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Ugo Amaldi Jr, Gloria Campos Venuti, Giorgio Cortellessa, Gabriele Fronterotta, Armando Reale, Paolo Salvadori

The (e,e',p) reaction in the Be^9 nucleus

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Fisica. — *The* $(e, e' p)$ *reaction in the* Be^9 *nucleus* (*). Nota di UGO AMALDI Jr. (**), GLORIA CAMPOS VENUTI (**), GIORGIO CORTELLESSA (**), GABRIELE FRONTEROTTA (**), ARMANDO REALE (**) e PAOLO SALVADORI (**), presentata (***) dal Corrisp. M. AGENO.

In recent years, the availability of intense proton beams from high energy particle accelerators, has opened a new field of investigation of nuclear structure. Quantum mechanics predicts, for nucleons within a nucleus, the existence of discrete energy states. Nuclear models and, among others, essentially the shell model, allows us to classify these states in a way not very far from the usual spectroscopic classification proved valid for atomic electrons. Through these models, the nucleus is described as a potential well, with suitable depth and radius both variable with the mass number A, in which nucleons move on orbits characterized by a set of quantum numbers. Energy levels corresponding to the same principal quantum number are split by a comparatively strong spin-orbit interaction. This nuclear model, known as " independent particle model " has been refined in recent years and is to date shortly indicated as shell model. It is not our purpose to discuss the principles underlying this model, nor the successes achieved in describing nuclear properties. It is our aim to stress the fact that the more important prediction, mainly the existence of discrete energy states of nucleons within the nucleus, has been directly verified only during the last seven years.

The experiment to see inner nucleon levels has been done through the $(p, 2p)$ reaction in light nuclei [1–3]. Basically the experiment is the following: monoenergetic protons on a target extract nuclear protons. The two final particles are detected and their energy measured. If both initial beam energy and final state particle energy are known, it is possible to compute the difference:

$$E_B = E_0 - (E_1 + E_2) \tag{1}$$

and to plot, varying e.g. the sum E_1+E_2, the counting rate against this sum. If nuclear protons are bound in definite energy states, when then difference E_B corresponds to the binding energy of a level, the counting rate goes through a maximum. With experiments of this type proton levels have been detected and measured and the shell model of nuclei has acquired a more definite physical ground. The $(p, 2p)$ reaction has a serious experimental drawback, that is to

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(**) Laboratori di Fisica dell'Istituto Superiore di Sanità, Roma.

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say, protons are strongly interacting particles and nuclear absorption of each of the three protons involved in the reaction is heavy. Suggestions have been made by theoreticians to overcome this difficulty using electrons as bombarding particles. Our group as thus tried to detect a $(e, e' p)$ reaction in nuclei, in spite of the difficulties arising from the fact that the electron–proton scattering cross section is small when compared with the available beam intensities of circular electron accelerators. Linear electron accelerators are out of question because of the too low duty cycle.

After having overcome the experimental difficulties, we have been able to show that the $(e, e' p)$ reaction gives the same answer as the $(p, 2p)$ reaction on some nuclei, in addition we have seen very strongly bound protons in intermediate nuclei, where the $(p, 2p)$ reaction cannot give a fruitful answer, owing to the already pointed out proton absorption [4].

It is highly probable that we may extend the knowledge of nuclear structure far beyond mass number $A = 50$ and specially on inner shell of nuclei. The purpose of the present note is to show some results on Be^9 that is in the domain of light nuclei, because we think that also for light nuclei $(e e' p)$ reaction may be a source of valuable information.

In the case of $(e, e' p)$ reaction, relation (1) transforms into:

$$E_B = E_0 - (E_e + E_p) \tag{2}$$

where E_0 is the incident electron energy, E_e and E_p are scattered electron and final proton energies. Rest energies cancel between initial and final state so that all energies are kinetic energies. The counting rate is measured, for technical reasons, changing E_0 and not the sum offinal energies.

The experimental apparatus is shown in fig. 1. The incident electron beam is the Frascati Synchrotron internal beam. Scattered electrons are focused by a magnetic channel (two quadrupolar lenses plus a zero gradient bending magnet) on a focal line where five counters define five momentum channels. On the other side, a one steradiant aperture proton telescope is set to measure protons with kinetic energy between 97 and 103 MeV. The energy spread depends on four indipendent sources of energy definition. First comes the energy spread of the incident beam, under suitable condition this may be reduced below 4 MeV reducing the radiation pulse lenghth to less than 1.5 ms. The second source is the radiative energy loss in the target of the incident beam. For this it is sufficient to use a thin enough target (e.g. less than 0.1 radiation lengths). Under our experimental condition the combined energy spread due to the electron beam and the target was less that 6 MeV total. The third cause is the energy acceptance of electron channels and the fourth the same but for the proton channel. We have choosen 6 MeV for each of these energy channels, owing to the low counting rates that do not allow for a further reduction. Combining all the causes we hoped for an energy resolution (full width at half height) of less than 10 MeV. Cheks on the resolution have proved that actually we have reached this limit.

