COULOMB DISSOCIATION EXPERIMENTS OF ASTROPHYSICAL SIGNIFICANCE*

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The Coulomb field of a heavy nucleus provides an intense source of quasi-real photons acting on passing nuclear particles. This fact has many applications in studies of nuclear structure problems. Coulomb dissociation of fast projectiles has been proposed as a novel method to investigate radiative capture processes (time-reversed to photodisintegration). This is a new access to a specific class of radiative capture reactions at low energies, relevant for nuclear astrophysics, and it does overcome various limitations of direct measurements. This lecture puts emphasis on a general discussion of the favourable experimental conditions, of related theoretical problems of the analysis and possible pitfalls of the approach. Various cases of actual astrophysical interest and current applications are discussed.

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O perpetual revolution of configured stars,
O perpetual recurrence of determined seasons,
O world of spring and autumn, birth and dying,
The endless cycle of idea and action,
Endless invention, endless experiment.

T.S. Elliot, Choruses from "The Rock"
(quoted by Z. Szymanski at the Mazurian Lakes School)

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1. Introduction

Relativistic heavy-ion collisions do not only probe nuclear matter under extreme conditions of pressure and temperature, they are also an important tool for traditional nuclear physics research with new experimental possibilities. These are based on what happens in *distant* high-energy collisions between nuclei without nuclear contact, completely governed by electromagnetic interaction and very different from frontal collisions. In such situations the cross sections are enhanced by large factors Z^2 and Z^4 for one- and two-photon processes, respectively. Due to the Lorentz contraction of the field, generated by the fast passing nucleus, the interaction partners feel an extremely short time-pulse whose equivalent photon-spectrum is very intense and extends to comparatively large energies. This lecture is focussed to applications of these features to laboratory nuclear astrophysics.

Understanding of nucleosynthesis at various sites of primordial and stellar burning requires the knowledge of an ever increasing number of reaction rates. This knowledge is a prerequisite for testing the consistency of models describing the big-bang scenario and stellar evolution processes in quiescent and more explosive phases, more and more with the quest for rates involving radioactive species.

As the relevant collision energies are comparatively small, measurements of the requested cross sections are, in general, a rather difficult and frustrating task. The expected values are among the smallest to be studied in the laboratory, experimentally accessible only with special efforts in suppressing background. The standard laboratory approach involves the bombardment of rather *thin targets* by *extremely low-energy projectiles,* in particular in case of a specific class of thermonuclear fusion: *radiative capture processes.* The Coulomb barrier strongly suppresses the cross sections at low energies (stellar temperatures). Usually they are obtained by extrapolations from the laboratory energy region over several decades downwards. The extrapolation procedures, using the concept of the astrophysical S-factor, are not free from theoretical bias and have led to incorrect results in some cases. The situation can be illustrated by reminding of some examples of central astrophysical interest.

(i) The $^3\mathrm{He}(\alpha,\gamma)\,^7\mathrm{Be}$ and $^7\mathrm{Be}(p,\gamma)\,^8\mathrm{B}$ capture reactions are in the proton-proton chain by which our Sun produces energy, with a central temperature equivalent to 15 keV. The experimental lower limit of these cross sections are far off, but their solar values substantially affect the solar neutrino flux, recorded in the solar neutrino detectors.

(ii) Similarly the rates of the key reaction for stellar helium burning, $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$, determining the C–O abundances, are unknown at the relevant energies.

(iii) ^{7}Li and ^{6}Li are partially synthesized in the expanding universe, a few minutes after primordial big-bang. The $(\alpha + t)$ and $(\alpha + d)$ reactions are important building blocks of the light-element nucleosynthesis network, testing cosmological scenarios.

In view of the limitations of the standard experimental approach for capture reaction studies, an alternative experimental access to the electromagnetic matrix elements, determining the radiative capture processes, has been proposed [1] as a novel approach: *Reversing the electromagnetic capture by dissociation of the fused system in the Coulomb field of a large Z nucleus, i.e.* inducing photodisintegration of fast projectiles. The method has been worked out and successfully demonstrated [2] by a pilot experiment at the Karlsruhe Isochronous Cyclotron, studying Coulomb breakup of 156 MeV ^{6}Li projectiles. A topical review discussing details of the Coulomb dissociation approach and the status of current experiments has been published in 1994 [3]. This lecture sketches the most important features with emphasis to implications of the method and applications to cases of current astrophysical interest.

