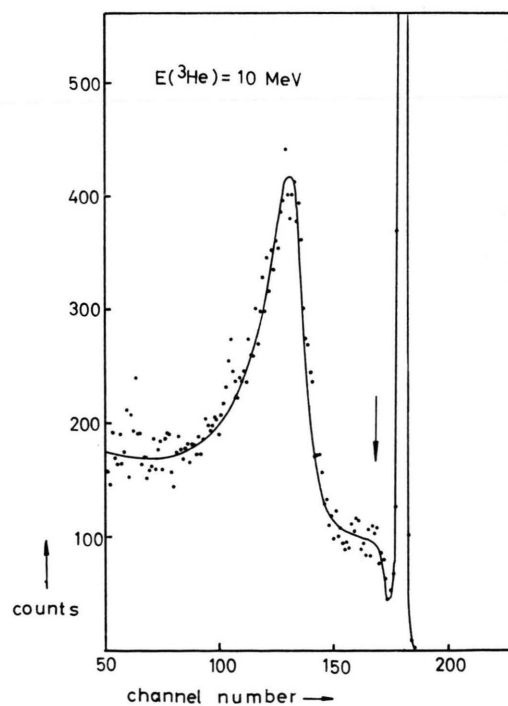

Fig. 1. Pulse heigh spectrum of protons from reactions (1) and (2). Beam energy is $E(^3He) = 10$ MeV, reaction angle $\Theta = 170°$. Arrow marks position of ghost peak between ground and first excited state peak of ^{8}Be.
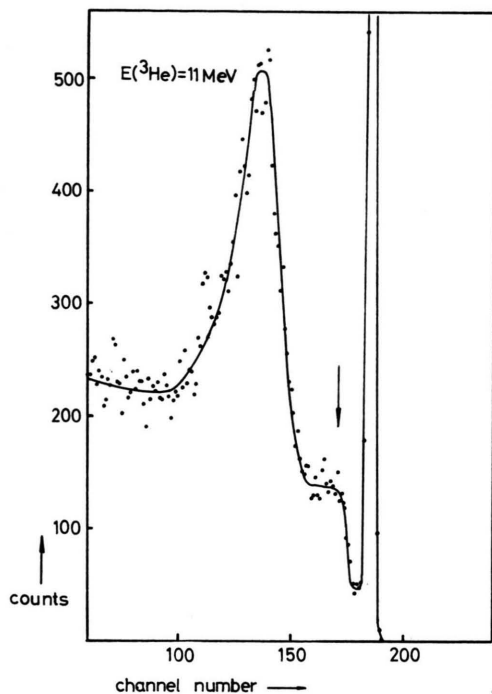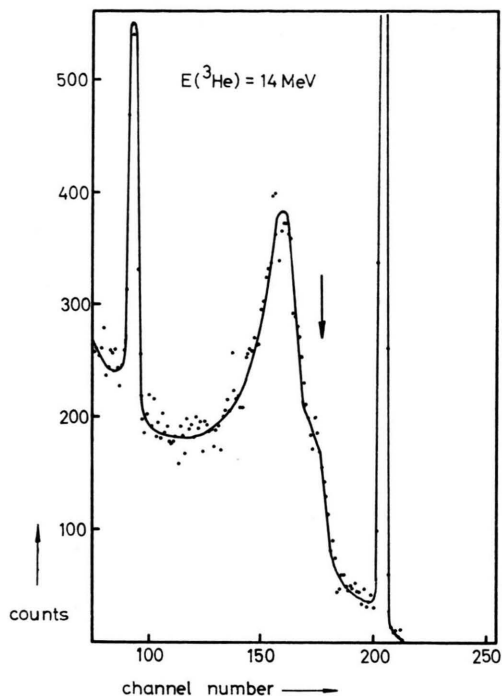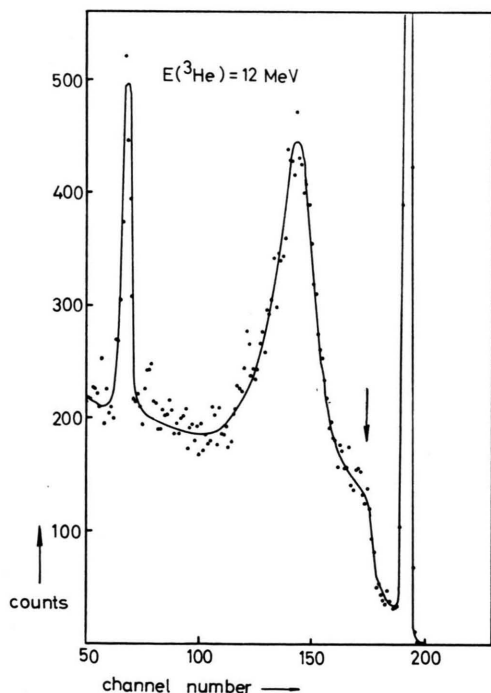
[1] G. C. Phillips, T. A. Griffy, and L. C. Biedenharn, Nucl. Phys. **21**, 327 [1960].