With this apparatus we have run a curve with a beryllium target. Experimental results are shown in figure 2. On the horizontal axis we have a double scale, the upper one is machine energy, the lower binding energy. The correspondance between the two scales is checked within not more than 3 MeV

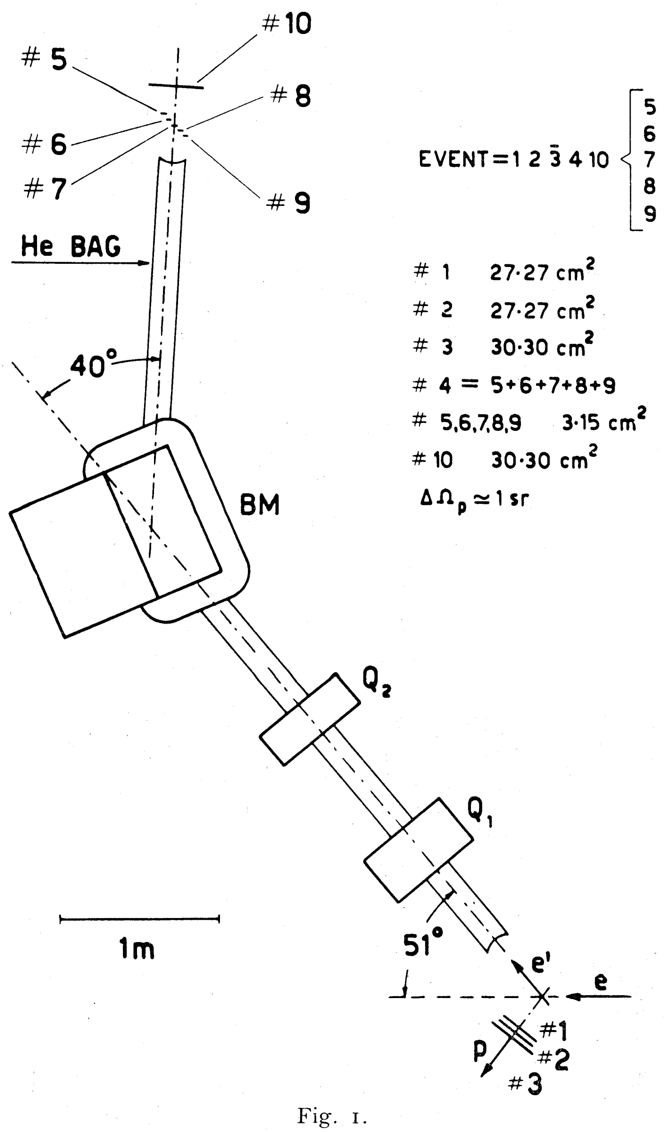

Fig. 1.

with magnetic measurements on the magnetic channel and range energy curves together with careful measurement of proton absorber thicknesses. An indipendent confirmation, that allows us to normalize our measurements within 1 MeV with other experiments, comes from a measurement of elastic scattering on hydrogen and $(e, e' p)$ reaction in carbon. Both gives as a zero of our energy scale 507 ± 0,5 MeV.

The experimental points have been fitted with a statistical best fitting numerical computation using two different hypothesis. Is is known, from shell model consideration, that protons in beryllium shoud divide into two groups; that is $1\,s_{1/2}$ protons and $1\,p_{3/2}$ protons. The spectrum should show at least two peaks at the binding energy of $1\,s$ and $1\,p$ shell. The $(p\,,2\,p)$ experimentation has actually shown three peaks, corresponding to binding energies of 16.4, 25.4, 32.3 MeV respectively. We can see that the first two peaks have a distance of less than our experimental energy resolution and thus may be hardly seen in our experiment. From $(p, 2\,p)$ experiment it is possible to assign these peaks to $1\,s_{1/2}$ and $1\,p_{3/2}$ protons. No assignement

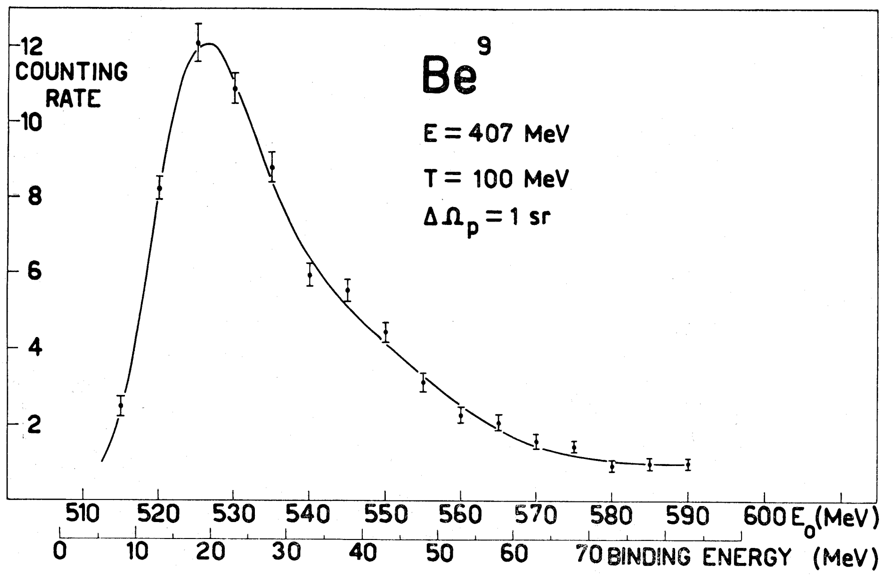

Fig. 2.

has been given for the third peak. Moreover only recent $(p\,,2\,p)$ experiments have actually shown this third peak the presence of which is very interesting. As a matter of fact, from two proton group in the initial nucleus, three binding energies are possible only if the *final nucleus* may be formed in a definite excited state.