2. Coulomb dissociation of fast projectiles

A sufficiently fast charged nuclear projectile, when peripherally passing the Coulomb field of a heavy nucleus experiences a copious source of quasi-real photons. They induce photodisintegration processes, determined by the same electromagnetic matrix elements as the time-reversed capture processes. The experimental advantages are the following:

(i) At high projectile energies the fragments emerge with fast velocities (around the beam velocity). This facilitates their detection and enables the use of thicker targets with higher rates.

(ii) Simultaneously adequately tuned kinematical conditions for coincidence measurements enable studies of rather low relative energies (virtually down to zero), observing near parallel emission (see Fig. 1) and isolating the elastic breakup, *i.e.* that mode when the target stays in the ground state. This mode is of specific interest. The three-body kinematics allows to study the excitation of the projectile continuum along a well defined kinematical line of the fragment energy correlation, and the so-called magnifying glass effect leads to an accurate determination of the relative energy of the fragments.

(iii) In addition, the large number of quasi-real photons seen by the passing projectiles leads to an enormous enhancement of the cross section, which can be (in first order) theoretically factorized, for each multipolarity, in the photodisintegration cross section $\sigma_{\mathrm{EL}}^{\mathrm{Photo}}$ and an amplification factor $dN_{\mathrm{EL}}/d\Omega$, the virtual photon number per unit solid angle.

$$\frac{d^2\sigma}{d\Omega dE_x} = \frac{1}{E_x}\frac{dN_{\rm EL}}{d\Omega}\sigma_{\rm EL}^{\rm Photo}$$

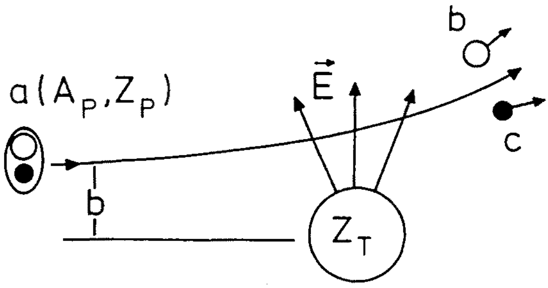

Fig. 1. Coulomb dissociation of a projectile $a \to b+c$ in the field of a target nucleus ($Z_{\rm T}$).

In order to reach the nuclear continuum by means of electromagnetic excitation, the equivalent photon spectrum should contain the corresponding high frequency components ω. The "safe bombarding condition" of (sub)-Coulomb excitation implies a severe limitation of the equivalent photon spectrum to rather low energies. Therefore it is advantageous to use projectile velocities v well above the Coulomb barrier, in order to overcome the adiabaticity condition

$$\hbar\omega \leq \frac{\hbar c}{b}\left(\gamma\frac{\nu}{c}\right), \tag{1}$$

where b is the impact parameter, and $\gamma = 1/\sqrt{1-(\nu/c)^2}$. Electromagnetic excitation processes occur dominantly for sufficiently large values of $b > R_1 + R_2$, the sum of the nuclear radii, *i.e.* at very forward angles. Nuclear excitation effects originate from grazing collisions. These grazing collisions can in principle also lead to forward scattering angles and may interfere with the electromagnetic excitation characterized by l-values much beyond grazing. Thus, the "footprints" of nuclear and electromagnetic excitation show up clearly in the angular distribution. These effects can be quantitatively studied in a DWBA approach. Simpler methods, of the eikonal type, and trajectory calculations [2] can be very helpful to explore the physics of the interference of Coulomb and nuclear excitation and to adjust optimum conditions.

A severe and challenging problem arises especially for direct transitions into the continuum: "Post-acceleration" or "Coulomb final-state-interaction" change the relative energy between the outgoing fragments which is determined by the asymptotic kinematics of coincident experimental observation. Since the strength of the Coulomb interaction scales with $1/v$, these effects are expected to be especially strong for low beam energies. As sufficiently