[2] F. C. Barker and P. B. Treacy, Nucl. Phys. **38**, 33 [1962].

[3] E. H. Beckner, C. M. Jones, and G. C. Phillips, Phys. Rev. **123**, 255 [1961].

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Fig. 2. Same as Fig. 1, but for $E(^3\text{He}) = 11$ MeV.

Fig. 4. Same as Fig. 3, but for $E(^3\text{H}) = 14$ MeV.

Fig. 3. Same as Fig. 1, but for $E(^3\text{H}) = 12$ MeV. The $^{12}\text{C}(^3\text{He,p})^{14}\text{N}$ peak is seen at the far left.
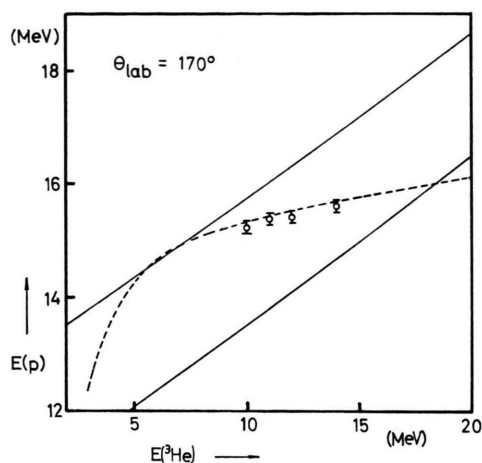
To account for this behaviour by the ghost state interpretation of [1-3] is difficult, but an explanation is offered by the competing reaction

$$^3\text{He} + {}^6\text{Li} \rightarrow {}^5\text{Li}^+ + {}^4\text{He} \rightarrow \text{p} + 2\,{}^4\text{He} . \qquad (2)$$
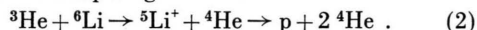
The first step of this reaction has to be visualized as the pick-up of a neutron from the target nucleus. If one further assumes the ^5Li nucleus to be formed in its well known $3/2^+$ state at 16.7 MeV above ground state [5], the experimental results can be understood. The direct reaction mode of the first step in reaction (2) leads one to expect a strongly forward peaked angular distribution of the ^4He particles. At an incident energy of approx. 10 MeV this corresponds to a backward peaked distribution of the $^5\text{Li}^+$ nuclei. If protons from reaction (2) are observed under a laboratory angle near $180°$, their spectral energy distribution should develop a peak close to the maximal energy, attained when the velocity vectors of the $^5\text{Li}^+$ nucleus and the proton produced by its decay are parallel. This accounts for the steap high energy shoulder of the "ghost" peak in Fig. 1 — 4.

The energies of protons formed either by reaction (1) or (2) can be computed by simple cinematic calculations. In Fig. 5 the energies of protons formed by reaction (1), corresponding to the formation of ^8Be in its ground and first excited state (drawn lines), are

[5] See for instance: J. N. BLAIR, N. M. HINTZ, and D. M. VAN PATTER, Phys. Rev. **96**, 1023 [1954], and other references cited in F. AJZENBERG-SELOVE and T. LAURITSEN, Nucl. Phys. **11**, 1 [1959].