Starting from these considerations coming from $(p\,,2\,p)$ reaction we have at first tried to fit our experimental points [5] with a sum of two maxwellian distribution.

$$y = h\,\frac{(x - x_0 + \sigma)^2}{2}\,\exp\left[1 - \frac{(x - x_0 + \sigma)^2}{2}\right]$$

(this shape has been choosen to simulate the so called "radiation tail") plus a straight line to account for a small background of inelastic events different from the $(e\,,e'\,p)$ reaction that seem to be present specially at higher energies. The best fit gives, at a substantially good confidence level (30 %) the parameters collected in Table I.

TABLE I.

h (counting rate)	σ (MeV)	x_0 (MeV)
9.0 ± 0.9	13.2 ± 1.0	524.9 ± 0.7
4.3 ± 1.6	26.2 ± 2.7	539.4 ± 1.9

From Table I we have a confirmation of the existence of a first group of protons bound with approximately 18 MeV binding energy and of a second group with about 33 MeV binding energy. The first group clearly corresponds to the sum of the contributions of the two 1 $s_{1/2}$ and 1 $p_{2/3}$ levels not sufficiently separated because of the inadequate resolution. The fit shows, however a systematic deviation of computed versus experimental points in the region of the first peak. A second fit has been attempted even if the total number of experimental points is barely sufficient to fit the points within statistical meaning. The three peak best fit has a confidence level of a little more than 5 % thus on the border of statistical significance. The three proton groups (Table II) have approximately 15, 20, 31 MeV binding energy.

TABLE II.

h (counting rate)	σ (MeV)	x_0 (MeV)
4.4 ± 1.0	11.0 ± 2.0	522.0 ± 1.2
5.3 ± 1.0	11.8 ± 1.9	527.0 ± 1.2
4.6 ± 0.5	26.4 ± 2.5	538.3 ± 1.7

The tables give amplitude and width of the distributions. The first peak of table 1 decomposes, according to table 2 in two peaks each of about half area.

This feature, if the interpretation of the two peaks is correct, corresponds to the existence of two 1 $s_{1/2}$ and two 1 $p_{3/2}$ protons in beryllium. This leaves the interpretation of the third peak completely open. It may be added that the width of this peak may still be due to an underlying structure, however this seems not to be the case also from $(p, 2p)$ reaction, looking to the fact that, in this energy region, the fit seems to be particularly good, as it may be seen from the curve of fig. 2. This curve is the sum of the interpolation of two maxwellian distributions plus the straight line background.

The conclusion that may be drawn from $(e, e' p)$ measurement of beryllium is further evidence of the existence of a proton group in the vicinity of 32 MeV binding energy, togheter with a confirmation of the $1\,s_{1/2}$ $1\,p_{2/3}$ structure even if lack of resolution does not add new knowledge about these binding energies.

This 32 MeV level, has still a comparatively narrow energy distribution in $(p, 2p)$ experiment, even if it may have a structure, and this feature points out to the fact that it is necessary further investigation even in the field of proton binding energies of light nuclei, because this may disclose more important informations about excited states of nuclei. It is for this reason that our group is not only investigating inner levels of heavier nuclei, but also plans to study higlhy excited states of light nuclei, using the $(e, e' p)$ reaction eventually improving energy resolution to study the structures that may lay in the high energy portion of the spectra.

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Riassunto. — *La reazione $(e, e'p)$ per il nucleo di berillio.* Dal 1957 ad oggi si è aperto un nuovo campo di ricerche di fisica dei nuclei. Gli esperimenti in cui si studia la reazione $(p, 2p)$ in nuclei hanno permesso di verificare direttamente l'esistenza dei livelli energetici dei protoni nello stato fondamentale dei nuclei stabili e di misurare l'energia di legame relativa a questi livelli. La tecnica fondata sulla reazione $(p, 2p)$ incontra serie limitazioni dovute alla forte interazione dei protoni entranti e uscenti con il nucleo stesso, queste limitazioni portano alla pratica impossibilità di studiare i livelli interni di nuclei che abbiano numeri di massa ancora non molto elevati. Questa difficoltà praticamente non sussiste per la reazione $(e, e'p)$. Discusse le caratteristiche di questo tipo di misura, si danno i risultati sperimentali per il nucleo di berillio e se ne discutono gli aspetti più interessanti.