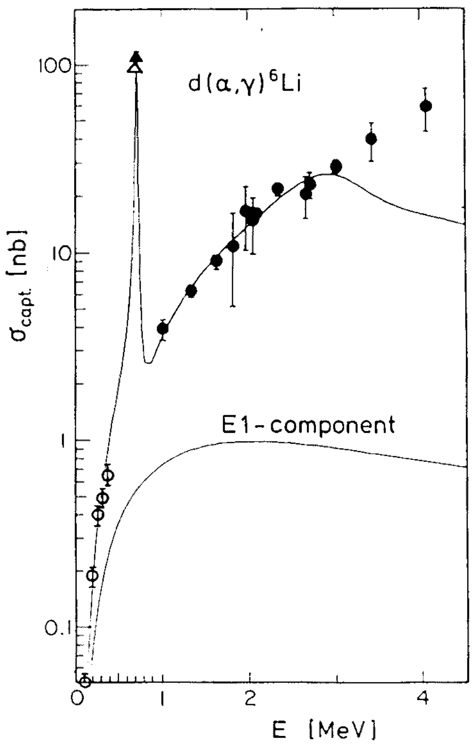

Fig. 2. Cross section for the $d(\alpha,\gamma)^6$Li capture reaction. The low-energy data (open circles) are deduced from Coulomb dissociation of 156 MeV ^{6}Li projectiles [2].

high energies, which are of actual interest, a tremendous simplification occurs due to $\tau_{\text{coll}} \ll \tau_{\text{nucl}} = h/(E_n - E_0)$. Consequently we can apply the sudden approximation or Glauber theory ("frozen nucleus") [4]. These approaches have the merit that the response of the nucleus, which is excited, is treated in a fully quantal way. The semiclassical picture of a classical relative motion of projectile and target can be retained. Interesting problems related to the time-dependent response of the projectile system to the transient Coulomb field of the target nucleus arise. It is a hope to use the time-dependent Coulomb field as a "clock" with investigating the time-dependence of nuclear excited states. The investigation of the time-dependent tunnelling problem is of special interest. It is well known that the radial matrix-element of low-energy radiative capture peak at radii well beyond the range of nuclear interactions. At careful discussion of the time-dependence of the projectile wave function will be necessary to judge the relevance of the overlap of the wave-function of the break-up fragments with the target nucleus. Taking into account the time-dependence of the projectile wave-function, strong interaction effects are considerably reduced [3].

Fig. 2 displays the result of the Karlsruhe pilot experiment [2] investigating the dissociation of ^{6}Li $\Rightarrow \alpha + d$, which is a case of minimal post-acceleration effects and provides an ideal testing ground. The low-energy data, deduced from the Coulomb dissociation measurements, being before experimental "terra incognita", demonstrate the potential of the approach.

Though the integrated cross section measured at $E_{\rm Li} = 60$ MeV [5] are in agreement with an interpretation in terms of first-order Coulomb excitation theory, the angular correlations of the nonresonant breakup exhibit considerable discrepancies. This feature may indicate some distortions due to nuclear contributions at low energies.

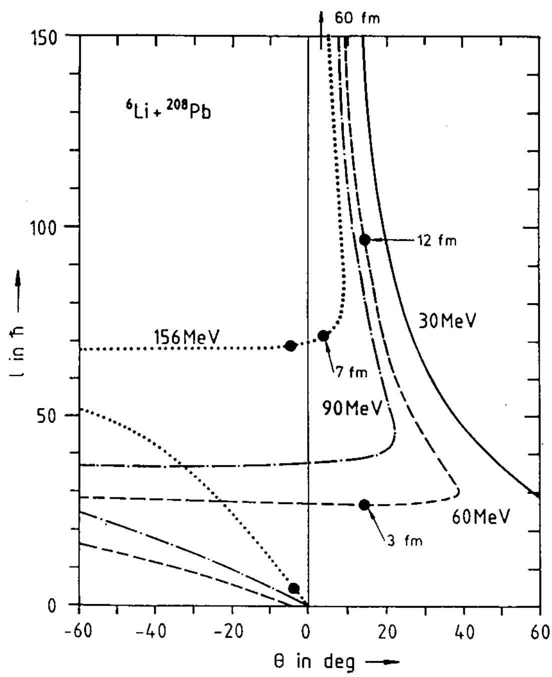

Fig. 3. Deflection functions for the ^{6}Li + ^{208}Pb system under the influence of the nuclear and Coulomb interactions, indicating the "loci of operation" of different experimental conditions [2].

This conjecture is corroborated by the semiclassical deflection functions (Fig. 3). The points show the loci of operation at particular values of very forward angles. In case of 156 MeV, one of the working points (60 fm) corresponds to trajectories far from the nuclear edge, while the others are well inside the strong absorption radius of ^{208}Pb, hardly contributing to *elastic* breakup.