Fig. 5. Energies of protons corresponding to ground and first excited state peak of ^{8}Be (drawn lines) and maximal energy of protons from reaction (2) as functions of the beam energy. Data points represent maximum values of protons formed by reaction (2), taken from spectra shown in Fig. 1—4.

plotted together with the extremal energy of protons formed by reaction (2) (dashed line). Data points in this figure represent maximum values of the peak in question, error bars express the uncertainly in assigning their positions. The explanation proposed seems to be confirmed.

The author feels deeply indepted to Prof. W. GENTNER for his interest in and generous support of this work. Thanks are due to Prof. TH. MAYER-KUCKUK for the initiative causing its begin, and especially to Prof. H. MORINAGA for his counsel, suggestions and discussions during its progress.

Photo-Induced Electron Transfer in Dye-dimethylsulfoxide-metal Ion Complexes: Electron Spin Resonance Investigations

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Dedicated to Professor Dr. W. GENTNER *on the occasion of his 60th birthday*

Fluorescence quenching and sensitized photoconduction was observed recently by several investigators in systems containing aromatic amines [1] or sulfhydryl proteins [2] and a fluorescent dye. The mechanism proposed for this effect is based on an electron transfer from the amine or protein to the excited dye molecule. In this communication it will be shown that an electron transfer also occurs during illumination of a methylene blue (MB)-dimethylsulfoxide (DMSO) system. Added metal ions, such as Cu^{2+}, were observed to act competitively with the dye in their electron accepting ability.

The quenching of the fluorescence of the dye by electron transfer has been investigated by electron spin resonance (ESR) technique. A Varian Model V 4500 100 kc ESR spectrometer at a frequency of 9.5 Gc/sec with a liquid sample accessory was used for these studies. The position of the signals was determined with a standard DPPH (diphenylpicrylhydrazil) reference signal for which $g = 2.0036$. All measurements were done at room temperature.

Methylene blue (Allied Chemical and Dye Corp., New York) was dissolved in DMSO (Matheson Scientific, Inc., East Rutherford, N. J.) ; concentrations used varied from 2.3 to 9.4 mM. In order to study the influence of metal ions on the charge transfer reaction, varying amounts of cupric chloride ranging from 0 to 171.6 μM were added to a 10 mM MB-DMSO solution. These Cu^{2+}-concentrations were too small to produce an ESR signal.

Illumination of the MB-DMSO system with white light resulted in a single line about 8 Gauss wide and located at $g = 2.003$. No signal was obtained when DMSO alone was illuminated. The light-induced ESR signal increased with illumination time as well as with the concentration of MB; it reached a plateau after about 20 to 30 min (see Fig. 1). A possible explanation for the effect observed might be that the excited dye reacts with DMSO transferring an electron from DMSO to the dye. This results in an oxidized DMSO and a reduced dye molecule, leaving, as was observed, the leuco (colorless) form of MB. A negative charge, associated with the oxygen atom as a result of its electronegativity, along with the electron donating effects of the two methyl groups, is probably involved in the electron release. The fact that no signal was observed during illumination of solutions with constant MB-concentration, using water, glycerol, ethanol, acetone or formamide as a solvent, supports this concept. Since acetone and DMSO differ in structure only by the replacement of a carbon atom by a sulfur atom, we might conclude that sulfur is important for this electron release. Furthermore, these results are consistent with a similar electron transfer mechanism for the fluorescence quenching of a dye proposed by WEISS [3] and interpreted later on by KASHA [4] in terms of a collisional perturbation of spin-orbital coupling.

A light-induced oxidation-reduction reaction seems to be involved in the fluorescence quenching effect observed. Since no reduction occurred without ex-

[1] W. C. NEEDLER, J. Chem. Phys. 42, 2972 [1965].
[2] E. FUJIMORI, Nature (London) 201, 1183 [1964].

[3] J. WEISS and H. FISCHGOLD, Z. physik. Chem. B 32, 135 [1936].
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