3. Experimental sites of the Coulomb dissociation approach

The Coulomb dissociation approach is preferably applicable to systems with low particle decay thresholds (of a few MeV) and with a relatively simple energy level structure. This condition is often met with exotic nuclei and favours the use of radioactive beams. The choice of the most suitable conditions in energy and angular range needs a careful consideration of the specific features of each particular case, along the arguments of minimizing disturbances by nuclear interference and higher-order processes. In general, large projectile energies are favourable. They assure the non-adiabacity condition

$$\xi(b) = \frac{\omega b}{\gamma v} \ll 1 \tag{2}$$

which guarantees the dominance of Coulomb excitation at $E_x = \hbar\omega$ and reduces problems arising from post-acceleration effects.

High projectile energies, however, shrink the forward angular range with large impact parameters (characterized by $\sigma_{\mathrm{elast}}/\sigma\mathrm{Ruth} \simeq 1$) and lead to difficulties to achieve the required angular accuracy and resolution. Actually, from kinematics the minimum relative energy $E_{bc}^{\min}$ of the fragments

$$E_{bc}^{\min} = \frac{1}{m_b + m_c}\left(m_c E_b + m_b E_c - 2\sqrt{m_b m_c E_b E_c}\cos\Theta_{bc}^{\min}\right) \tag{3a}$$

and the limiting energy resolution

$$dE_{bc} = \frac{2\sqrt{m_b m_c E_b E_c}}{m_b + m_c}\sin\Theta_{bc} d\Theta_{bc} \tag{3b}$$

are dominantly defined by the relative emission angle Θ_{bc} and the angular uncertainty. Therefore, a careful optimization of the experimental setup with this respect is crucial for studying low relative energies.

The pilot ^{6}Li experiment [2] used a magnetic spectrograph ("Little John"), specially equipped for extreme-forward angle observation of near parallel emission of the fragments, which are coincidentally detected by a split focal plane detector, and allowing event-by- event retracing by adequate x-y position sensitive devices installed in the beam line.

4. Astrophysical sites

There is obviously a broad field of possible applications for astrophysical problems (see Table I).

TABLE I

Radiative capture reactions of interest for light element synthesis accessible by Coulomb dissociation of fast projectiles.

Reaction	$T_{1/2}$ (projectile)	Astrophysical Site	Reference
$^{3}He(\alpha,\gamma)^{7}Be$	53.3 d	Solar neutrino problem	
$^{7}Be(p,\gamma)^{8}B$	770 ms	^{3}He abundancy	Motobayashi *et al.* 1994 [6]
$^{7}Be(\alpha,\gamma)^{11}C$	20.4 m		
$^{4}He(d,\gamma)^{6}Li$	stab.	Primordial nucleosynthesis	Kiener *et al.* 1989, 1991 [2]
$^{6}Li(p,\gamma)^{7}Be$	53.3 d	of Li- Be- B-isotopes	
$^{6}Li(\alpha,\gamma)^{10}B$	stab.		
$^{4}He(t,\gamma)^{7}Li$	stab.		Utsunomiya *et al.* 1990 [7]
$^{7}Li(\alpha,\gamma)^{11}B$	stab.		
$^{11}B(p,\gamma)^{12}C$	stab.		
$^{9}Be(p,\gamma)^{10}B$	20.4 m		
$^{10}B(p,\gamma)^{11}C$			
$^{7}Li(n,\gamma)^{8}Li$	842 ms	Primordial nucleosynthesis	
$^{8}Li(n,\gamma)^{9}Li$	178 ms	in Inhomogeneous	
$^{12}C(n,\gamma)^{13}C$	stab.	Big Bang	
$^{14}C(n,\gamma)^{15}C$	2.45 s		
$^{14}C(\alpha,\gamma)^{18}O$			
$^{12}C(p,\gamma)^{13}N$	10 m	CNO-cycles	
$^{16}O(p,\gamma)^{17}F$	65 s		Motobayashi *et al.* 1991 [8],
$^{13}N(p,\gamma)^{14}O$	70.6 s		Kiener *et al.* 1993 [9]
$^{20}Ne(p,\gamma)^{21}Na$	22.5 s		
$^{11}C(p,\gamma)^{12}N$	11 ms	Hot *p–p* chain	Lefevbre *et al.* 1995 [10]
$^{15}O(\alpha,\gamma)^{19}Ne$	17.2 s	rp-process	
$^{31}S(p,\gamma)^{32}Cl$	291 ms		
$^{12}C(\alpha,\gamma)^{16}O$	stab.	Helium-burning	Tatischeff *et al.* 1995 [11]
$^{16}O(\alpha,\gamma)^{20}Ne$	stab.		Utsunomiya *et al.* 1994 [12]
$^{14}N(\alpha,\gamma)^{18}F$	109.7 m		

Presently there are now at least five successful experiments [2, 6, 8–10], providing new data for astrophysical considerations. The results of the two Coulomb dissociation experiments: $^{14}O \Rightarrow {}^{13}N + p$, at $E_0 = 87.5$ MeV/A [8] and $E_0 = 70$ MeV/A [9], respectively, compare well with each other and with a capture experiment [13] using a radioactive ^{13}N beam.

The radiative capture process $^{11}C(p,\gamma)^{12}N$ is part of the reaction network in the hot p–p chain, and it is also important for the synthesis of ^{11}B in novae. The Coulomb dissociation technique has been used [10] to determine the radiative width of the $E_x = 119$ keV level of ^{12}N and its contribution of the direct capture process.

A really challenging case with continuum transitions of mixed multipolarities is the breakup of $^{16}O \Rightarrow \alpha + {}^{12}C$. The importance of the $^{12}C(\alpha,\gamma)^{16}O$ radiative capture process for nuclear astrophysics is discussed with controversial results of the astrophysical S-factor at low energies (see [11, 12]). The Coulomb dissociation approach was theoretically outlined in Refs [1, 14]. Due to the relatively high threshold ($Q = -7.162$ MeV) large incident ^{16}O energies are necessary to overcome the adiabaticity condition. The problem that E2 equivalent photon numbers are strongly dominating over E1 has been also emphasized, and the sensitivity of angular correlations to E1–E2 interferences has been pointed out [14]. Several research groups are discussing the feasibility of experiments and preparing measurements [11, 12].

The investigation of the ^{7}Be (p,γ) ^{8}B cross section is of central importance for the solar neutrino problem. This background and a first experimental attempt [6] of Coulomb dissociation of ^{8}B are discussed in the following section.

5. The Coulomb dissociation of ^{8}B and the solar neutrino flux

The flux of neutrinos, produced in the weak-interactions steps within the solar nuclear burning processes (predominantly the proton-proton fusion chain) is currently measured by different types of detectors. The so-called solar neutrino problem results from a deficit of the observed flux as compared to the predictions of (various versions of) the standard solar model (SSM). The result of 25 years of data collection of the HOMESTAKE-experiment [15], based on the chemical detection of the Ar from the reaction

$$v_e + {}^{37}Cl \Rightarrow {}^{37}Ar + e^-,$$

is

$$2.55 \pm 0.25 \text{SNU} \ (1\sigma)\,.$$

(SNU: Solar Neutrino Unit = 1 capture / s 10^{36} target atoms) compared to the expectation

$$8.00 \pm 1.00 \text{ SNU} \ (1\sigma)$$

according to Bahcall's SMM [16]. Due to energy threshold (814 keV) for neutrino capture, the Cl-detector is blind for the most abundant pp neutrinos, but it can detect neutrinos from the ^{7}Be and ^{8}B decays of the side-cycles of the proton-proton fusion chain of solar energy production. A deficit of the high-energy neutrino flux from ^{8}B ($E_v \geq 7$ MeV) is also indicated by the real-time measurements of the KAMIOKANDE experiment [17] observing neutrino-electron scattering in large water Cerenkov detectors. (A recent comparative data summary of the current neutrino experiments, including the GALLEX and SAGE experiments is given in Ref. [17]). However, the neutrino flux $\phi_{\rm KA}$ (originating exclusively from ^{8}B-decay), observed by the KAMIOKANDE detector, is not consistent with the result $\phi_{\rm Cl}$ of the Cl-experiment:

$$\phi_{\rm Cl}(^7{\rm Be} + {}^8{\rm B}) < \phi_{\rm KA}(^8{\rm B}) .$$

This exhibits an additional puzzle. In the discussion of these findings, among the most uncertain ingredients entering in the theoretical estimates there are the rate of the ^{7}Be (p, γ) ^{8}B and additionally the rate of the ^{3}He (α, γ) ^{7}Be, opening the branch for high-energy neutrino production. A first attempt to measure the reaction rate of ^{7}Be (p, γ) ^{8}B via the Coulomb dissociation method has been made by Motobayashi ıet al. [6]. From point of view of the theoretical analysis the case $^8{\rm B} \Rightarrow {}^7{\rm Be}+p$ is very favourable for the Coulomb dissociation approach. Due to the low breakup threshold ($E_{\rm th} = 137$ keV) rather low energies of the equivalent photons are relevant for the astrophysical interest, and for projectile energies of ca. 50 MeV/A corrections for post-acceleration effects appear to be reliably tractable. The situation has been recently reviewed [19]. ^{8}B has been produced by bombarding a ^{9}Be target with a ^{12}C beam at 92 A MeV, accelerated in the RIKEN cyclotron. The reaction products were separated by the RIKEN projectile separator (RIPS). The averaged ^{8}B energy at the target was 46.5 A MeV with an intensity of 2 10^4 s^{-1}. A ^{208}Pb has been bombarded with the secondary ^{8}B beam. The breakup products, proton and ^{7}Be were measured by a plastic scintillator hodoscope; it consists of a 5 mm thick ΔE plane, segmented horizontally into 10 strips and a 6 mm thick E plane, subdivided vertically in 16 strips, *i.e.* altogether in 10×16 segments. The energy of the particles was measured by time-of-flight methods, and the complete breakup kinematics has been determined.

It should be noted that with the actual restrictions in energy and angular resolution a minimum relative energy of 600 keV has been reached (Fig. 4), and a (preliminary) value of $S_{17}(0) = 16.7 \pm 3.2$ eV b has been extracted by extrapolation. This results leads to a considerable reduction of the ^{8}B solar neutrino flux. We note that the Coulomb dissociation process is rather insensitive to the M1 component, since the flux of quasi-real M1 photons scales with β^2. Thus the 1^+ state of ^{8}B at $E_x = 632$ MeV is not excited. This implies a 10% correction when comparing with the result of direct radiative capture reaction. There had been an slightly aggressive discussion about the existence of an E2 component, which, however, could

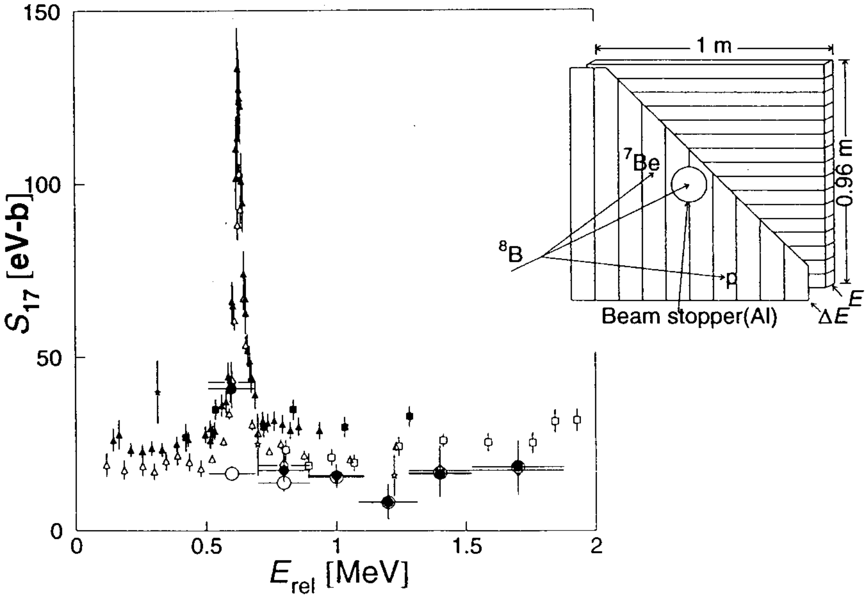

Fig. 4. The astrophysical S_{17} factor [20] deduced from the RIKEN Coulomb dissociation experiment [6], plotted together with existing (p,γ) data [21] renomalized by Fillipone(see [20]), according to a recent critical reevaluation of the capture experiment.

be excluded after a careful re-analysis [22]. More recently Dutt-Mazunder and Shyam [23] has analyzed the data independently with the result of $S_{17}(0) = 15.8 \pm 2.4$ eV b. There are experimental efforts in GSI to extend the measurements to lower relative energies of the fragments [20].

6. Concluding remarks

The Coulomb dissociation approach is appreciated as a major methodical progress for laboratory nuclear astrophysics. The theoretical implications and problems associated with the method are well identified, and interesting new results have been obtained [24]. The approach gains particular importance with the advent of facilities which produce high- energy radioactive beams. However, we are approaching a status for a quest of more dedicated facilities, not only just as side user of experimental arrangements optimised for other purposes. The layout should enable improved experimental techniques, in particular improving ecomically the quality of radioactive beams and applying refined spectroscopic techniques like ray tracing methods for suitable magnetic spectrographs. I am advocating a dedicated cooler ring setup devised for the necessities of the Coulomb dissociation method.

I would like to thank G. Baur for pleasant and fruitful discussions.

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